Nature-Based Climate Solutions

Expert Panel on Canada's Carbon Sink Potential

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This project was undertaken with the approval of the Board of Directors of the Council of Canadian Academies (CCA). Board members are drawn from the Royal Society of Canada (RSC), the Canadian Academy of Engineering (CAE), and the Canadian Academy of Health Sciences (CAHS), as well as from the general public. The members of the expert panel responsible for the report were selected by the CCA for their special competencies and with regard for appropriate balance.

This report was prepared for Environment and Climate Change Canada (ECCC). Any opinions, findings, or conclusions expressed in this publication are those of the authors, the Expert Panel on Canada's Carbon Sink Potential, and do not necessarily represent the views of their organizations of affiliation or employment, or the sponsoring organization, ECCC.

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The Expert Panel on Canada's Carbon Sink Potential would like to acknowledge the Inuit, Métis, and First Nations Peoples who have been stewards of the lands now known as Canada. For generations, Indigenous Peoples have lived in reciprocal relationships with the land, applying practices to sustainably harvest natural resources and preserve natural cycles.

The Council of Canadian Academies (CCA) acknowledges that our Ottawa offices are located in the unceded, unsurrendered ancestral home of the Anishinaabe Algonquin Nation, who have nurtured the land, water, and air of this territory for millennia and continue to do so today.

Though our offices are in one place, our work to support evidence-informed decision-making has broad potential impact across Canada that may contribute to collective actions to reduce greenhouse gas emissions in ways that empower Indigenous decision-making and ethically include Indigenous knowledge systems.

We at the CCA recognize the importance of drawing on a wide range of evidence, knowledge and experiences to inform policies that will build a stronger and more equitable and just society.

The Council of Canadian Academies

The CCA is a not-for-profit organization that supports independent, science-based, authoritative expert assessments to inform public policy development in Canada. Led by a Board of Directors and advised by a Scientific Advisory Committee, the CCA's work encompasses a broad definition of science, incorporating the natural, social, and health sciences as well as engineering and the humanities. CCA assessments are conducted by independent, multidisciplinary panels of experts from across Canada and abroad. Assessments strive to identify emerging issues, gaps in knowledge, Canadian strengths, and international trends and practices. Upon completion, assessments provide government decision-makers, researchers, and stakeholders with the high-quality information required to develop informed and innovative public policy.

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Expert Panel on Canada's Carbon Sink Potential

Under the guidance of its Scientific Advisory Committee, Board of Directors, and founding Academies, the CCA assembled the **Expert Panel on Canada's Carbon Sink Potential** to undertake this project. Each individual was selected for their expertise, experience, and demonstrated leadership in fields relevant to this project.

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Message from the President and CEO

As a signing party to the 2015 Paris Agreement, the Government of Canada has committed to reducing greenhouse gas (GHG) emissions 30% below 2005 levels by 2030. Along with other signatories, Canada has been exploring strategies to help it meet these reduction targets, including harnessing natural systems for carbon storage. A globally significant stock of carbon is stored in Canada's vast and ecologically diverse landscapes, from wetlands to forests, grasslands to croplands, and across marine coastal zones. Keeping those stocks intact and actively managing systems to reduce GHG emissions could help in efforts to combat climate change.

The term nature-based climate solutions, or NBCSs, refers to the protection, restoration, or expansion of ecosystems that sequester carbon, or reduce emissions to the atmosphere. These types of solutions can include actions such as restoring forest cover, managing nutrient inputs to croplands, and avoiding deforestation or wetland drainage. NBCSs can also provide valuable environmental and social co-benefits.

With growing recognition of the potential role carbon sinks can play in regulating GHGs in the atmosphere, Environment and Climate Change Canada asked the CCA to examine the potential for enhancing carbon storage and reducing emissions through NBCSs to support climate change mitigation and adaptation planning in Canada.

Despite increasing attention on the potential of natural carbon sinks to support climate policy, there are limitations to this approach. *Nature-Based Climate Solutions* provides an overview of natural carbon sinks, including the significance of Canadian carbon sinks in the global context; options for enhancing carbon sequestration or reducing emissions in various ecosystems; and the potential co-benefits and barriers to implementing NBCSs in Canada. The report also explores how Indigenous Peoples are key partners in carbon sequestration initiatives in Canada.

I extend my thanks to the Panel, led by Chair Glen MacDonald, for their extensive expertise in carbon sinks and the respective ecosystems in which they are found. My deepest appreciation to the Indigenous knowledge holders who made vital contributions to the panel discussions.

Further oversight and key guidance during the assessment process were provided by CCA's Board of Directors; Scientific Advisory Committee; and its founding Academies, the Royal Society of Canada, the Canadian Academy of Engineering, and the Canadian Academy of Health Sciences. I extend my thanks to them all.

Eric M. Meslin, PhD, FRSC, FCAHS
President and CEO, Council of Canadian Academies

Message from the Chair

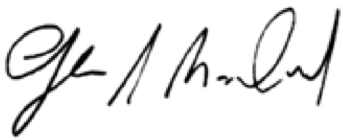
The existential threat posed to humans and the environment by climate change can no longer be considered one that awaits us at the end of the century. The world is already experiencing escalating climatic catastrophes induced by increasing GHG concentrations in the atmosphere. In 2019, Canada ranked 9th among GHG emitting countries in terms of total emissions and is currently experiencing some of the most rapid temperature changes observed worldwide. The Government of Canada has committed to reducing GHG emissions 30% below 2005 levels by 2030 and to achieving net-zero emissions by 2050. These are ambitious but necessary targets. To meet them, Canada must adopt a multisectoral approach. One component of such an approach is the use of nature-based climate solutions (NBCSs) which aim to capture and store atmospheric carbon. Given its size and abundance of natural ecosystems, Canada's potential to sequester carbon with NBCSs is much greater than that of most countries.

The question posed to our Panel was daunting — to be answered fully, it required expertise in a wide range of areas including climatology, ecology, agronomy, and economics. Further, Indigenous knowledge was key to complementing western scientific data and to highlight the role of Indigenous communities in caring for the land and waters. The Panel considered current carbon sequestration potential alongside future potential as impacted by factors such as climate change. These deliberations also extended to the economic, political, and cultural feasibility of NBCSs. In addition, potential deleterious trade-offs and positive co-benefits were examined.

We concluded that NBCSs can contribute to meeting Canada's emissions reduction commitments, but this contribution is modest and thus, will require strong action in many other sectors. To achieve the scale of implementation required for significant deployment of NBCSs, integrated approaches involving the public and all levels of government would be essential. The Panel recognized that these solutions also offer many important environmental and cultural co-benefits that would help achieve other targets.

During the assessment process, two key findings arose. First, Canada possesses huge carbon stocks in its forests, soils, and aquatic environments. These stocks are at risk of being released to the atmosphere. The implementation of NBCSs can be an important mechanism to preserve these carbon stocks *in situ*. Second, Canada has the potential to be a leader in the successful implementation of NBCSs and expand the impact of its efforts globally. We hope our report will meaningfully contribute to both Canadian and international efforts to implement NBCSs to meet the challenges of climate change.

I wish to thank the Panel members who worked so hard and thoughtfully on this report. This was one of the most challenging tasks I have undertaken but one of the most pleasant, intellectually stimulating, and inspiring, because of our Panel. I also thank the Indigenous experts who contributed their knowledge and wisdom during our workshop. The indefatigable project team of the CCA was simply incredible, and we owe them much for their hard work. We also owe a debt to the many reviewers who scrutinized a draft of the report. Finally, on behalf of the Panel, I thank Environment and Climate Change Canada and the six supporting federal departments and agencies for sponsoring this work, and the CCA for having faith in our Panel, allowing us to make what we feel is an important contribution to Canada and the planet.



Glen MacDonald, FRSC
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Peer Review

This report was reviewed in draft form by the individuals listed below — a group of reviewers selected by the CCA for their diverse perspectives and areas of expertise.

The reviewers assessed the objectivity and quality of the report. Their confidential submissions were considered in full by the Panel, and many of their suggestions were incorporated into the report. They were not asked to endorse the conclusions, nor did they see the final draft of the report before its release. Responsibility for the final content of this report rests entirely with the authoring Panel and the CCA.

The CCA wishes to thank the following experts for their review of this report:

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The peer review process was monitored, on behalf of the CCA's Board of Directors and Scientific Advisory Committee, by **Nicole A. Poirier, FCAE,** President, KoanTeknico Solutions Inc. The role of the peer review monitor is to ensure that the Panel gives full and fair consideration to the submissions of the peer reviewers. The Board of the CCA authorizes public release of an expert panel report only after the peer review monitor confirms that the CCA's report review requirements have been satisfied. The CCA thanks Dr. Poirier for her diligent contribution as peer review monitor.

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Graeme Reed, Senior Policy Advisor, Environment, Lands and Water Branch, Assembly of First Nations

Frank Brown, Proprietor, See Quest Development

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Executive Summary

Reducing greenhouse gas (GHG) emissions has become a global priority, evidenced by the 195 signatories to the Paris Agreement — a binding international treaty on climate change. Among available means to mitigate climate change are solutions that can naturally remove carbon from the atmosphere. Nature-based climate solutions (NBCSs) are increasingly viewed as potentially significant contributors to GHG reductions, especially in countries such as Canada, which has a vast and ecologically rich landscape. NBCSs may help advance climate change mitigation goals by intentionally enhancing carbon sequestration or reducing emissions from natural systems. They consist of practices aimed at protecting, restoring, or managing ecosystems that sequester carbon or reduce release of GHGs to the atmosphere.

Recognizing the need to better understand the potential contribution of NBCSs to Canada's 2030 emissions reduction and 2050 net-zero targets, Environment and Climate Change Canada (ECCC) and six supporting federal departments and agencies asked the CCA to convene an expert panel to answer the following question:

> What is the potential for nature-based solutions to help meet Canada's GHG emission reduction goals by enhancing carbon sequestration and storage, and reducing emissions, in managed and unmanaged areas (e.g., wetlands, agricultural and forest systems, harvested wood, and as blue (marine) carbon), and taking into account the major non-CO_2 climate impacts that can be reliably estimated (e.g., non-CO_2 GHG emissions, albedo, and aerosols)?

To address the charge, the CCA assembled a multidisciplinary panel of 15 experts (the Panel) from Canada and abroad. Panel members' expertise covered many of the ecosystems found in Canada, as well as carbon and nitrogen cycling and modelling, economics, public policy, and Indigenous knowledge. Additional Indigenous knowledge-holders, academics, and practitioners also contributed to the Panel's analysis.

The Panel's Approach

NBCSs are subject to various definitions and for the purpose of this report, the Panel defined them as:

> protection, management, and restoration actions applied to managed and unmanaged ecosystems that provide additional climate change mitigation by way of carbon sequestration or reduced GHG emissions, relative to a defined baseline. Beyond climate change mitigation, optimal NBCSs provide co-benefits and minimize adverse effects.

Canada's extensive land mass, long coastlines, and diverse ecosystems offer a wide range of opportunities for implementation of NBCSs. However, these opportunities differ in key aspects, including the magnitude and timing of their impacts on GHG fluxes and the nature of the constraints they may face. Effective implementation of NBCSs requires policies and interventions uniquely designed for the ecosystems, regions, and political contexts where they are deployed. Policymakers also require an understanding of the overall potential and limitations of NBCSs, as well as a sense of which NBCSs are most promising as reliable strategies to support.

The Panel undertook a comparative analysis of NBCSs, with a focus on (i) GHG mitigation potential (either through carbon sequestration or avoided emissions), (ii) constraints on continued sequestration and the permanence of carbon stocks, (iii) economic costs and feasibility of implementation, and (iv) co-benefits and trade-offs. The Panel's assessment included various Indigenous perspectives on, and experiences with, NBCSs in order to reflect a more comprehensive understanding of the potential benefits (or harms) associated with these activities.

The Panel assessed the quality and quantity of the evidence available for each proposed NBCS along with the magnitude of sequestration potential, the longevity of or limits on sustained sequestration, feasibility, co-benefits, and trade-offs. Each of these elements was considered for NBCSs in forests (Chapter 3), agriculture and grasslands (Chapter 4), inland freshwater ecosystems (Chapter 5), and the marine coastal zone and blue carbon (Chapter 6). Chapter 7 provides a synthesis of the Panel's findings, including an assessment of the overall potential associated with a range of NBCSs. It also characterizes the limits on sequestration and the vulnerability of carbon stocks to atmospheric release.

Report Findings

NBCSs are affected by ecosystem responses to a changing climate, can produce additional climate effects, and have mitigation potentials that operate on different timescales

NBCSs are increasingly viewed as a means of achieving potentially significant reductions in atmospheric GHGs; however, their mitigation potential cannot be assessed in isolation. As suggested in the Panel's charge, changes in land use and land management practices may not only alter the rates of uptake or release of GHGs but can also alter the surface temperature of the Earth. A changing climate can also impact an ecosystem's ability to sequester carbon or alter its GHG emission rates. Rising temperatures and changes in precipitation can lead to shifts in environmental conditions and may lessen the efficacy of NBCSs.

The timing of the mitigation potential of NBCSs also varies. Interventions that avoid or reduce emissions can result in immediate benefits, while those involving land-use and ecosystem changes have impacts associated with gradual increases in carbon sequestration over longer timeframes. Some NBCSs involve ecosystems that lack well-defined biophysical limits on carbon sequestration, and which can continue to sequester and store carbon indefinitely under favourable environmental conditions. In others, sequestration can continue only up to a threshold, after which the net carbon flux reaches equilibrium.

National estimates of NBCS mitigation potential in Canada are based on limited evidence and remain highly uncertain

Evidence on how NBCSs change GHG fluxes in Canadian carbon sinks is often limited, and studies based on similar ecosystems in other regions are not always applicable. More importantly, uncertainties are magnified when attempting to estimate the GHG mitigation potential of these practices across Canada. These estimates rely on the ability to calculate the area over which such practices can be deployed, often depending on underlying assumptions that can be subject to debate. Assumptions might relate to jurisdiction and regulatory controls and coordination, the accessibility of solutions, the acceptability of impacts on other sectors or economic activity, the ecological and environmental suitability of regions or areas for a given intervention, and the social and behavioural barriers to adoption. Even excluding considerations related to socioeconomic feasibility, existing geographical and environmental data are inadequate, in some cases, when it comes to identifying areas over which NBCSs can be implemented or expanded.

Successful implementation of NBCSs can play a supporting role in achieving Canada's GHG reduction targets but would need to supplement stringent GHG reduction policies across sectors

Despite this high level of uncertainty, existing national estimates of NBCSs' mitigation potential generally provide, in the Panel's view, a credible and useful baseline for Canadian policymakers. The assumptions or evidence underlying some estimates, however, may result in over- or underestimation, and may be influenced by a short-term time constraint (i.e., to 2030). Using these estimates as a guide, full implementation of NBCSs would mitigate a small fraction of Canada's current annual emissions, even with aggressive support and deployment. To achieve Canada's targets, implementation of NBCSs would need to complement other stringent policies aimed at reducing emissions from fossil fuel combustion and other sectors.

Forest, agricultural land, grassland, and peatland NBCSs have the highest national GHG mitigation potential over the next three decades

Practices in forests, agricultural lands, grasslands, and peatlands have the greatest potential to sequester additional carbon or reduce emissions over the next three decades. In the short term, actions that avoid emissions in demonstrably at-risk areas tend to lead to immediate mitigation benefits; these include avoided conversion of forests, grasslands, and peatlands. Yet demonstrating the additionality of avoided conversion can be problematic, especially when projecting into the future of mid- to long-term timescales. Over decades, however, the impacts of improved management and restoration actions become more significant. Restoration of forest cover on managed and unmanaged land has the theoretical potential to sequester appreciable amounts of carbon by 2050, though the adoption of this NBCS at larger scales is subject to many implementation challenges. The expansion of forest cover may also have minor negative implications; decreased albedo from expanding canopy, and thus surface warming, occurs early, while biomass accumulation from growth accrues slowly over decades as forests mature. In contrast, interventions in crop and soil management practices can lead to immediate benefits in soil organic carbon stocks or emissions reductions; however, the rate of soil carbon accumulation gradually diminishes over time, eventually reaching a saturation point, while atmospheric fluxes eventually become net neutral.

The vulnerability of Canada's carbon stocks represents a significant climate change liability that could easily counteract any identified mitigation potential

All carbon stocks implicated in NBCSs are potentially vulnerable to being emitted to the atmosphere due to biophysical and socioeconomic factors. However, NBCSs are not uniform in the way they affect the vulnerability of carbon stored in these systems. For example, some forest management NBCSs may decrease the risk of large losses of stored carbon, while others may reduce resilience to future disturbances and are less likely to effectively store carbon over long time periods. However, increased release of carbon from natural sources may reduce the efficacy of NBCSs and thus, the protection or conservation of these systems is imperative to successful climate action.

Indigenous self-determination is a precondition and catalyst for the implementation, adoption, and long-term deployment of NBCSs

Indigenous Peoples are critical to the long-term success of many of the NBCSs analyzed in this report, as all carbon stocks across Canada exist on their traditional territories. As such, the story of carbon sequestration in Canada is intrinsically interconnected with ongoing Indigenous-led land and resource management (and, by extension, reconciliation). When communities themselves engage in ecosystem management efforts, in accordance with their traditions and values, decision-making processes for sustained NBCS use may be enhanced.

Existing and future Indigenous Protected and Conserved Areas (IPCAs) are one of the ways through which Indigenous self-determination may enhance the ongoing sequestration of atmospheric carbon as well as emissions reduction. As agreements which extend beyond local ecosystems to broader issues of self-determination and sovereignty over land, IPCAs may be an effective means of respecting Indigenous communities, their relationships to the land, and the environment more generally. Another example of collaborative and respectful relationships between Indigenous and non-Indigenous communities are Indigenous Guardians programs. As Indigenous-led bodies collaborating and engaging with land-users, industry representatives, researchers, and governments directly, Indigenous Guardians ensure that communities have the capacity to make well-informed decisions based on their chosen values and priorities.

A comprehensive assessment of carbon sink potential must consider political and socioeconomic aspects related to feasibility and cost of implementation

Estimates of mitigation potential can be misleading due to costs, jurisdictional challenges, and socioeconomic barriers to NBCS implementation in some sectors. Understanding the practicalities of implementation requires consideration of both the direct costs of these interventions as well as related factors, such as opportunity costs associated with other potential land uses, social and cultural barriers to adoption, risks of emissions leakage, and the availability of suitable policy and regulatory tools for supporting deployment. Cost estimates for select NBCSs are uncertain, since they are often based on a limited number of studies focusing on specific regions or contexts. Factors such as leakage, commodity market effects, efficacy of policy instruments, additionality, transaction costs, and behavioural or social resistance to the adoption of new practices are often unaccounted for, leading to costs that are more likely to be underestimated than overestimated.

Of the NBCSs assessed in this report, four were found to have relatively low barriers to adoption outside of costs: crop management, improved grassland management, and the avoided conversion of both freshwater mineral wetlands and seagrass meadows. The feasibility challenges in other NBCS categories are more significant for various reasons, including behavioural and sociocultural factors that may slow adoption rates on private land.

Increased monitoring of NBCSs is needed to realize their full potential

Accurate and sustained monitoring of various NBCSs was identified as a critical need across all ecosystems and action types. Many NBCSs are reliant on sparse or coarse datasets, some of which may not represent the complexities and variance associated with GHG fluxes. This contributes to policy-making uncertainties. Increased knowledge about the successes (or shortcomings) of NBCSs would enable decision-makers to better assess the true costs of these actions, which may differ from simulated costs; this is critical if carbon-related markets are to be established. Monitoring is also needed with respect to the implementation and practice of policy mechanisms intended to support and ensure the success of NBCSs. However, increased NBCS monitoring does not come without added costs, which must also be considered when assessing the feasibility of any given project or activity.

Wider implementation of many NBCSs in Canada may be desirable due to their co-benefits, even without additional carbon sequestration

Many NBCSs can provide tangible social and economic co-benefits, including those associated with property values, avoided flood damages, improvements in recreation experiences, improvements in threatened species' conditions, and biodiversity maintenance. Even where GHG mitigation benefits are low, these co-benefits alone often justify wider adoption of such practices. However, co-benefits vary depending on the location of the NBCS activity and the surrounding natural and human environments. They also depend on other factors that affect land use, such as human population growth, urbanization, and the economic conditions of the energy, agricultural, and forestry sectors. To properly estimate the value of NBCS co-benefits, further study is warranted in: up-to-date and regionally distributed studies, promising practices in non-market valuation methods, changes to peoples' behaviours and preferences as well as to the state of the environment itself.

A better understanding of the value of co-benefits, supported by policy, can help reduce perceived market-related trade-offs

Negative market-related effects, and the uncertainties associated with them, are primary trade-offs when implementing NBCSs. Loss of yield in crops or wood products, reduction in profits, and risks to employment are all cited as significant concerns to those considering NBCSs. These trade-offs should be carefully considered when implementing NBCSs but should not act as a deterrent. While initial costs may increase, some may be temporary in nature. More importantly, making strides to better quantify co-benefits, and using policy instruments and funding programs to help mitigate trade-offs, can help reduce overall negative economic effects.

Behavioural barriers are significant yet uncertain elements when determining the feasibility of NBCSs

Behavioural barriers can limit the acceptance of certain activities or practices and can play a significant role in determining the feasibility of NBCSs. They can impede acceptance of NBCSs despite high mitigation potential and cost-effectiveness. Additionally, there is a potential for optimism bias (i.e., the tendency for individuals to believe they are less likely to experience negative outcomes than others) to impede the acceptance of NBCSs; some individuals may view practices to mitigate potential harm as beneficial but unnecessary for the success of their particular project. Behavioural barriers represent a critical element in feasibility considerations despite their considerable uncertainty. While many NBCSs may have high technical and economic potential, there is no guarantee of high adoption rates due to the context-dependent nature of individual decision-making.

Applying NBCSs can help lessen the risks of rising GHG emissions from Canadian ecosystems, which are of global significance and represent a liability to successful global climate change mitigation

The global climate risks associated with increasing (and accelerating) emissions from Canada's terrestrial, aquatic, and coastal ecosystems are substantial. Preserving and protecting Canada's current carbon stocks is consequently of significant importance for reducing future global climate change and its impacts. However, Canada cannot unilaterally preserve all its carbon stocks; preservation of current carbon stocks requires a reduction in overall GHG emissions. Limiting warming to 1.5–2°C will likely only occur in the face of forward-looking climate mitigation policies that move to rapidly reduce anthropogenic emissions across sectors, thereby helping safeguard carbon stocks within such ecosystems.

Ultimately, the Panel believes that Canada's — and the world's — future depends on how effectively Canada's vast carbon stocks are preserved, rather than the extent to which rates of natural carbon sequestration in these systems can be enhanced.

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Introduction

Evidence of dangerous anthropogenic (i.e., human-caused) interference on Earth's climate system continues to grow (Rogner *et al.*, 2007; Pörtner *et al.*, 2021). According to the Intergovernmental Panel on Climate Change (IPCC), each of the last four decades has been successively warmer than any preceding decade since 1850. Temperatures between 2011 and 2020 exceeded the most recent recorded comparable warm period, which occurred approximately 6,500 years ago (a warming of 0.2–1°C relative to the 1850-1900 baseline) (Pörtner *et al.*, 2021). Warming in Canada is now occurring at a rate about double the global average and, in the Arctic, closer to triple (Bush & Lemmen, 2019). To reduce the negative, long-lasting impacts of climate change, actions that limit global warming to 1.5°C must be undertaken (Pörtner *et al.*, 2021). The Government of Canada acknowledged this alongside 194 other countries when it signed the Paris Agreement in 2015 (GC, 2016). The goal to limit warming is at the heart of many of the Government of Canada's recent climate action commitments, including the goal of achieving net-zero greenhouse gas (GHG) emissions by 2050.

Nature-based climate solutions (NBCSs) are increasingly viewed as potentially significant contributors to these GHG reductions, both nationally and globally (e.g., Griscom *et al.*, 2017; Drever *et al.*, 2021). They are practices aimed at protecting, restoring, or expanding ecosystems that sequester carbon or reduce the release of GHGs to the atmosphere (including carbon dioxide [CO_2], methane [CH_4], and nitrous oxide [N_2O]). NBCSs can potentially help governments achieve their climate change mitigation goals and can take many forms, including improved forestry and agriculture practices, wetland conservation and restoration, and other conservation and land management strategies. The Government of Canada has recognized the importance of NBCSs and has identified the need to "embrac[e] the power of nature to support healthier families and more resilient communities" as one of the pillars of its updated climate plan (ECCC, 2020a). The Glasgow Climate Pact, signed by all participant countries during the 26th UN Conference of the Parties (COP26), also affirmed "the importance of protecting, conserving and restoring nature and ecosystems" for climate action (UNFCCC, 2021a).

Many natural systems in which NBCSs may be deployed are threatened by the changing climate. These systems are subject to a variety of impacts and feedbacks[1] (IPCC, 2014a; Cooley & Moore, 2018), possibly crossing critical thresholds after which changes may become irreversible (Collins *et al.*, 2013). These changes can influence the extent to which the systems function as a net source or sink of atmospheric carbon (Cooley & Moore, 2018). For example, as temperatures increase, it is likely that the frequency and intensity of wildfires will do so as well, causing rapid releases of carbon from stocks in forests and peatlands (Flannigan *et al.*, 2009; Granath *et al.*, 2016; ECCC, 2022b).

A better understanding of the degree to which natural systems sequester or emit GHGs beyond CO_2, including CH_4 and N_2O, is also required. Uncertainties also arise around the breadth of variables (both biologic and socioeconomic) influencing these systems, the timeframe of these practices (i.e., are the GHG sequestration and/or emissions reductions permanent or temporary?), as well as gaps and limitations in the available evidence. Despite these uncertainties, mitigation planning involving NBCSs is already underway (e.g., ECCC, 2020a; PMO, 2021b). A more comprehensive understanding of the potential for Canada's natural systems to aid in sequestering carbon is necessary to better support this work and clarify the role of NBCSs in helping the Government of Canada meet its climate commitments.

1.1 The Charge to the Panel

Recognizing the need to better understand the potential role of NBCSs in helping Canada meets its 2030 emissions reduction target, as well as its 2050 net-zero goal, Environment and Climate Change Canada (ECCC) and six supporting federal departments and agencies[2] (referred to collectively as the Sponsor) asked the CCA to convene an expert panel to answer the following question and sub-questions:

1 Climate feedbacks are processes that either intensify (positive feedback loop) or lessen (negative feedback loop) the effects and drivers of climate change.

2 Agriculture and Agri-Food Canada (AAFC), Canadian Wildlife Service (CWS), Fisheries and Oceans Canada (DFO), Infrastructure Canada (INFC), National Research Council Canada (NRC), and Natural Resources Canada (NRCan).

What is the potential for nature-based solutions to help meet Canada's GHG emission reduction goals by enhancing carbon sequestration and storage, and reducing emissions, in managed and unmanaged areas (e.g., wetlands, agricultural and forest systems, harvested wood, and as blue (marine) carbon), and taking into account the major non-CO_2 climate impacts that can be reliably estimated (e.g., non-CO_2 GHG emissions, albedo, and aerosols)?

- What are key uncertainties, and to what extent may achievement of enhanced sequestration be affected by impacts of climate change, carbon leakage (e.g., displaced elsewhere), non-additionality (e.g., sequestration would have happened anyway), impermanence (e.g., due to wildfires, drought, or land conversion) and other implementation issues?
- What are the implications, benefits, or risks of implementing nature-based solutions focused on enhancing carbon sequestration, including for biodiversity, ecosystem services, economic factors, and Canada's GHG emissions?
- To what extent do Canadian carbon sinks and potential enhanced sequestration influence or contribute to future global emission pathways and warming, consistent with the Paris Agreement goal of holding global average temperature increases to well below 2°C?

To answer the charge, the CCA assembled a multidisciplinary panel of 15 experts (the Expert Panel on Canada's Carbon Sink Potential, hereafter the Panel), with expertise in climate and carbon modelling, nitrogen cycle modelling, public policy, economics, biogeochemistry, soil science, and ecology. Together, Panel members had significant research experience in many of the ecosystems where carbon sinks are found. This report was also informed by a comprehensive peer review process, whereby additional experts provided further evidence and guidance. The Panel met six times over the course of 2021 and 2022 to collect and review evidence.

1.2 The Panel's Approach

At the beginning of the assessment process, the Panel met with the Sponsor to discuss the charge and establish the scope of the project. Consistent with the literature and other discussions of NBCSs, technological options for enhanced carbon sequestration (e.g., direct air capture) were excluded from consideration.

Given the Sponsor's interest in *naturally occurring* carbon sinks, practices in the agricultural sector to mitigate enteric emissions (i.e., CH_4 released via the digestive processes of livestock) and manure management were also considered out of scope. Abiotic (chemical and/or physical, not biologic) carbon fluxes between the ocean and atmosphere (and related interventions, such as ocean alkalization) were similarly excluded. As with other research on blue carbon, the Panel's investigation of marine carbon sequestration opportunities focused on salt marshes and seagrass meadows. Due to the Sponsor's focus on the potential of NBCSs, the Panel was charged with assessing the science behind these activities; a full analysis of policy and regulatory instruments was deemed to be out of scope. The Sponsor and Panel also agreed that, despite this focus, understanding the international and domestic policy context for enhancing carbon sequestration through NBCSs is critical. The feasibility of NBCSs, including considerations related to their administration and socioeconomic acceptability, was a key concern to be included in the Panel's assessment.

The Panel made several additional decisions on the scope of the assessment. First, as specified in the charge, carbon sinks found on both managed and unmanaged lands were considered. A significant portion of land area in Canada is considered *unmanaged*[3] and is not fully captured in the Government of Canada's annual GHG reporting. Natural GHG emissions from unmanaged areas, for example, are not included in Canada's emissions reporting and do not, therefore, count against the Government of Canada's pledged GHG reduction targets. However, the Panel opted to also consider these unmanaged lands and associated GHG fluxes to the extent possible given available evidence. In the Panel's view, a failure to do this would risk overlooking significant gaps in the knowledge base and disregard the Government of Canada's responsibility to understand and account for all major carbon fluxes arising from Canadian territory. Similarly, the Panel considered NBCSs that are not currently eligible for carbon credits, or as emissions reductions in existing GHG reporting conventions. For example, the Panel considered practices related to wildfire suppression and prevention to be potential NBCSs, even though GHG emissions from wildfires are not currently included in the Government of Canada's official national emissions totals, as they are not considered anthropogenic emissions.

Second, although the assessment's focus was primarily on understanding NBCSs' potential to enhance carbon sequestration and reduce GHG emissions, the Panel also considered non-GHG-related co-benefits (as well as potential trade-offs or

3 According to NRCan (2020b), 115 of the 347 million hectares of forested land in Canada are considered unmanaged. This distinction is made "based on the occurrence of management activities for timber or non-timber and on the level of protection against disturbances" (ECCC, 2022a). This definition includes all management activities carried out within Indigenous Protected and Conserved Areas (IPCAs) (e.g., GC, 2021g).

risks) associated with these interventions. Knowledge of these co-benefits and trade-offs is critical to decisions on whether to finance or mandate implementation of NBCSs, since some NBCSs may potentially contribute to (or impede progress on) other simultaneous policy and land management objectives.

Third, the Panel considered carbon fluxes associated with permafrost thaw in the Arctic as mostly out of scope. The scale of permafrost carbon stocks and associated risks arising from permafrost thaw caused by climate change are increasingly evident (Box 2.2). Although protecting vegetative cover may help insulate permafrost and prevent rapid thawing, and while localized engineering interventions may help stabilize landscapes and prevent thawing on small scales, the research, practices, and technologies in these areas are not yet comparable to other, more developed NBCSs. As the charge to the Panel focuses primarily on carbon sinks, practices for preventing or managing permafrost thaw in the Arctic were therefore not considered. However, the Panel discussed interactions between permafrost and carbon cycle dynamics in other ecosystems, including forests and wetlands.

Fourth, as the charge to the Panel is concerned with the *potential* of NBCSs, the Panel chose to express its findings in terms of CO_2e (CO_2 equivalent)[4] for ease of cross-sector comparability (for a more detailed explanation of the metrics chosen by the Panel, see Section 1.2.1). Values of CO_2e take into account the sequestration of carbon (or the sink function of an ecosystem, in CO_2) as well as the reduction of non-CO_2 emissions (i.e., CH_4 and N_2O). Further, while the Panel recognized that there are a number of definitions of NBCSs in the literature, it chose to focus its assessment on the climate change mitigation potential of these actions, as emphasized by the charge. However, in certain circumstances, the mitigation and adaptation benefits of actions are closely related and cannot be discussed in isolation; therefore, where adaptation is deemed relevant, it is considered to be an NBCS co-benefit.

Finally, as the Panel's charge is concerned with understanding the potential of NBCSs, governance and issues related to jurisdiction were considered out of scope. The Panel recognized that, in many instances, governments at the provincial or community level (including Indigenous governments) have jurisdiction over land management decisions that will influence the implementation of NBCSs. However, due to the charge's focus on national-scale potential, challenges surrounding policy implementation were discussed in terms of federal-level actions.

4 1 megatonne (Mt) CO_2 is equivalent to 1 Mt CO_2e; where evidence measures carbon sequestration/reduced emissions in CO_2, the Panel reports it as such.

1.2.1 Terminology and Metrics

Throughout this report, the Panel used several terms that have complex or differing meanings. To ensure clarity, the Panel adopted the following definitions of key terms (Box 1.1).

Box 1.1 Definitions of Key Terms

Carbon Sinks and Related Terms: When terrestrial, wetland, and aquatic ecosystems and their components (e.g., soils, plants, sediments) take up more carbon from the atmosphere than they release, they are considered to be carbon *sinks*. All natural carbon sinks are supported by the ecosystems within which they operate, and thus ecosystems themselves are typically considered carbon sinks (e.g., a forest ecosystem stores carbon in its soils through various activities, including photosynthesis, burial, and soil development). When these systems emit more GHGs than they take up, they are referred to as *sources*. *Stocks* refer to the amount of carbon stored in these systems (as reservoirs or pools) at any given time (USGCRP, 2018). *Flux* refers to transfers of GHGs between the atmosphere and vegetation, soils, sediments, or waters (USGCRP, 2018). *Sequestration* refers to the removal of carbon (primarily in the form of CO_2) from the atmosphere and its storage in natural ecosystems, either as the result of natural processes or through deliberate actions that enhance or expand on those processes.

Nature-Based Climate Solution (NBCS): For the purposes of this report, and building on the charge, the Panel defines *NBCSs* as protection, management, and restoration actions applied to managed and unmanaged ecosystems that provide additional climate change mitigation by way of carbon sequestration or reduced GHG emissions, relative to a defined baseline. Beyond climate change mitigation, optimal NBCSs provide co-benefits and minimize adverse effects.

CO_2e comparability metrics are complex and vary among studies

To ensure comparability across NBCSs, the Panel also chose to adopt a consistent measurement metric. The climate effects of non-CO_2 GHG emissions associated with NBCSs are expressed in this report in terms of CO_2 equivalents using the sustained global warming potential (SGWP) (Neubauer & Megonigal, 2015, 2019). The SGWP differs from the conventional global warming potential (GWP) metric by comparing the radiative forcing[5] of sustained GHG emissions rather than pulse emissions (Neubauer & Megonigal, 2015). Recent literature indicates that, for policy objectives related to the temperature goals of the Paris Agreement, a more accurate approach consists of comparing the radiative forcing or warming from sustained emissions of a short-lived GHG (e.g., CH_4) to the effect of a pulse emission of CO_2 (these metrics are denoted as combined global warming potential, or CGWP, and combined global temperature change potential, or CGTP) (Collins *et al*., 2020). An additional issue introduced by policy objectives is that of timeframe considerations. Many of the metrics available (including SGWP) are calculated using a 100-year time horizon (e.g., Neubauer & Megonigal, 2015), yet many policy objectives envision a significantly shorter timeframe (e.g., 15 to 30 years). However, the Panel chose to use the SGWP metric for consistency with national mitigation estimates (i.e., Drever *et al.* (2021)). Where SGWP could not be calculated, or where data used were given in GWP rather than SGWP, the inconsistency is noted.

1.2.2 Evidence-Gathering Methods

The Panel reviewed multiple sources of evidence throughout its assessment. Preliminary academic literature reviews related to the carbon sequestration potential of Canada's ecosystems were carried out in order to build an initial evidence base. Peer-reviewed literature covering carbon sinks and NBCSs (and analogous terms or concepts) is extensive. This evidence base was supplemented by ongoing research and Panel expertise as the report was developed.

No original research was commissioned for this report; however, several experts outside of the Panel were invited to share their experiences and knowledge (see Acknowledgements page). Information gained from these presentations was used to deepen the Panel's understanding, insights, and deliberation of key areas of concern. At the start of this assessment, an extensive new study by Drever *et al.* (2021), estimating the mitigation potential associated with many NBCSs in Canada, was released, which also informed this report.

5 Radiative forcing is the change in energy flux that occurs when the amount of energy entering the Earth's atmosphere differs from the amount leaving it. Radiative forcing can be caused by both natural and anthropogenic factors.

The Panel recognized the importance of Indigenous Peoples' rights and values while producing this report, in particular the role of Indigenous knowledge and land management. To ensure such evidence was included in this report, the Panel hosted a virtual Indigenous Knowledge and Perspectives session to hear and gain insight from Indigenous experts located in diverse regions and ecosystems across Canada (see Acknowledgements page). These experts shared their knowledge and land management experience related to carbon stocks and fluxes in natural systems, as well as their experiences with carbon sequestration initiatives and environmental governance. This provided the Panel with invaluable information about the relevance of carbon sink management with respect to reconciliation, as well as insights into the feasibility of certain NBCSs, including potential opportunities and risks.

1.2.3 A Framework for Assessing the Potential of Carbon Sinks

The Panel was asked to assess all NBCSs suitable for the Canadian context. As it did so, it recognized that the comparability and interoperability of data are critical for supporting decision-making. The Panel also recognized the importance of reflecting the quality and robustness of the supporting evidence, including uncertainties. The Panel adopted an assessment framework composed of five elements to guide its work and inform evidence evaluation and synthesis. Structured scales were developed to guide the Panel's evaluation of each element (see the Appendix for additional details and definitions).

First, an *evidence rating scale* was used to categorize the quality and quantity of the evidence available for each NBCS, taking into account variables across disciplines as well as the role of Indigenous knowledge. This scale was adapted from IPCC guidance on the treatment of uncertainties (Mastrandrea *et al.*, 2010) and is used to characterize the robustness of evidence underlying key findings in the Panel's overall assessment based on three categories: limited, moderate, and robust (Table 1.1). The application of the evidence scale is informed by the Panel's expert opinion.

Table 1.1 Panel Evidence Ratings and Definitions

Evidence Rating	Description
Limited	**Limited or inconsistent evidence from few studies of uncertain quality or applicability** (e.g., limited availability of peer-reviewed studies and/or evidence from few study sites; questionable applicability to the Canadian context; limited applicability to the regional context; limited supporting evidence and/or evidence of uncertain quality/reliability; inconsistent lines of evidence)
Moderate	**Multiple, mostly consistent lines of evidence** (e.g., independent, peer-reviewed studies with mostly consistent findings or evidence from multiple sites; direct or indirect relevance to the Canadian context; regional applicability; possibly supported by other types of evidence, including Indigenous knowledge)
Robust	**Multiple, consistent independent lines of high-quality evidence** (e.g., numerous independent, peer-reviewed studies with consistent findings or evidence from many study sites; direct relevance and applicability to the Canadian and/or regional context; accompanied by additional supporting evidence, including Indigenous knowledge)

Second, the Panel evaluated the *magnitude of sequestration potential* for each NBCS (or related NBCSs). Estimates are expressed in Mt CO_2e/yr (Section 1.2.1) to be consistent with Canada's *National Inventory Report* emissions data (ECCC, 2022b). These estimates represent the Panel's judgment (based on the best available evidence) of the combined amount of carbon sequestration that can reasonably be expected with the adoption of these NBCSs in Canada (in addition to what would be expected based on a continuation of current practices and trends). These estimates factor in temporal considerations by focusing on the following periods: the present to 2030 and 2030 to 2050. Given significant uncertainties surrounding the sequestration potential for all NBCSs, the Panel presents estimates of sequestration potential in five ranges: 0–1, 1–5, 5–15, 15–25, and greater than 25 Mt CO_2e/yr. Further, consideration is given to the potential effects of NBCSs on climate, including effects and uncertainties related to GHGs other than CO_2.

Third, the Panel employed an evaluative framework for the longevity of an NBCS. *Limits on sustained sequestration* reflect the extent to which biophysical or technical constraints prevent the sequestration of carbon on an ongoing basis, while *permanence* reflects how vulnerable any additional carbon sequestered through an NBCS may be to disturbance and release back to the atmosphere (encompassing both biophysical and socioeconomic factors). Considerations of sustained sequestration and permanence are made throughout the report based on a 2022–2050 time horizon; however, the Panel comments where evidence is available on the longer-term potential of NBCSs (e.g., 2050 onwards). Where possible, the Panel also considered the potential for carbon leakage, wherein a reduction of emissions resulting from an NBCS is offset by increased emissions elsewhere.

Fourth, the Panel's assessment framework evaluates the *feasibility* of each NBCS by exploring the technological, biophysical, socioeconomic, and political barriers that may impede or prevent its implementation. The Panel adopted a definition of feasibility that includes both cost considerations and barriers to implementation. Factors considered as elements of feasibility include (a) the availability of policy and regulatory tools, (b) the requirements for verification, monitoring, and enforcement, and (c) alignment with the needs, expertise, and priorities of Indigenous communities.

Fifth, the Panel also assessed *co-benefits* and *trade-offs* for each NBCS. Types of co-benefits considered include impacts on climate adaptation, biodiversity, economic conditions, social and cultural implications, and any other notable effects documented or predicted in the literature. Trade-offs, risks, and adverse impacts on other policy or land management priorities are also noted and described where supported by the evidence.

While not an explicit assessment criterion, the Panel considered *Indigenous rights, land management, and knowledge* to be fundamentally important in assessing NBCSs. Recognizing that Indigenous communities hold rights that will impact the feasibility of NBCS options, claim a long history of managing lands and carbon stocks, and possess knowledge about their local environments and ecosystems, the Panel sought Indigenous knowledge and perspectives to meaningfully inform the report findings within each of the above-mentioned elements.

With respect to certain large, national-scale studies (such as Drever *et al.*, 2021), however, the evidence scale does not adequately reflect the Panel's process in assessing the quality of evidence and methodologies used to come to conclusions within these studies. To address this, the Panel established a confidence scale to assess individual studies or findings where a multitude of evidence sources were unavailable (Table 1.2). The conclusions presented in this report reflect the Panel's consensus judgment.

Table 1.2 Panel Confidence Scale

Confidence Rating	Description
Limited	The Panel is **not confident** in the quality or applicability of the evidence and/or assumptions underlying the estimated values. Additional lines of evidence are very likely to change the estimates (e.g., Canada-specific evidence, evidence from multiple sites, Indigenous knowledge). Impacts of climate change, though difficult to fully predict in terms of net outcome, are very likely to pose great risks that will alter estimated values.
Moderate	The Panel is **moderately confident** in the quality or applicability of the evidence and/or assumptions supporting the estimated values. Additional lines of evidence could change the estimates (e.g., Canada-specific evidence, evidence from multiple sites, Indigenous knowledge). Impacts of climate change, though difficult to fully predict in terms of net outcome, could pose at least a moderate risk of altering estimated values.
High	The Panel is **confident** in the quality or applicability of the evidence and/or assumptions supporting the estimated values; additional lines of evidence or climate change impacts are unlikely to substantially change the sequestration potential estimates.

Throughout the report, key national and international studies are used as the basis for the Panel's analysis of NBCSs (e.g., Drever *et al.*, 2021; Roe *et al.*, 2021). However, the Panel recognizes the difficulties of using data that rely on national or global assumptions for analyzing NBCSs that vary regionally. Overall, the Panel chose to use the estimates provided by Drever *et al.* (2021) as the foundation for much of its quantitative analysis since these currently represent the only Canada-wide estimates for many of the solutions outlined. However, the Panel notes that, while national-scale estimates may be useful in assessing the differences among NBCSs, many assumptions underlie such estimates, and regional nuances often go overlooked. The Panel then provided additional analysis where necessary to address these nuances and explore aspects not considered by Drever *et al.* (2021), such as socioeconomic feasibility.

1.3 Organization of the Report

To facilitate the practical application of its findings, and to be consistent with other reviews, the Panel explored NBCSs in relation to the types of ecosystems where they can be deployed. **Chapter 2** provides a general overview of natural carbon sinks, their role in the global carbon cycle, and their potential for mitigating climate change, including commentary on the significance of Canadian carbon sinks in the global context. It also explores Indigenous climate leadership and expertise in NBCSs, as well as the role of NBCS partnerships between Indigenous communities and the federal government. These are key considerations, as large carbon sink areas in what is now Canada are subject to Indigenous governance and land rights; the Government of Canada's legal commitment to these rights, and to reconciliation, requires full and meaningful Indigenous participation in NBCS implementation.

Chapters 3 through 6 explore options for enhancing carbon sequestration across Canada's diverse ecosystems. **Chapter 3** focuses on enhancing carbon sequestration and reducing CO_2 emissions in Canada's forests with respect to below- and aboveground biomass and soil organic carbon. **Chapter 4** explores the carbon sequestration potential of Canada's agricultural sector and grasslands, while **Chapter 5** assesses options for enhancing carbon sequestration in Canada's freshwater wetlands, lakes, rivers, and reservoirs. **Chapter 6** addresses the potential to enhance blue carbon sequestration in marine coastal ecosystems, including a discussion of tidal salt marshes and seagrass meadows. Each chapter includes context on the importance of Indigenous communities in managing the land in the past and present, as well as the role of communities in the preservation of carbon stocks.

Chapter 7 synthesizes the evidence and compares the sequestration potential associated with all options explored. It summarizes the Panel's judgment regarding the potential benefits of these NBCSs in Canada, and discusses the issues and barriers associated with their implementation, as well as future research needs and next steps. It also presents a brief synthesis of the Panel's key findings in relation to the charge, and its final reflections.

2

Carbon Sinks and Climate Change Mitigation in Canada

Within Canada, there is a growing appreciation of the role carbon sinks play in regulating the concentrations of GHGs in the atmosphere. Carbon stocks contained in Canada's forests, wetlands, grasslands, and agricultural lands are globally significant and can play a critical role in mitigating, but also accelerating, climate change (ECCC, 2020a).

2.1 GHGs and their Climate Impacts

2.1.1 The Natural Carbon Cycle

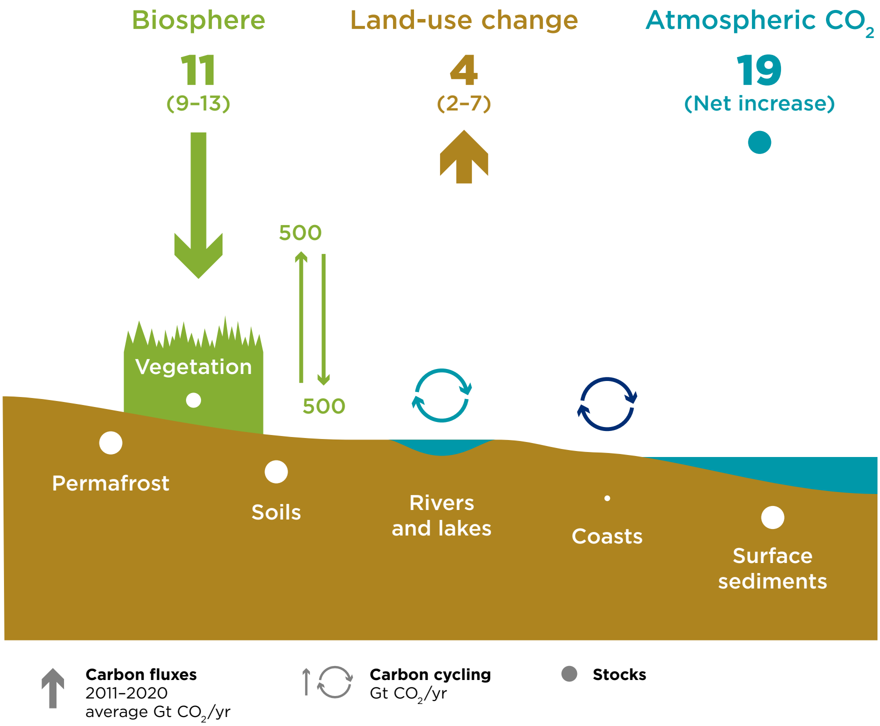
Carbon is constantly circulating between atmospheric, terrestrial, and aquatic reservoirs through a variety of channels; this is collectively known as the carbon cycle

Atmospheric carbon, in the form of carbon dioxide (CO_2) and methane (CH_4), plays a critical role in regulating climate through the absorption and re-radiation of long-wave radiation.[6] Alongside water vapour, nitrous oxide (N_2O) and various other gases (e.g., ozone) produce the greenhouse effect and are collectively known as GHGs. Shifts in the composition of the Earth's atmosphere, specifically the amount of GHG, alters the radiation balance of the planet, resulting in changes in surface temperature. Carbon also plays a significant role in energy production through the burning of carbon-based fossil fuels such as coal, oil, and natural gas. The combustion of these fuels releases CO_2, CH_4, and other gases to the atmosphere, altering the natural carbon cycle and the Earth's climate by returning the carbon sequestered over millions of years back to the atmosphere over the course of a century.

On Earth, carbon is naturally stored in rocks, sediments, aquatic systems, soils, biomass, and the atmosphere. Excluding rocks, the largest global reservoir of carbon is the deep ocean, which holds approximately 80% of Earth's carbon (Bruhwiler *et al.*, 2018). The remainder is stored in soils and permafrost (9%); oceanic sediments (4%); oil, gas, and coal reserves (3%); oceanic surface waters (2%); the atmosphere (2%); and vegetation (~1%) (Bruhwiler *et al.*, 2018). Carbon transfers, known as fluxes, occur among these reservoirs of carbon, also known as stocks or pools (Box 1.1). These fluxes happen in response to physical, chemical, and biological processes that can be affected by climate change and cause carbon cycle-related climate change feedbacks (Section 2.1.2).

6 Radiation emitted from the Earth.

Figure 2.1 illustrates part of the global carbon cycle, with current estimates of natural stocks and fluxes. Fluxes between land or ocean carbon pools and the atmosphere are generally subject to higher levels of uncertainty than emissions from fossil fuel combustion; rather than being measured directly, they are estimated at a range of scales, using either *top-down* or *bottom-up* approaches (Box 2.1).



Adapted with permission: Global Carbon Project (2021)

Figure 2.1 The Global Carbon Cycle

This figure shows estimates of carbon reservoirs in gigatonnes (Gt) of CO_2 and fluxes in Gt CO_2/yr, globally averaged for the years 2011–2020. The magnitude of the carbon stocks is represented by the size of the associated circles. Wide arrows represent anthropogenic perturbations of the natural carbon cycle, which itself is illustrated with thin arrows (see Global Carbon Project (2021) for a complete breakdown of how the values were estimated). Upward arrows indicate emissions to the atmosphere while downward arrows indicate uptake by the environment. Values in Gt CO_2 are estimated for reservoirs and fluxes of CO_2 only; CH_4 and CO fluxes and stocks are not included, nor are lateral fluxes.

Box 2.1 Estimating Carbon Fluxes Over Large Areas

To estimate terrestrial carbon fluxes over large areas, or even globally, a combination of measurements and modelling is required; these approaches are commonly referred to as either top-down or bottom-up. For the purposes of monitoring fluxes associated with NBCSs, bottom-up (or biosphere-based) approaches are most often used. They rely on field and remote sensing measurements and ecosystem process models to determine the magnitude and variability of land-based carbon sinks (Hayes *et al*., 2018). These approaches are favoured in some large-scale carbon assessments where extensive datasets are available to track fluxes between carbon pools; however, the under-sampling of carbon pools, ecosystems, or regions can lead to errors, including the under- and overestimation of fluxes or large uncertainties (Pan *et al*., 2011; Hayes & Turner, 2012; Saunois *et al*., 2020). One critical uncertainty is the lack of data on the areal extent of entire ecosystems (due in part to a lack of agreement on what constitutes an ecosystem), which the Panel views as a significant barrier to implementing and scaling up NBCSs.

The carbon cycle operates on both fast and slow timescales

Fast carbon exchanges include fluxes between the lower layer of the atmosphere and the upper layer of the ocean or biosphere, operating on the order of days to years (Ciais *et al*., 2013). On such timescales, CO_2 exchanges between the atmosphere and biosphere can occur through metabolic processes of photosynthesis and respiration (Ciais *et al*., 2013). The slow carbon cycle involves exchanges among reservoirs such as the deep ocean, ocean sediments, and rocks, taking hundreds to millions of years to cycle.

Carbon stored in terrestrial environments can be released back to the atmosphere directly, or transferred in various forms to the aquatic environment, where it can be emitted to the atmosphere, buried, or further transported (Cole *et al*., 2007; Raymond *et al*., 2013). CO_2 exchange between the ocean and atmosphere depends on the concentration difference between the atmosphere and surface ocean, which varies as a function of ocean circulation (e.g., release of CO_2 from upwelling regions; uptake of CO_2 in deep water formation) and net primary production by marine organisms (Bruhwiler *et al*., 2018; Canadell *et al*., 2021).

Methane is an important GHG within the carbon cycle

Carbon also cycles in the Earth system in the form of CH_4. Although present in much lower atmospheric concentrations than CO_2, CH_4 is a more powerful GHG, approximately 30 times more effective at trapping heat over a 100-year timeframe (Forster *et al.*, 2021b). Once in the atmosphere, CH_4 has a lifetime of approximately nine years (Prather *et al.*, 2012). This makes rapid-action efforts to reduce CH_4 emissions attractive, resulting in the stabilization or reduction of atmospheric CH_4 concentrations within a few decades (Saunois *et al.*, 2020). While the contribution of CH_4 sinks relative to the concentration of atmospheric CH_4 is largely uncertain (Kirschke *et al.*, 2013; Saunois *et al.*, 2017; Turner *et al.*, 2019), it is fairly well understood that freshwater wetlands and lakes are major CH_4 sources, and that these emissions are related to anaerobic (i.e., oxygen-depleted) conditions resulting from the decomposition of organic matter (Saunois *et al.*, 2020). Fires, oceans, geological sources (e.g., sediments), and enteric fermentation[7] in animals also contribute to overall CH_4 emissions (Bruhwiler *et al.*, 2018; Saunois *et al.*, 2020). Anthropogenic sources of CH_4 emissions include elements and activities such as fossil fuel extraction, landfills and waste treatment, rice paddy agriculture, and ruminant livestock (Ciais *et al.*, 2013).

2.1.2 Human Impacts on the Carbon Cycle

Fossil fuel combustion and other anthropogenic emissions are affecting the global carbon cycle, increasing atmospheric GHG concentrations

Anthropogenic emissions perturb the carbon cycle primarily through combustion of fossil fuels and land-use changes that release or degrade natural carbon stocks (Bruhwiler *et al.*, 2018). These emissions have pushed the atmospheric concentration of CO_2 from ~280 parts per million (ppm) in pre-industrial times to over 418 ppm in recent years, representing approximately a 45% increase (MacFarling Meure *et al.*, 2006; NOAA, 2022a). CH_4 concentrations have also risen from pre-industrial values by about 171%, from ~700 parts per billion (ppb) to over 1,900 ppb today (MacFarling Meure *et al.*, 2006; NOAA, 2022b).

Globally, terrestrial and marine carbon sinks take up just over half of annual anthropogenic CO_2 emissions

Worldwide terrestrial carbon sinks have absorbed approximately 30% of annual anthropogenic CO_2 emissions since 1850, with marine systems accounting for a further 26% (Friedlingstein *et al.*, 2021). While anthropogenic emissions have risen

7 Enteric fermentation is part of the digestive process of large hoofed, herbivorous grazing animals "where microbes decompose and ferment food present in the digestive tract or rumen. Enteric CH_4 is one by-product of this process and is expelled by the animal through burping" (FAO, 2016).

during the past century, so too have the absorption rates in terrestrial carbon sinks due to rising CO_2 and nitrogen inputs on plant growth (i.e., fertilization) combined with a longer growing season, which itself is an effect of climate change. Similarly, the ability of the ocean to absorb CO_2 has increased over the past decade, with the largest increase in uptake in the North Atlantic and Southern Oceans. Together, terrestrial and marine carbon sinks have removed approximately 55% of anthropogenic emissions since 1960 (Friedlingstein *et al.*, 2021).

As the temperature increases, environmental conditions will change and further impact the carbon balance of ecosystems

The increase in GHG concentrations since pre-industrial times has, by extension, increased the total amount of radiative forcing acting on the Earth, resulting in a global average surface temperature increase over the past decade (2011–2020) of 1.1°C above pre-industrial levels (Pörtner *et al.*, 2021). These temperature changes have also resulted in changes in the amount, distribution, and timing of rainfall, and increased the frequency and intensity of extreme hydrological events (Pörtner *et al.*, 2021). Climate changes further affect disturbance processes such as insect infestations, wildfires, droughts, and disease; this causes alterations to net primary production, which in turn affects the carbon balance of ecosystems, releasing carbon back to the atmosphere as a positive climate feedback (Arias *et al.*, 2021). Wildfires, for example, are expected to become more severe and occur more frequently which, when considered alongside changes in vegetative composition associated with climate change, represent a positive carbon climate feedback loop and will likely accelerate warming moving forward (Canadell *et al.*, 2021). However, the Panel noted that not all climate change-induced alterations will result in positive feedbacks; in some cases, they may even result in negative feedbacks (e.g., Walker *et al.*, 2021).

As global GHG emissions continue to rise, the capacity of terrestrial and marine carbon sinks is expected to decrease

Many carbon-cycle processes are sensitive to climate changes, affecting the capacity of terrestrial and marine sinks to absorb carbon over time. For example, soil respiration is expected to increase in a warmer climate, resulting in a larger release of CO_2 to the atmosphere (Li *et al.*, 2020). Warming also reduces the solubility of CO_2 in seawater and increases ocean stratification, reducing the ability of the ocean to take up CO_2 (Arias *et al.*, 2021). While the amount of CO_2 taken up by terrestrial and marine carbon sinks is expected to grow as atmospheric concentrations of CO_2 increase, climate feedbacks are projected to decrease the effectiveness of these sinks, leaving a larger share of emitted CO_2 in the atmosphere (Arias *et al.*, 2021).

2.1.3 The Nitrogen Cycle

Some NBCSs also affect the nitrogen cycle, serving as sources or sinks of N_2O

Nitrogen is an essential nutrient for life and plant growth but, in many cases, it is only taken up by primary producers in its reactive forms (i.e., ammonium, nitrite, and nitrate). Greater availability of nitrogen for primary producers can enhance the sequestration of atmospheric CO_2 by spurring photosynthesis and plant growth if rates of organic matter decomposition and nitrogen loss are held constant (Zhang *et al.*, 2020), while climate warming can enhance nitrogen cycling and carbon inputs to soils in Canadian boreal forest ecosystems with sufficient water supply (Philben *et al.*, 2016; Ziegler *et al.*, 2017).

There are also negative consequences to increased concentrations of reactive nitrogen. Runoff of nitrogen-based fertilizers causes the eutrophication[8] of both terrestrial and marine environments, which is associated with increased emissions of nitrogen oxide and N_2O (Gruber & Galloway, 2008; Zhang *et al.*, 2020). Eutrophication has implications beyond nitrogen cycling, as it promotes emissions of CH_4 via anaerobic respiration. Human activities — primarily fossil fuel combustion, expanded cultivation of legumes, and widespread use of nitrogen rich fertilizers (Gruber & Galloway, 2008; Fowler *et al.*, 2013; Zhang *et al.*, 2020) — have increased the amount of available nitrogen in terrestrial, aquatic, and marine ecosystems. The involvement of N_2O complicates the analysis of some NBCSs (e.g., agricultural practices that sequester soil carbon), since increased N_2O emissions may offset the benefits of enhanced carbon sequestration (Li *et al.*, 2005; Powlson *et al.*, 2011) (Section 4.3.1).

2.1.4 Other Climate Impacts from NBCSs

An accurate assessment of the effects of NBCSs requires consideration of other climate impacts, including albedo and aerosols

The impacts of NBCSs extend beyond direct intervention in the carbon and nitrogen cycles — they can also alter processes that determine the energy balance at the Earth's surface and thus surface temperature. One effect is a change in surface albedo, or the "fraction of incoming solar radiation reflected back into space by the Earth's surface" (Bright *et al.*, 2016). Light surfaces, such as snow or ice cover, strongly reflect larger amounts of solar radiation, while darker surfaces, such as dense tree cover, reflect lesser amounts, allowing the radiation to be absorbed and

8 Eutrophication is the increase in the concentration of nutrients in an aquatic system, which "restricts water use ... because of increased growth of undesirable algae and aquatic weeds and the oxygen shortages caused by their death and decomposition" (Khan & Mohammad, 2014). Such conditions can enhance denitrification and emission of N_2O.

warm the surface. Other effects include changes in evapotranspiration and cloud cover, which increase cooling (Bright *et al.*, 2017; Cerasoli *et al.*, 2021; Duveiller *et al.*, 2021). Modifying land surface albedo has the potential to counteract or amplify the climate mitigation benefits of increased carbon sequestration in terrestrial ecosystems (e.g., Myhre *et al.*, 2013; Settele *et al.*, 2014). In the forestry sector, practices such as the restoration of forest cover actively reduce the surface albedo of a given geographical area, thereby increasing the absorption of incoming solar radiation and in turn surface temperature (De Wit *et al.*, 2014; Settele *et al.*, 2014). This effect is particularly pronounced in regions with seasonal snow cover, where trees mask the high albedo of snow (Betts, 2000). In contrast, changes in agricultural practices, such as no-till management and use of cover crops during fallow periods, have been shown to increase surface albedo and result in local cooling (Davin *et al.*, 2014; Hirsch *et al.*, 2018; Lugato *et al.*, 2020).

Some NBCSs also contribute to climate impacts by altering atmospheric aerosol loads. Aerosols — fine particles suspended in the atmosphere — are emitted directly from both anthropogenic and natural sources (Després *et al.*, 2012; Paasonen *et al.*, 2016), or form in the atmosphere through the oxidation of biogenic volatile organic compounds (VOCs) (Laothawornkitkul *et al.*, 2009). Many NBCSs emit biogenic VOCs that serve as precursor substances for the formation of secondary organic aerosols and can thus alter atmospheric loads (Petäjä *et al.*, 2022). Aerosols affect the Earth's radiative balance directly by scattering and absorbing sunlight, and indirectly by modifying cloud cover and cloud albedo, thereby impacting the amount of solar radiation reflected back into space (Boucher *et al.*, 2013; Zhou *et al.*, 2014). Despite the potential significance of feedbacks among biogenic VOC emissions, aerosol formation, and climate, the current state of knowledge on these effects is subject to high levels of uncertainty, part of which can be attributed to the varied role of cloud cover in these feedbacks. The effects of these feedbacks, as well as those related to changes to surface albedo, are addressed where possible throughout this report. Albedo effects are considered in relation to the uncertainties associated with determining the magnitude of sequestration potential of NBCSs, while other effects are assessed separately.

There is even further complexity related to the climate impacts of NBCSs. For example, Zickfeld *et al.* (2021) have noted asymmetric effects of CO_2 emissions and removals. Over a period of 100 years, CO_2 emissions are more effective at raising atmospheric CO_2 levels than the equivalent removals are at lowering them (Zickfeld *et al.*, 2021). Thus, for the purposes of climate change mitigation, carbon sequestration — through terrestrial sinks or other means — should not be assumed to be equivalent to avoided emissions.

2.1.5 The Scale, Distribution, and Significance of Carbon Stocks in Canada

Globally significant amounts of carbon are stored in terrestrial ecosystems in Canada

As interest in the role of NBCSs in carbon sequestration grows, achieving a better understanding of the size and distribution of terrestrial carbon stocks in Canada (and globally) has become a priority. Canada's national inventory estimates have been criticized for not accurately reflecting the total carbon stock distribution in both managed and unmanaged land-use categories (e.g., Harris *et al.*, 2022; Sothe *et al.*, 2022). These estimates currently only report carbon stocks in soil organic matter and above- and belowground biomass in managed land areas (ECCC, 2022a). Such estimates underrepresent potential carbon stocks; managed forests, for example, account for only ~65% of Canada's total forest area (ECCC, 2022b). Previously reported assessments of soil carbon stocks are also likely to be underestimates, as they are based on the top 30 cm and/or 1 m of soil in peatlands, whereas studies have shown that peat depths can extend beyond 2.5 m (Hugelius *et al.*, 2020; Sothe *et al.*, 2022).

Carbon sequestered in soils represents the majority of the country's carbon stocks. According to FAO (2018), Canada holds 12% of the global soil organic carbon stock (80,200 Mt C), when estimated to a depth of 30 cm. However, this may underestimate soil carbon stored in peatlands, which cover approximately 107 Mha of the Canadian boreal and tundra ecosystems (Olefeldt *et al.*, 2021). Further, a significant proportion of soil carbon in Canada is stored in permafrost (Box 2.2), which affects approximately 30% of the country's peatland (Olefeldt *et al.*, 2021). In total, northern Canadian peatlands store ~150 Gt of carbon in their soils (Joosten, 2009; Hugelius *et al.*, 2020).

Box 2.2 Permafrost, Carbon Fluxes, and Climate Feedbacks

Permafrost is a soil in which the lower layers remain frozen year-round, while a surface layer, termed the *active layer*, is subject to seasonal thawing (Schuur *et al.*, 2018). These soils hold large amounts of organic material that rapidly decomposes upon thawing, releasing CO_2 and CH_4 to the atmosphere (Canadell *et al.*, 2021). Anthropogenic emissions have led to high-latitude warming, which will accelerate permafrost thaw (Jia *et al.*, 2019) and affect large areas of northern Canada in the coming decades (Derksen *et al.*, 2019).

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Permafrost temperature increases of 0.1°C per decade have been observed in the Central Mackenzie Valley, Northwest Territories, accompanied by a thickening of the active layer by 10% since 2000 (Derksen *et al.*, 2019). Future permafrost thaw and related GHG emissions will amplify climate warming (Canadell *et al.*, 2021). The net CO_2 release from permafrost ecosystems could be between 11 and 174 billion tonnes of carbon by 2100 (Schuur *et al.*, 2015; Gasser *et al.*, 2018; Natali *et al.*, 2019), which would be equivalent to a significant portion of the remaining carbon budget required to meet the Paris Agreement target of limiting warming to 1.5°C (Rogelj *et al.*, 2019). Permafrost thaw also has widespread adverse impacts on northern communities by damaging or destabilizing local infrastructure (Hjort *et al.*, 2018) as well as shifting local hydrological conditions (Varner *et al.*, 2021).

Significant uncertainty remains surrounding the potential strength of the permafrost carbon feedback despite a high level of confidence that increased warming will lead to higher GHG emissions from thawing soils (Canadell *et al.*, 2021). This is in part because the extent to which GHGs will be released to the atmosphere, and the approximate timescale within which such losses will occur, are unknown (Rogelj *et al.*, 2019; Canadell *et al.*, 2021). Additional uncertainties include the relative contribution of CO_2 and CH_4 emissions. Given the scale of potential fluxes, as well as the likelihood of continued GHG emissions released from permafrost regions regardless of emissions scenarios (Abbott *et al.*, 2016), more research is warranted to extend measurement technologies and monitoring activities (including drone-based surveys and aircraft-based LiDAR), fund monitoring sites, collect additional data in accessible repositories, and improve earth system models (Turetsky *et al.*, 2019). Achieving a better understanding of the dynamics of carbon releases associated with permafrost thawing, and adequately incorporating those dynamics in earth system models and integrated assessment models, are critical research priorities for anticipating and managing changes in the carbon cycle, and any associated climate risks (Natali *et al.*, 2021).

Furthermore, Sothe *et al.* (2022) estimated that Canada's forests store 14,000 Mt C in aboveground biomass (compared to the 11,500 Mt C total reported by Kurz and Apps (1999)). Aboveground biomass in non-forest ecosystems stores roughly 200 Mt C (Sothe *et al.*, 2022).

Much of the carbon stored in Canadian ecosystems would be irrecoverable on human timescales if released to the atmosphere

As noted above, Canada contains a significant share of the carbon stored in terrestrial ecosystems globally. If lost to the atmosphere, much of that carbon could not be re-sequestered on human timescales. These carbon stocks represent an additional uncertainty for NBCSs, as little is known about how losses will impact the ability of NBCSs to sequester or reduce further carbon emissions. Despite this uncertainty, however, these carbon stocks also represent an opportunity for improved ecosystem management and protection in Canada.

In an analysis of global carbon stocks, Noon *et al.* (2022) found that, in some places, terrestrial and coastal carbon stocks are vulnerable to release due to human activity and, if lost, are not likely to be fully restored from the remaining carbon budget. Noon *et al.* (2022) also found that, globally, the Earth's ecosystems contain approximately 139.1 Gt of irrecoverable carbon, representing roughly 20% of the total manageable ecosystem carbon. In Canada, the boreal peatlands in northern Ontario and northern Manitoba have been identified as a region high in such irrecoverable carbon stocks (Noon *et al.*, 2022).

2.2 The Evolving NBCS Research and Policy Context

2.2.1 Global and Canadian NBCS Research

Research and policy interest in NBCSs is growing; recent studies suggest they could play a significant supporting role in climate change mitigation

Recognition of the sequestration potential of natural carbon sinks is leading to increasing attention to their ability to play a role in climate policy. A growing body of evidence outlines the potential of various NBCSs, reinforcing the findings of the IPCC (2020), which highlighted the possibility for sustainable land management to help mitigate and potentially reverse the negative impacts of climate change on the land. A series of recent international studies have explored the GHG mitigation potential of interventions in these systems at a global level.

Griscom *et al.* (2017) investigated a number of actions involving conservation, restoration, and improved land management that increase carbon storage and/or reduce GHG emissions; these collectively had a maximum global mitigation potential of 23.8 Gt CO_2e/yr (using 2030 as a reference year). However, about half of this total represents actions undertaken in tropical forest ecosystems which are not applicable in the Canadian context. With the inclusion of cost considerations, this value represents approximately 37% of the mitigation required to increase the likelihood of holding global warming to the agreed-upon 2°C threshold (Griscom *et al.*, 2017). Similarly, Roe *et al.* (2021) undertook an assessment of the mitigation potential for 20 land-based measures, including country-level feasibility criteria. They identified a global sequestration potential of approximately 8–13.8 Gt CO_2e/yr between 2020 and 2050, with Canada having a sequestration potential of 0.4 (+/- 0.2) Gt CO_2e/yr, placing it among the top 15 countries (Roe *et al.*, 2021). Girardin *et al.* (2021) reviewed a series of NBCS assessments, determining that NBCSs play a significant role in reducing global mean temperature when sustained. Yet, there remains significant uncertainty in estimating the global mitigation potential of NBCSs, as regional and ecosystem-specific variations will impact overall sequestration potential alongside other considerations, such as cost, barriers to implementation, and technological advances.

> “NBCSs compensate for only a modest share of current and projected GHG emissions in Canada and globally.”

As such, NBCSs have become a focus of climate policy discussion and studies in Canada. Although their potential in Canada varies among studies (see Drever *et al.*, 2021; Roe *et al.*, 2021), Drever *et al.* (2021) report a maximum mitigation potential of approximately 78.2 (41.0 to 115.1) Mt CO_2e/yr by 2030. If successfully implemented, this represents an overall technical potential of ~11.6% of annual Canada’s annual emissions, which in 2020, were estimated at approximately 672 Mt CO_2e (ECCC, 2022b). All recent NBCS research and findings indicate that interventions in natural carbon sinks have the potential to play a role in mitigating global GHG emissions. However, in the Panel’s view, even under the most optimistic scenarios, NBCSs compensate for only a modest share of current and projected GHG emissions in Canada and globally.

2.2.2 NBCSs and Federal Climate Policy in Canada

NBCSs are included in several recent policy commitments by the Government of Canada, including a legislated commitment to achieve net-zero emissions by 2050

As a signing party to the Paris Agreement, the Government of Canada committed to reducing GHG emissions 30% below 2005 levels by 2030, amounting to a reduction of 221.7 Mt CO_2e (ECCC, 2015, 2021c). In 2021, the Government of Canada increased its climate change mitigation ambitions, announcing an enhanced emissions reduction target of 40–45% below 2005 levels by 2030, a total estimated reduction of 295.6–332.6 Mt CO_2e (ECCC, 2021c; PMO, 2021a). This followed closely behind a commitment to protect 25% of Canada’s land and oceans by 2025 and 30% by 2030, “using nature-based solutions to fight climate change and reaching net-zero greenhouse gas emissions by 2050” (GC, 2021a, 2021d). These commitments seek to build on existing strategies by not only protecting the natural environment from the effects of the changing climate but also utilizing natural systems as a means of climate adaptation and mitigation (for examples of how these commitments interact with existing and proposed strategies and provincial regulations, see Sections 3.5.2, 4.5.2, 5.5.2, and 6.5.2).

In 2020, the Government of Canada released an updated climate plan, *A Healthy Environment and A Healthy Economy*, which includes 64 new or enhanced federal policies, programs, and investments to ensure the country is on track to meet its 2030 Paris Agreement goals (ECCC, 2020a). These include additional actions related to NBCSs, such as planting trees, conserving and restoring ecosystems, improving management of lands and waters, and establishing Indigenous Protected and Conserved Areas (IPCAs) (ECCC, 2020a). Another key development was the passage of the *Canadian Net-Zero Emissions Accountability Act* (Bill C-12) in June 2021, which formalized the Government of Canada's target to achieve net-zero emissions by the year 2050 (GC, 2021b). This commitment requires that the entire Canadian economy either emit zero GHGs by 2050 *or that emissions are offset* through various actions and technologies, potentially including NBCSs (GC, 2021c).

The Government of Canada is also working to expedite the implementation of NBCSs through new investments in climate solutions, including the On-Farm Climate Action Fund (as part of the Agricultural Climate Solutions Initiative) (GC, 2021f; AAFC, 2022). Further initiatives are expected to provide GHG mitigation opportunities and additional co-benefits, such as the federal government's commitment to plant two billion trees over the next 10 years, the 2021 *Glasgow Leaders' Declaration on Forests and Land Use*, which seeks to achieve a balance between sustainable development and forest loss (UNFCCC, 2021b), the establishment of new IPCAs, and the continuation of Indigenous Guardians programs (Section 2.4). These initiatives aim to reduce pollution, increase community resiliency to extreme climate events, create thousands of jobs, and improve people's mental health and well-being through increased access to nature (ECCC, 2020a, n.d.; GC, 2021f, 2021g). The federal government has also pledged to ensure that implementation of these commitments will be grounded in science, Indigenous knowledge, and local perspectives (ECCC, n.d.).

2.3 Challenges for NBCS Implementation in Canada

Policy commitments allowing nations (or industry) to offset emissions with actions that enhance carbon sequestration in natural sinks are not universally supported. Despite signalling ambitious climate policy goals, net-zero commitments, such as those made by the Government of Canada, have sometimes been met with concern and opposition — either on the grounds that they allow selective policy implementation by industry or countries as a result of the ambiguous nature of what it means to be net-zero (Nature, 2021), or that they diminish the sense of urgency about emissions reduction (Dyke *et al.*, 2021). NBCSs are also subject to the same policy and regulatory challenges facing other types of carbon offsets or credits. Carbon offset programs (which could be based on NBCSs as well as other forms of carbon credits) allow organizations, corporations, or countries that have exceeded their permitted emissions levels to purchase credit from programs or countries that have not (UNEP, 2019). However, such programs create a variety of challenges for governments and regulators, both in terms of establishing their cost-effectiveness as GHG mitigation measures, and because of other policy and implementation issues, such as high transaction costs, additionality, permanence, carbon leakage, and monitoring.

2.3.1 Assessing the Economic Costs of NBCSs

Accurately assessing NBCS costs requires consideration of many underlying factors

The costs of NBCS implementation are variable by type, across geographic regions, and among environmental and economic contexts. Estimating these costs is also subject to substantial evidence limitations. For practices already widely deployed — such as improved management practices in the forestry and agricultural sectors — economic costs, expected adoption, and implications can be assessed or modelled in more detail. For those where there is limited direct experience, current estimates provide only rough approximations. NBCS research attempts to estimate the expenditures associated with an action on both global (Griscom *et al.*, 2017; Girardin *et al.*, 2021; Roe *et al.*, 2021) and national (Cook-Patton *et al.*, 2021; Drever *et al.*, 2021) scales by analyzing marginal abatement costs (MACs), which indicate the amount of mitigation possible at a given price. The MACs used throughout this report represent the mean cost of an NBCS, however, they do not include values associated with transaction or monitoring costs in their calculations (Cook-Patton *et al.*, 2021). Thus, the value of \$100/tonne of CO_2e, which is often used as a cut-off for identifying "cost-effective" land-based mitigation opportunities, can be insufficient. Grafton *et al.* (2021) note that transaction costs are themselves influenced by the governance associated with the programs put in place, and thus tend to range between 10–90% of the total production cost. This variability, when excluded from calculations of mean marginal abatement, results in potential inconsistencies of approximately 9–47% of the total cost (Grafton *et al.*, 2021).

The *social cost of carbon* (SCC),[9] another metric often used when discussing the costs of NBCSs, is the estimated economic cost of carbon emissions (measured in tonnes of CO_2), including expected damages from climate change.[10] The SCC represents the estimated impact of carbon emissions or the economic benefit of a reduction in carbon emissions (Nordhaus, 2017). It provides information for determining economically efficient investments in climate actions by comparing the cost of carbon abatement measures to the SCC. The SCC differs from the *carbon tax*, which reflects a price levied on carbon emissions and is typically determined on the basis of achieving a particular target (e.g., net-zero by 2050). While economic theory suggests that, in some contexts the two measures should align, there are many reasons why they may not, including differences in damage and/or benefit accrual at the community level as well as project level decision-making in the determination of optimal investments (Rennert *et al.*, 2021).

Comparing the MAC of an NBCS with the SCC (the benefit of mitigation) can determine whether a practice is economically efficient, but it does not provide a complete assessment of whether an NBCS's social benefits are greater than the total social cost. Social cost and benefit estimates need to consider a wide range of underlying factors, including:

- **Opportunity costs –** Costs in terms of forgone expected net revenue (or non-monetary benefits) from other potential land uses.
- **Maintenance costs –** Costs incurred to maintain the functionality of the NBCS over time.
- **Monitoring and compliance costs –** Costs associated with monitoring and compliance activities to ensure carbon remains stored.
- **Timing and discount rates –** Considerations related to the time when costs are incurred and what discount rates are used in analyzing their present value.
- **Mechanism used to generate the supply of NBCSs –** The approach used to establish contracts for the provision of NBCSs. This will affect the cost of supply. Conservation auctions, direct payments, cost-share programs, land purchases, or other approaches will generally result in different costs per tonne.
- **Transaction costs –** Costs included in making decisions, implementing programs, legal elements, and other monetary and non-monetary costs associated with the transaction. These can be as high as 50% of total costs, with significant heterogeneity depending on the scale and nature of the program (see Noga & Adamowicz, 2014; Palm-Forster *et al.*, 2016; Grafton *et al.*, 2021).

9 Currently, the social cost of carbon in Canada is \$50/t CO_2 (measured in 2019 dollars). However, under the federal government's proposed climate plan, the carbon tax will be increased incrementally, reaching a total of \$170/t CO_2 by 2030 (ECCC, 2020b). This will likely, in turn, increase the SCC, which is estimated to rise to between \$135 and \$440/t CO_2 (Canada Gazette, 2020).

10 See ECCC (2016) for Canadian technical guidelines relating to SCC estimates.

- **Nuisance costs –** Additional costs related to inconveniences that arise as a result of NBCS implementation (e.g., increased travel and associated fuel costs) (see De Laporte *et al*., 2021b).
- **Heterogeneity –** The costs of supplying an ecosystem service affected by the scale of the program due to heterogeneity in farm, landowner, or rights-holder characteristics (e.g., Lloyd-Smith *et al*., 2020).
- **Failure rates and risks –** Considerations related to the potential failure rates or risks to implementation and how those are factored into cost calculations.
- **Adoption probability –** Factors relating to what is known about the likelihood of landowners adopting NBCS practices when they are deployed on private land, and how that likelihood changes in relation to the length of the commitment or market conditions.
- **Public vs. private costs –** The relative distribution of costs (and benefits) between public and private landowners, and implications for policy design.
- **The value of co-benefits –** Considerations related to an NBCS's value to society (public and private) in terms of resulting co-benefits and ecosystem services, which in some cases — such as coastal flood control — exceed the costs of implementation (Sutton-Grier *et al*., 2015; Seddon et al., 2020a). This also applies to potential trade-offs that may arise because of the implementation of an NBCS.

In general, landowners and land managers with low opportunity costs will be the first to take advantage of NBCSs, while those with higher opportunity costs will require larger payments or incentives to adopt new practices or make changes to their existing land-use decisions (e.g., Lloyd-Smith *et al*., 2020).

2.3.2 Policy and Implementation Challenges

While a fulsome review of policies available for implementing and maintaining NBCSs in Canada is beyond the scope of this report, the Panel noted that development and evaluation of policy and programs for implementation represent challenges and uncertainties for the deployment of NBCSs. There are often three main types of policy approaches employed: provision or extension services, positive incentives (e.g., subsidies or payments for ecosystem services), and negative incentives (e.g., penalties or regulations for altering or diminishing ecosystem services) (Pannell, 2016). The provision of subsidies or payments to those implementing NBCSs is the primary policy mechanism that could be used to encourage and support NBCS deployment in the Canadian context, as negative incentivization through strict regulations or penalties is often, in the Panel's view, politically infeasible. Payments, which represent the exchange of value for land management practices in support of critical ecosystem services (including, but not limited to, carbon sequestration), may be supported directly by the users of the ecosystem services ("user-financed"), by third parties acting on behalf of the users ("government financed," although this may include private entities such as NGOs, as well), or through the exchange of credits or offsets ("compliance") (Salzman *et al.*, 2018) (e.g., Box 3.2). However, the Panel noted that, despite the seemingly feasible nature of payments for ecosystem services as a means of supporting NBCSs, the solutions do not necessarily guarantee the successful accrual of environmental benefits (e.g., Badgley *et al.*, 2022) and may be costly. Other policy mechanisms have also been identified as potential means of supporting ecosystem services, such as enhanced education, communication, and support for changes in land management; the development of improved land management options (e.g., strategic research and development); and informed inaction (i.e., taking no action where private net benefits outweigh public net costs) (Pannell, 2016).

> "Additionality refers to the requirement that any emissions reduction associated with a carbon offset program could not have occurred in the absence of that program."

However, the Panel noted that there is no single best option for supporting NBCSs across Canada. As Salzman *et al.* (2018) pointed out, "ecosystem services often span across the domains of different agencies and political jurisdictions, creating high transaction costs to mediate the different regimes." Additional variables to be considered include ecosystem type and land ownership (i.e., private vs. public). As such, successful policy must consider the specific contexts involved in the implementation and management of NBCSs (Hoberg *et al.*, 2016; Pannell, 2016).

In the view of the Panel, NBCSs also face challenges common to other types of carbon credits or offsets, which must be satisfied to ensure that emissions reduction benefits are genuine, appropriately accounted for, and sufficiently long-lasting to achieve their objectives, regardless of the policy framework within which they are deployed.

NBCSs must be able to establish that emissions reductions are additional to those that would have occurred in the absence of government policy or support

Additionality refers to the requirement that any emissions reduction associated with a carbon offset program could not have occurred in the absence of that program (Mason & Plantiga, 2013; Michaelowa *et al.*, 2019). It typically requires comparison with a projected baseline of expected emissions in the absence of any new action or intervention. At the federal level, the assessment of additionality uses a baseline that is "reasonable, conservative and justifiable" (GC, 2018). However, the Government of Canada notes that determining such a baseline will require that a number of assumptions be made (GC, 2018), and as a result may be subject to uncertainties related to the specific context of each individual offset project and the overall trajectory of the changing climate.

Across Canada, programs often assess additionality in one of two ways. Some may use what is known as the *common practice test*, wherein a practice is considered additional only if it is taken up by no more than a set percentage of industry practitioners (Climate Smart Group, 2017). Determining what is considered common practice varies; the international standard is set at an uptake rate of 5%, while others could range up to the 40% market penetration baseline set out by the Alberta Emissions Offset System (Climate Smart Group, 2017). The second way additionality may be assessed in Canadian carbon offset programs is through the implementation of a barriers test — that is, the requirement that a program developer demonstrate need for the program by identifying barriers which, in the absence of the proposed action or activity, would have prevented carbon sequestration (Climate Smart Group, 2017). Yet, regardless of the forms taken by NBCS programs, proving additionality is a critical element in the accounting of carbon sequestration (Mason & Plantiga, 2011). Key issues considered in the development of these programs include the availability and accessibility of data; the assumptions used in the analysis of these data; whether the project applies the most up-to-date version of relevant protocols; the project's offset revenue in comparison to other cost savings it may achieve; and whether the project would cease emissions reductions if policy support were no longer received (Greenhouse Gas Management Institute & Stockholm Environment Institute, n.d.).

A further concern with additionality is that of perceived fairness. Actions are only considered additional when they would not have otherwise been carried out — but this results in significant differences when it comes to organizations or individuals who have chosen to implement certain land management techniques at their own expense, prior to an action being deemed viable for offset credits or payment, versus those who have not. Where individuals or organizations have chosen to implement NBCSs (e.g., converting from intensive tillage to no-till agriculture) based on personal preference (e.g., perceived monetary benefits, climate mitigation), those actions would not be considered additional, despite their additional nature in other situations where individuals or organizations have not adopted them. As such, concerns have been raised about whether additionality considerations in policy programs are fair (e.g., Pannell, 2022) and whether this uneven application of policy may result in a perverse incentive, inadvertently encouraging individuals to hold off on implementing NBCSs until they are included in climate mitigation policy as additional actions to be funded.

In the Panel's view, assessing the fairness of policy is not easily quantified. As Pannell (2022) notes, individuals, organizations, and NBCS programs "are heterogeneous and any given action would not produce benefits in excess of costs for everybody. The people who have not adopted may have made a judgment that the benefits to them are less than the costs." Thus, while the fairness of a policy or program should be considered, the Panel believes that what is most critical in assessing additionality is whether it ensures support for NBCSs that will actively contribute to climate change mitigation.

The permanence of carbon storage in terrestrial and coastal sinks — and its sustainability over time — is open to debate

A second key issue regarding offset projects, especially those related to carbon sequestration, is permanence. Terrestrial and coastal carbon stocks are not necessarily permanent and could potentially be re-released to the atmosphere due to natural and human disturbances (Osman-Elasha *et al.*, 2018). Such releases can either be gradual or sudden and are related to underlying issues of biophysical and socioeconomic vulnerability. *Biophysical vulnerability* highlights the risk of carbon being rapidly released back to the atmosphere as a result of climate change or when certain unplanned events occur (e.g., forest fires). S*ocioeconomic vulnerability* refers to the possibility of an NBCS being reversed by a return to historical practices, thus requiring carbon sequestration projects to be supported and maintained through ongoing investments (of time and/or capital) (Kim *et al.*, 2008; Dynarski *et al.*, 2020). Permanence can also be affected by the stringency of policy commitments and legal requirements (e.g., financial liabilities or penalties incurred for carbon releases), by changing economic conditions and carbon prices, or by other socioeconomic factors (Herzog *et al.*, 2003).

Furthermore, for any given NBCS, the ability of a system to *sustain sequestration* over a given timeframe must also be considered. Many carbon offset projects have an attainable maximum relating to the system's ability to sequester and store carbon; thus, consideration must be given to the potential for differential rates of accumulation over time, as well as the vulnerability of those stocks to release, even after a system's ability to sequester carbon is exhausted (Paustian, 2014; Groupe AGÉCO *et al.*, 2020). Under the current federal carbon pricing system, the Government of Canada requires that projects seeking to enhance the sequestration of carbon in natural sinks or reservoirs for offset credits be monitored to ensure longevity (GC, 2018), although evidence of long-term, careful monitoring is difficult to find. Moreover, programs are required to have risk mitigation provisions in place to lessen the chances of reversal and, if a reversal were to occur, to ensure minimal environmental damage (GC, 2018).

While permanence, vulnerability, and sustained sequestration are critical elements to consider when it comes to carbon offset projects, it is worth noting that even temporary carbon sequestration can provide global climate benefits if implemented alongside ambitious emissions reductions. Temporary carbon storage could aid in reducing peak atmospheric CO_2 concentrations and warming while energy systems transition to low- or zero-emissions energy sources (IPCC, 2018; Matthews *et al.*, 2022).

NBCSs can cause the leakage of emissions across borders in certain contexts

Leakage — the phenomenon whereby emissions reductions are offset due to an increase in GHGs outside a given project's scope — can occur at various levels of individual projects, cities, or nations, and in different ways (Blanco *et al.*, 2014). For example, if deforestation in one region is reduced or halted for the purposes of reducing emissions, yet increases in response in another region without a net reduction, any carbon credits associated with the project would be invalid (González-Eguino *et al.*, 2017). Similar effects can occur with conservation of other ecosystems if an NBCS shifts land-use activity, causing GHG emissions rather than reducing them. Throughout this report, consideration of possible leakage is given within discussions of feasibility where supported by the evidence.

Accurately monitoring and accounting for changes in carbon stocks pose challenges for implementing NBCSs

Monitoring and enforcement requirements pose challenges for NBCSs. Accounting protocols and procedures for stored carbon are sometimes contested. Although various guidelines and promising practices have been established (e.g., Aalde *et al.*, 2006), there is no single system or methodology for accounting carbon emissions and reductions, resulting in challenges related to consistency, interoperability of data, and long-term accountability. Monitoring and verification pose additional challenges (Sarabi *et al.*, 2020). Although many natural systems in Canada are monitored (for carbon sequestration or other ecological services), much of the carbon stock is sequestered in unmanaged (ECCC, 2022a) or remote locations or over large spatial areas, making any attempts at ongoing monitoring a challenge both in terms of technological and financial capacity.

Monitoring and enforcement efforts can also be complicated by a misalignment between short-term actions and long-term goals (Kabisch *et al.*, 2016). While many programs seek to develop knowledge on the implementation and immediate impacts of NBCSs, Kabisch *et al.* (2016) found that there is considerable uncertainty about "the impacts they have in terms of human-environment relationships over time." Enforcement challenges are particularly acute for voluntary carbon offset projects, which often lack transparency and third-party standards or verification (Kollmuss *et al.*, 2008). Without third-party verification, offset projects are subject to little or no quality assurance or to legal liability upon failures to comply. Credible use of NBCSs to reduce emissions will require monitoring and verification approaches that are practical, affordable, and methodologically and scientifically defensible (Kollmuss *et al.*, 2008), making it an important element in assessing feasibility (e.g., Grafton *et al.*, 2021). For a discussion of uncertainties and challenges associated with the monitoring and accounting of specific NBCSs, see Sections 3.5.2, 4.5.3, 5.5.3, and 6.5.2.

2.4 Carbon Sinks and Indigenous Peoples

Attempts to enhance carbon sequestration in naturally occurring carbon sinks will not succeed without Indigenous knowledge, involvement, and leadership in decision-making

NBCSs are critically relevant to Indigenous people in Canada. Recognizing that First Nation, Métis, and Inuit people across the country are currently engaged in climate leadership within their own communities, the Government of Canada's climate plan identifies Indigenous climate leadership as a cornerstone of the federal government's climate policy moving forward (ECCC, 2020a). Active and engaged partnerships among various orders of government, including Indigenous governments, will play a key role in addressing the challenges faced by these communities due to a changing climate: the disproportionate impacts due to flooding, wildfires, permafrost thaw, changing patterns in wildlife habitats, diminishing access to traditional food sources, and other social, cultural, and economic impacts.

In Canada, all natural carbon sinks are located on the traditional lands of Indigenous people — lands that have been and continue to be under Indigenous control (i.e., title, treaties, modern land claims). Attempts to enhance carbon sequestration in these systems will not succeed without Indigenous knowledge, involvement, and leadership and would contravene the Government of Canada's legal commitments to Indigenous people and reconciliation (Box 2.3). Concerns about heightened barriers to Indigenous involvement and the potential for misuse of Indigenous knowledge were echoed in discussions at a workshop exploring NBCSs hosted by Townsend *et al.* (2020); on this matter, they suggested that, "[g]iven the overlap of Indigenous territories and carbon sinks in Canada, it is unlikely that nature-based solutions could be widely implemented without upholding Indigenous rights to lands and resources and respecting Indigenous governance and knowledge systems in climate change policy." Indigenous leadership is essential for NBCSs and management actions affecting natural carbon sinks.

NBCS proposals are sometimes met with skepticism and concern over the acknowledgement of land rights. Dr. Kyle Whyte, a member of the Citizen Potawatomi Nation in the United States, noted that, despite current positively framed discourse on the topic of NBCSs, they also carry with them "a lot of different potential harms [as they] have a high likelihood of just being land theft" (Dr. Kyle Whyte as cited in ICA, 2021a). Dion *et al.* (2021) further emphasizes that "the current framing of nature-based solutions tends to conflict with Indigenous worldviews by commodifying nature in terms of offsets and by viewing the land as empty and open for development, effectively erasing the presence of Indigenous Peoples." Others associate NBCSs with a continuation of colonial practices that can be used to "exclude and further remove Indigenous peoples from their lands and waters" (Sinclair, 2021), likening them to a new form of "land grab" (Goldtooth, 2010) or "green grab" (the appropriation of areas of land and associated resources for the purpose of conservation) (Vidal, 2008). Even when lands are deemed "protected," Indigenous people may be dislocated or alienated from their ancestral lands and practices in the name of conservation (ICA, 2021a). Criticism also frequently focuses on related concerns about the use of carbon offsets (including nature-based offsets) to avoid reducing fossil fuel extraction and combustion activities (Seddon *et al*., 2020b; ICA, 2021a). Furthermore, there continue to be concerns that Indigenous experts are being excluded from the development of federal climate policies in Canada, given their current underrepresentation in provincial and federal decision-making bodies (ICA, 2021b).

Box 2.3 Canada’s Legal Obligations to Indigenous Peoples

Interventions related to the management of carbon sinks in Canada occur within a complex legal and jurisdictional context. Indigenous Peoples’ right to govern their territories (which encompasses both the lands and waters) are recognized under by a multitude of laws at a variety of levels including Indigenous and common law systems as well as the international level (Brown & Yates, 2021). Section 35 of the Canadian Constitution affirms and recognizes existing Aboriginal and treaty rights (GC, 1982), thereby ensuring Indigenous Nations’ authority over their territories in terms of the land, resources, and governance. The Constitution also requires consultation (“duty to consult”) any time a course of action proposed by the Crown has the potential to negatively impact those rights, even where they are yet to be “proven” (SCC, 2004). The Government of Canada has also published principles to support reconciliation, acknowledging the “unique rights, interests, and circumstances of the First Nations, the Métis Nation, and Inuit” (JUS, 2018).

The *United Nations Declaration on the Rights of Indigenous Peoples* (UNDRIP) (enacted in Canada in 2021) also recognizes “the inherent rights of Indigenous Peoples which derive from their political, economic and social structures and from their cultures, spiritual traditions, histories and philosophies, especially their rights to their lands, territories and resources” (UN, 2007). The passage of the *United Nations Declaration on the Rights of Indigenous Peoples Act* requires that all Canadian laws must be consistent with UNDRIP, including the requirement of free, prior, and informed consent in any decision or program involving and/or impacting Indigenous communities (in accordance with UNDRIP’s Article 28) (UN, 2007). Moreover, it recognizes the rights of Indigenous Peoples to “own, use, develop and control the lands, territories and resources that they possess” per UNDRIP’s Article 26 (UN, 2007). Given the commitment to UNDRIP, legislation at the federal, provincial, and territorial level must ensure consultation and cooperation with Indigenous Peoples where applicable, especially where cultural and intellectual property, as well as the embodiment of this property through law or custom, is involved (UN, 2007). These commitments, then, have direct implications for the incorporation of Indigenous knowledge, which may result in its prioritization over western scientific approaches (Brown & Yates, 2021).

Land management objectives, including carbon sequestration, need to be supported in ways that are consistent with Indigenous values and priorities

NBCSs can be implemented in ways that respect Indigenous self-determination and are consistent with the needs of Indigenous communities. The Panel noted that the only way for self-determination to be honoured, while carbon sequestration and emissions reductions are successfully enabled and enhanced, is to respect the rights of Indigenous communities to control their lands and resources as they so choose. As is often the case, carbon sequestration may not be the goal of Indigenous land management, but rather an outcome or co-benefit. This may stem from the concept of *all my relations* (*msit no'kmaq* in Mi'kmaq, *mitakuye oyasin* in Lakota, *nindinawemaganidog* in Anishnaabemowin, and *wahkotowin* in Cree), which acts as a reminder of the interconnection of all things and demands respect and care for all things, human and non-human (Nandogikendan, n.d.). When land is managed in accordance with Indigenous priorities and values, ecosystems tend to be conserved and cared for in ways that protect current carbon stocks, reduce emissions, and, potentially, enhance carbon sequestration.

One way the Government of Canada has committed to respecting and upholding Indigenous self-determination and climate leadership is through the creation of IPCAs, which are defined as "lands and waters where Indigenous governments have the primary role in protecting and conserving ecosystems through Indigenous laws, governance, and knowledge systems" (ICE, 2018). They are nation-to-nation agreements that reflect the ongoing stewardship role of Indigenous communities across the country (Indigenous Leadership Initiative, n.d.-a). IPCAs have been found to foster increased agency and self-determination for Indigenous communities by providing more economic and livelihood opportunities, as well as Indigenous leadership in key land-based decision-making processes (Artelle *et al.*, 2019; Tran et al., 2020). In doing so, they help maintain communities' relationships with the land and can support broader environmental goals (Indigenous Leadership Initiative, 2018). Since 2018, the Government of Canada has invested in the future development of 30 IPCAs (ECCC, 2020a).

However, the idea of establishing IPCAs primarily for carbon sequestration or meeting emissions reductions targets is recognized by the Panel as a colonial concept. The purpose of an IPCA — Indigenous self-determination and sovereignty over land — is inherently at odds with NBCSs, which seek to utilize nature as a means to an end. To advocate for such policies would, in the Panel's view, be another form of "land grab," in which the role of Indigenous communities as stewards of their lands is recognized only superficially and for the benefit of the Canadian state.

In addition, the governance of IPCAs can vary widely, and thus the level of protection afforded to land (and associated carbon stocks) within the boundaries of an IPCA would depend on a number of factors, including the IPCA's legal structure and the management goals of the community with decision-making power (Zurba *et al.*, 2019). Although not within an area legally designated as an IPCA, the peatlands of the Hudson Bay Lowlands in Ontario (Section 5.6) exemplify the potential tensions between Indigenous communities' land management goals and broader economic or conservation goals. The significant carbon stocks in this region overlap proposed mining areas; some First Nations have opposed the mining due to environmental and cultural concerns, while others are partnering with the Government of Ontario to build access roads, which will provide infrastructure and economic opportunities to their communities (McIntosh, 2022; Northern Ontario Business, 2022; Renner, 2022). As such, IPCAs and Indigenous land management, on their own, are not considered by the Panel to be NBCSs; however, where management strategies associated with NBCSs enhance carbon sequestration or emissions reductions, IPCAs can be an important contributor to the relative success of NBCS activities.

> "Without the expertise and involvement of Indigenous communities, the full potential of many NBCSs may not be realized, and the various possible co-benefits attached to these practices may not be attained."

Another way in which the Government of Canada has recognized the important role Indigenous communities play in climate leadership is through the establishment of Indigenous Guardians programs across the country. Indigenous Guardians are "trained experts who manage protected areas, restore animals and plants, test water quality, and monitor development" (Indigenous Leadership Initiative, n.d.-b). Representing a radical shift in how the federal government interacts with Indigenous nations, Guardian programs are Indigenous-led collaborative bodies that engage with land-users, industry representatives, and governments to determine how land is managed. With over 70 programs operating across the country, Indigenous Guardians help communities build capacity, strengthen decision-making, and honour traditional ways of being and knowing (Indigenous Leadership Initiative, n.d.-b). Under the current federal funding strategy, Indigenous Guardian programs undertaking NBCS work — such as "habitat stewardship for maintenance and improvement of ecosystem services" or "conservation, land use, and land relationship planning" — are eligible to receive financial support (ECCC, 2021d).

Other NBCS models would thus ideally be developed in ways that ensure carbon sequestration activities for natural systems are consistent with the values and goals of the affected Indigenous communities. The diversity of both Indigenous Peoples and carbon-sequestering ecosystems in Canada means that interventions will be most successful when adapted to the local context. Appropriate approaches, as well as the feasibility of such approaches, will differ depending on the context. However, based on both its own research and its discussions with Indigenous knowledge-keepers across Canada, the Panel believes that meaningful, ongoing Indigenous involvement and leadership in the development and implementation of NBCSs is essential to their long-term success. This is in part due to the inherent indigeneity of many NBCSs (e.g., prescribed burning practices; Box 3.3). Without the expertise and involvement of Indigenous communities, the full potential of many NBCSs may not be realized, and the various possible co-benefits attached to these practices may not be attained.

2.5 Conclusion

Recent global and Canadian studies show that carbon sinks could play a useful supporting role in GHG emissions mitigation, reducing emissions and often removing CO_2 from the atmosphere while potentially yielding co-benefits. As a result, policymakers are increasingly turning their attention to NBCSs, looking to see how these natural systems can be harnessed to support GHG reduction targets and net-zero commitments in Canada. However, rigorously assessing these opportunities is a complex process. It requires careful exploration of the underlying carbon-cycle dynamics, awareness of the implications for other GHGs, and an understanding of how land-use changes impact radiative forcing and climate change. Estimates of carbon fluxes and stocks in natural carbon sinks are often subject to high levels of uncertainty compared to energy-based emissions (and emissions reductions) calculations. In exploring opportunities to enhance carbon sequestration in naturally occurring terrestrial and coastal sinks, it is important to consider a wide range of implications, including issues surrounding permanence and sustained sequestration, feasibility, and co-benefits versus impacts. Further, engaging with Indigenous communities is also critical for the long-term success of many NBCSs. As all carbon sinks are located on Indigenous lands, Indigenous communities are often best placed to offer solutions to critical issues that potentially limit NBCSs; the importance of Indigenous leadership in decision-making cannot be overlooked.

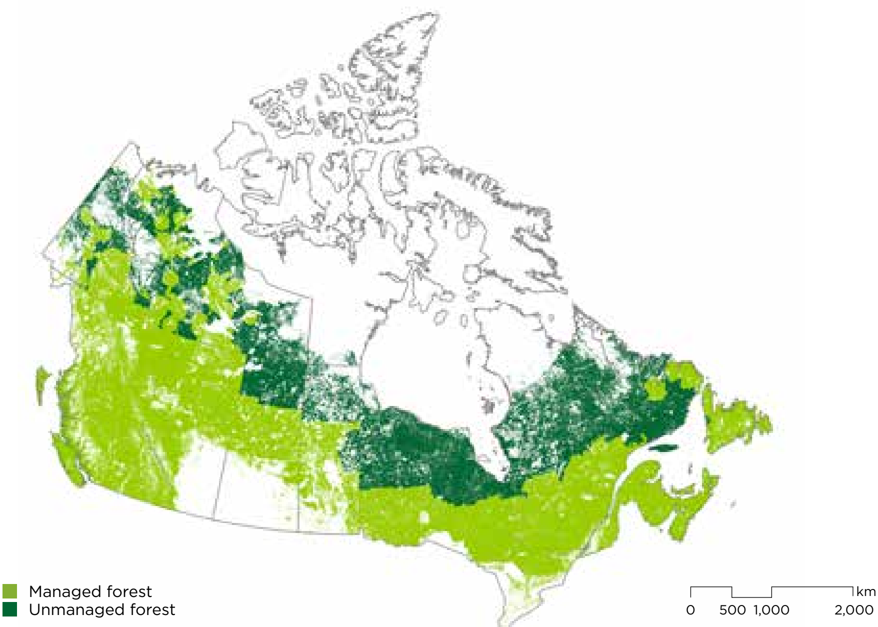
3

Forests

Chapter Findings

- Canada's extensive forests can enhance carbon sequestration (or mitigate emissions) when conversion to other land uses is avoided, management practices are improved, and forest cover is restored.
- The feasibility of implementing NBCSs in forests — particularly unmanaged forests — requires research on forest responses to NBCSs and climate change, as well as engagement with Indigenous communities.
- Carbon stored in Canadian forests is increasingly vulnerable to disturbances due to climate change, including loss of productive forest area, deficits in regeneration, and increased risk of fire and insect outbreak. By 2018, Canada's managed forests were estimated to be a net source of CO_2, due to large-scale natural disturbances, including the burning of more than 1.4 million hectares. Mitigating emissions from these disturbances may therefore have significant GHG emissions reduction potential, alongside actions to increase forest resilience and adaptive capacity.
- The effectiveness and feasibility of forest NBCSs vary due to specific local conditions, such as albedo changes that offset the mitigation benefits of expanding forest area. Generalizations made about forest management practices at a national scale cannot capture regional responsiveness and would benefit from regional research and monitoring.
- Critical gaps in research include (i) the current state of carbon stocks and fluxes in unmanaged forests to provide a baseline for NBCS implementation, and (ii) a better understanding of regional practices that have mitigation potential and assessing where these are most effective and feasible. These research efforts can be linked with the collection of information on biodiversity and social safeguards required to sustain these practices while reducing risks including the effects of climate. The implementation of regional forest NBCS projects, along with continued monitoring and research can quantify their longer-term contribution to emission reductions.

Forests cover approximately 347 Mha in Canada, accounting for about 9% of the world's forests (NRCan, 2020a). Twenty-eight percent of the global boreal forest is in Canada; over three-quarters of Canada's forest is in the boreal zone (Brandt, 2009; NRCan, 2020a). Sixty-five percent of Canadian forest area is considered *managed* forest, subject to active management and stewardship.[11] The remaining 35% is considered *unmanaged* and located primarily in northern Canada (NRCan, 2020b) (Figure 3.1). Forests are the largest terrestrial carbon sink on the planet (Domke *et al.*, 2018) and Canada's extensive forest ecosystems could offer globally significant opportunities for NBCSs given their size and scale. However, recent trends in Canada also show that forests are potentially large sources of GHG emissions due to impacts from forest disturbances, some of which are being amplified by climate change (Grosse *et al.*, 2011; NRCan, 2020a; ECCC, 2021b).



Reproduced with permission: NRCan (2020b)

Figure 3.1 Forest Area in Canada

Managed forests account for 65% of total forests in Canada (232 Mha), with unmanaged forests accounting for the remaining 35% (115 Mha) (NRCan, 2020b).

11 Forests vary in levels of management intensity. Managed forests include those managed for timber harvesting or non-timber resources (e.g., parks) as well as those subject to fire protection (ECCC, 2020c). For GHG reporting purposes, *forest management* is defined by the IPCC as "the process of planning and implementing practices for stewardship and use of the forest aimed at fulfilling relevant ecological, economic and social functions of the forest" (Penman *et al.*, 2003).

3.1 Opportunities for Enhancing Sequestration and Reducing Emissions in Forests

Forest carbon is stored in three main pools, which respond to changes in harvest and management practices on different timescales

Forests take up and sequester carbon from the atmosphere through photosynthesis, transforming CO_2 into biomass. This ability is affected by both biophysical and socioeconomic factors (Birdsey *et al.*, 2018b), and sequestration activity can be enhanced through a variety of NBCSs, including forest management activities, forest conservation, avoided conversion, restoration of forest cover, and increased urban canopy cover (Table 3.1).

The three major carbon pools in forests are above- and belowground live biomass, standing and fallen dead wood, and soil organic carbon (SOC), including humus, surface litter, and mineral soil layers (NASEM, 2019) (Figure 3.2).[12] While visible biomass dominates the discussion of forest NBCSs, more carbon is sequestered in boreal forest soils than in above- or belowground biomass, which together contain about 27% of the total carbon per hectare in managed forests (FAO, 2020). Woody litter and dead wood contain an additional 23% and 10% respectively, while the remaining 40% is accounted for by soil carbon (calculated to a depth of 55 cm belowground and excluding peat). When all three pools are considered, Canada's managed forests store approximately 208 t C/ha (FAO, 2020), but the variability of carbon sequestration potential across Canada (e.g., by ecological zone, forest type, stand age, disturbance history) makes regional estimates more informative.

Some studies indicate that substantial amounts of carbon are stored in deeper soil horizons. For example, one recent study of forested areas in Canada used a machine-learning approach to predict deeper soil carbon stocks where observations were quite limited, including those in forested peatlands (Sothe *et al.*, 2022). This resulted in an estimated total soil carbon stock of 306 Gt C (+/- 147) to a depth of one metre, with an additional 266 Gt C between one and two metres (Sothe *et al.*, 2022). Carbon pools respond differently to management practices, harvesting, and other types of disturbance (NASEM, 2019). Soil carbon stocks are reduced after harvest, but evidence suggests that, in most cases, their levels partially recover within several decades (Kishchuk *et al.*, 2016; Mayer *et al.*, 2020). However, some forest carbon is irrecoverable; that is, some forest carbon pools (e.g., old-growth forests) will not regain the lost carbon from disturbance in a timeframe relevant to effective climate action (Noon *et al.*, 2022).

12 "Herbaceous biomass and plant litter with short residence time [less than one year] are generally ignored in the context of carbon sequestration because they do not represent a persistent removal of CO_2 from the atmosphere" (NASEM, 2019). However, plant litters in Canadian forests have been reported to remain over several years (Prescott, 2010).

Data source: FAO (2020)

Figure 3.2 Relative Size of Carbon Pools in Canada's Managed Forests

Carbon stocks are listed in tonnes per hectare, with the percentage of total following. Estimates are for 2020 based on the Food and Agriculture Organization of the UN (FAO) data.

Changes in these pools occur gradually over decades, which means that measuring impacts is an ongoing process (NASEM, 2019). Timescales for NBCS impacts also vary. Activities and land-use changes that reduce emissions from forests (e.g., changing management practices and conservation) yield results in the short to medium term (10–30 years) or avoided conversion that is additional and limits leakage yields results instantaneously; while activities that increase carbon sequestration as forests grow (e.g., restoration of forest cover; Table 3.1) have more fulsome impacts over the long term (more than 30 years) (Drever *et al.*, 2021). Net mitigation benefits from these NBCSs stem from changes in carbon storage in all three pools (plus harvested wood products), as well as secondary impacts related to changes in albedo, the substitution of biomass for fossil fuel energy, or emissions-intensive building materials (Drever et al., 2021).

Table 3.1 Forestry NBCSs

Definition of NBCS	Mechanism
Improved Forest Management	
Changing the **treatment of forest harvest residue** from the burning of logging slash after clearcutting to bioenergy production.	Reducing the area of slash burning in turn reduces carbon emissions to the atmosphere (Smyth *et al.*, 2020). Harvest residue may also be left to decay, emitting carbon in subsequent years; however, forest management regulations may require that harvest residue be actively managed (Dymond *et al.*, 2010; Lamers *et al.*, 2014; Ter-Mikaelian *et al.*, 2016; Smyth *et al.*, 2017).
Changing the **utilization of forest harvest residue and products** includes using this residue as harvested wood products (HWPs) for bioenergy (substituting fossil fuels with bioenergy and wood products), increasing the proportion of HWPs (which are long-lived), and increasing salvage harvesting (Dymond, 2012; Smyth *et al.*, 2014).	HWPs provide "[i] temporary storage of removed carbon while in use or disposal, [ii] substitution of wood for other construction materials that require substantial quantities of fossil energy to produce (avoided emissions), and [iii] use of wood for biofuel, which may reduce net emissions relative to burning fossil fuels" (NASEM, 2019).
Reduced harvesting and partial harvest alters the frequency or volume of the harvest and can therefore assist the regeneration of a stand.	Reduced harvesting limits the land available for harvest or extends harvest rotations, allowing trees to grow larger and sustain carbon storage rates (Zhou *et al.*, 2013). The relationship between forest carbon stocks and net emissions of carbon to the atmosphere with changes in harvest volume varies due to local forest conditions, including growth and disturbance rates (Ter-Mikaelian *et al.*, 2014, 2021).
Thinning and other silvicultural treatments (the growing and harvesting of trees as crops) can promote higher stand growth compared with untreated conditions (NASEM, 2019).	Although thinning results in carbon emissions in the short term, the practice reduces biomass available for burning, thereby reducing the risk of stand-replacing crown fires (fires which burn the entire tree). Management decisions about thinning depend on whether harvesting is used for long-lasting wood products or biomass energy, but also fire risk, tree species, site, thinning regime, and the length of the harvest interval (Ryan *et al.*, 2010). Thinning can occur commercially or non-commercially and may include partial cuts to increase biomass growth.
Improving forest productivity, stocking and extending timber harvest rotation can increase forest carbon stocks and substitution capabilities.	The extension of harvest rotations maintains the capacity of older forests to remove CO_2, avoids emissions associated with more frequent harvests, and directs more biomass into long-lived wood products that store carbon (NASEM, 2019).

Definition of NBCS	Mechanism
Artificial **regeneration** of forest stands can be actively managed and accelerated through improved planting techniques.	Regeneration can be expedited through site preparation, seeding, planting, and vegetation management, which can shorten the time required for harvested forest areas to absorb more carbon than they release (Ryan *et al.*, 2010; Kurz *et al.*, 2013). Forest management practices to improve regeneration vary by local climate and species selected, but techniques include controlling competing vegetation, increased fertilization, planting genetically modified stock, and selecting tree species with faster growth rates (Ryan *et al.*, 2010).
Other **forest management practices** may include prescribed burning, increasing productivity through scheduling, intensity and execution of operations (silviculture), vegetation, and adaptive management (Dymond *et al.*, 2020).	Forest management strategies that maintain or increase forest carbon while keeping forests productive provide the largest sustainable mitigation effects (Nabuurs & Masera, 2007). The intensity of silviculture impacts forest composition and carbon sequestration. Although prescribed burning can emit carbon in the short term, it may protect forests from larger and more intense fires in the long run (Hurteau *et al.*, 2008). Adaptive management maintains forest services by adjusting the mixture of tree species to anticipated future climate conditions (Temperli *et al.*, 2012). Mixed stands increase forest resilience to changes in precipitation rates, which have a larger impact on carbon sequestration than precipitation (Hof *et al.*, 2017). Vegetation type and management can impact sequestration, as soil carbon increases faster under broadleaves than coniferous trees (Nickels & Prescott, 2021).
Forest Conservation	
The **avoided conversion** of forests, including old-growth forest conservation, protects existing carbon pools by limiting agriculture, mining, and urban expansion; stopping overharvesting, overgrazing, pest outbreaks, and wildfires; and establishing protected areas.	Avoided conversion maintains carbon pools in forests and prevents emissions due to conversion. Key to this is reduction of conversion to agricultural and grazing land; agricultural development along the southern extent of the boreal forest is historically the largest contributor to deforestation, although the rate of forest conversion is estimated to be approximately 40,000 ha/yr (ECCC, 2020c). A key consideration is the planned conversion of land and expected trajectory of increasing agricultural prices and land values, which may make avoided conversion less likely. Avoided conversion of old-growth forest that prioritizes stands with relative site productivity within various ecosystems seems an appropriate method to increase the possible maintenance of ecosystem resilience (Price *et al.*, 2021).

Definition of NBCS	Mechanism
Restoration of Forest Cover	
Restoration of forest cover includes the planting of trees where forests were once the dominant land class, a practice often called **afforestation** in Canada (ECCC, 2022b) and **reforestation** globally (Jia *et al.*, 2019).	Restoration of forest cover increases the biomass of forests through tree planting as more carbon is stored within the increased vegetation. Abandoned agricultural land reverting to forests naturally or through planting may have a significant impact on carbon budgets (Drever *et al.*, 2021).
Urban canopy cover sequesters carbon in biomass in urban areas.	Planting new and replacement trees in urban areas increases canopy cover and enhances CO_2 sequestration (Drever *et al.*, 2021).

3.2 Indigenous Forest Management

Indigenous Peoples have been stewards and managers of forests for millennia, and the carbon stocks located on these lands have benefitted from the longevity of their care. Indigenous forest management practices, including burning (Box 3.3), have a lengthy history and are used in a variety of contexts. The variability of the boreal forest ecosystem has informed Indigenous management practices, which are adaptable to interactions with the environment (Sayles & Mulrennan, 2019).

As discussed in Section 2.4, IPCAs are one mechanism which can empower Indigenous-led conservation actions across the country. Four Anishinaabeg First Nations along the border between Manitoba and Ontario have protected the cultural and natural values of more than 2.9 Mha of boreal forest area, known as Pimachiowin Aki, a UNESCO World Heritage Site (Moola & Roth, 2019). In the boreal region, IPCAs and additional protection processes can assist Indigenous communities in codifying the protection of traditional territories impacted by industrial development (Moola & Roth, 2019).

Canada's colonial history of removing Indigenous people from their forests, including for the creation of national and provincial parks (Binnema & Niemi, 2006), has led to the assumption of jurisdiction of managed and unmanaged forest land (Moola & Roth, 2019) (Section 3.1). The re-Indigenizing of conservation reframes biodiversity conservation "to encompass the interrelated concepts of decolonization, inclusion, resurgence, and reconciliation" (M'sɨt No'kmaq *et al.*, 2021). Conservation practices should "simultaneously respect and promote the inherent rights of Indigenous Peoples [by] centering and privileging Indigenous worldviews and ways of knowing" (M'sɨt No'kmaq *et al.*, 2021).

Indigenous stewardship encompasses a wide variety of practices and goals for land management, which can include the protection of carbon stocks in these landscapes. Indigenous Guardian programs are one way in which communities can be empowered to monitor, use, and protect forests (Section 2.4). Guardians can play a key role in forest fire management (Box 3.3) as the intensity and frequency of forest fires increase; not only do they protect and actively manage land, but they can design, implement, and monitor forest NBCSs (SVA, 2016) (Section 3.5.2).

3.3 Magnitude of Sequestration and Emissions Reduction Potential

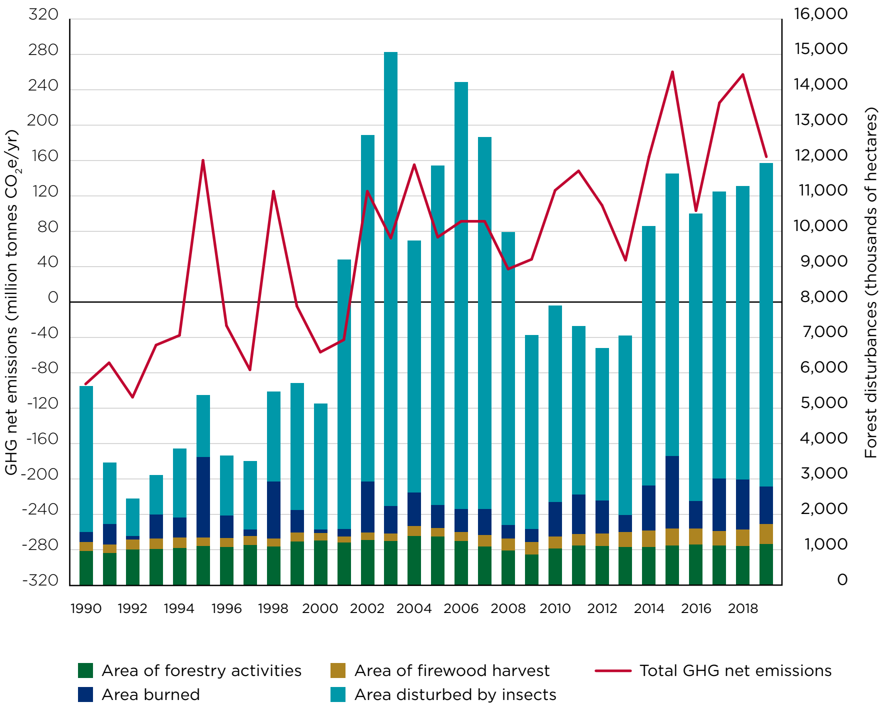
3.3.1 Estimating Forest Carbon Fluxes in Canada

Under the *United Nations Framework Convention on Climate Change* (UNFCCC), the Government of Canada is obligated to monitor and report changes in carbon stocks and GHG emissions or removals in its managed forests (NRCan, 2020b). Official estimates are quantified by Canada's National Forest Carbon Monitoring, Accounting and Reporting System (NFCMARS), informed by the 2006 IPCC *Guidelines for National Greenhouse Gas Inventories* (IPCC, 2006) and in line with the IPCC's *Good Practice Guidance for Land Use, Land-Use Change and Forestry* (Penman *et al.*, 2003; NRCan, 2020b). The calculation of forest carbon budgets involves the estimation of carbon dynamics over a defined area (e.g., stand- or landscape-level), often for a growing season or year (Kurz *et al.*, 2013).

These guidelines, however, often result in the incomplete reporting of emissions and removals. For example, although Canada's *National Inventory Report* models the carbon dynamics of harvested wood products (HWPs), the emissions of GHGs are not reported the moment they are out of use as many HWP are used as building materials; long-lived products end up in landfills for decades, and a smaller fraction slowly decays and emits CO_2 and CH_4 to the atmosphere (ECCC, 2022a). Therefore, the decision about whether to include HWPs in an accounting framework can significantly change the degree to which different management practices may yield additional sequestration benefits.

Managed forests in Canada have become a net source of CO_2 in recent years due to disturbances such as wildfires

Throughout the twentieth century, managed forests in Canada acted as a significant carbon sink (ECCC, 2022a). However, in recent years, factors such as wildfires, insect outbreaks, decreased rates of precipitation, and shifting annual harvest rates have contributed to Canada's forests becoming carbon sources instead of sinks (NRCan, 2020a) (Figure 3.3). By 2018, Canada's managed forests were estimated to be a net source of CO_2, due to large-scale natural disturbances, including the burning of more than 1.4 Mha (ECCC, 2020c). In 2018, these emissions were approximately 243 Mt CO_2e; calculations considered both human activities and natural disturbances (ECCC, 2020c) (Figure 3.3). Natural disturbances accounted for 257 Mt of emissions, while forest management activities (e.g., harvesting, slash-pile burning, regeneration, use and disposal of HWPs) sequestered 8 Mt of CO_2e in 2018 (ECCC, 2020c). Despite uncertainties in forest carbon flux measurements, the shifting of managed forests from sink to source of GHG emissions has important implications.



Data Source: NRCan (2020a)

Figure 3.3 Net GHG Emissions in Canada’s Managed Forests

In recent years, increased forest disturbances due to wildfires and insects have resulted in Canada’s managed forests becoming a net source of GHG (NRCan, 2020a). These estimates are only for managed forests. The Panel noted that this figure overemphasizes the importance of low-intensity insect disturbances, as direct emissions from insects are relatively small; a much larger share of insect-caused emissions comes from the decay of trees killed by insects and reduced growth of partially defoliated trees.

Forest carbon flux estimates are subject to large uncertainties, modelling limitations, and knowledge gaps

Forest carbon flux estimates are subject to significant uncertainty, particularly for the boreal forest, due to changes in environmental conditions affecting net primary productivity (NPP) and decomposition (e.g., climate change, CO_2 fertilization effect, nitrogen deposition); a limited understanding of disturbance processes; and interactions between disturbances and ecosystem production (Kurz *et al.*, 2013; Forzieri *et al.*, 2021). Higher levels of CO_2 in the atmosphere, for example, may accelerate forest growth in some contexts, but growth enhancement due to CO_2 fertilization in the boreal forest is disputed. Some studies indicate a positive effect (Walker *et al.*, 2021), while others show no impact (Jiang *et al.*, 2020). The productivity of nearly all Canadian forests is limited by nitrogen availability, so growth enhancement from elevated CO_2 is unlikely. Higher levels of CO_2 may, however, result in more CO_2 being fixed and released belowground as surplus, which could increase SOC (Prescott *et al.*, 2020). As most studies test a single environmental variable (Melillo *et al.*, 2011; Sistla *et al.*, 2014), understanding of disturbance processes — and interactions between disturbances and ecosystem production — remains limited (Chen *et al.*, 2000; Kurz *et al.*, 2013). Estimating the response of soil carbon stocks to environmental conditions and disturbances depends on the depth of the soil column, highlighting the importance of sampling at depth to gain accurate observations (Jobbágy & Jackson, 2000).

Moreover, regional variations exist for both carbon fluxes and their potential responses to climate change (e.g., Girardin *et al.*, 2016). Shifts in NPP and soil carbon maintenance due to warming, for instance, both depend on the availability of water and its interactions with local topography (Walker & Johnstone, 2014; D'Orangeville *et al.*, 2016, 2018; Ziegler *et al.*, 2017). With respect to Canada's boreal forest, even the form and timing of water input, as impacted by climate change (e.g., snow dynamics), are key drivers of dissolved organic carbon fluxes, in turn regulating soil carbon stocks (Bowering *et al.*, 2020, 2022). As more than 77% of Canada's forests are in the boreal zone, the regional responses of Canada's other forested zones (e.g., temperate forests) are not covered in depth (NRCan, 2020a). Temperate forests may be better sites than the boreal to implement NBCSs because of higher ecosystem productivity (37% of national wood volume), lower albedo deductions on mitigation potential, lower costs of implementation because they are often less remote, lower permanence risks from wildland fire, and higher additionality of avoided conversion (due to higher conversion risks) (NRCan, 2020a).

There is further uncertainty over changes in lateral carbon fluxes (i.e., fluxes of carbon between forests and adjacent ecosystems) and the fate of carbon directed to deeper soils versus carbon lost laterally to the aquatic environment (Campeau *et al.*, 2019; Bowering *et al.*, 2022). Models for the North American boreal forest must cover large geographic areas and consider data from all terrestrial and aquatic surface fluxes (Kurz *et al.*, 2013). Estimates therefore vary due to the size of the net flux in this zone (Huntzinger *et al.*, 2012; Kurz *et al.*, 2013), and there are uncertainties associated with the spatial resolution of regional fluxes. Modelling cannot always capture subtle changes in fluxes, which impacts our understanding of the permanence and vulnerabilities of forest carbon stocks and underscores the need for regional *in situ* observation and monitoring of regional forest carbon fluxes (Kurz *et al.*, 2013).

Inventory-based modelling of carbon stocks and fluxes has the advantage of being informed by datasets from many regions across the country (Kurz *et al.*, 2009), but cannot model future responses to environmental changes such as climate. Unlike the inventory-based approach, process models include the effects of climate change on simulated processes. However, process models estimating carbon fluxes in North America can disagree on the magnitude or direction of net carbon fluxes (Hayes *et al.*, 2012; Huntzinger *et al.*, 2012). A process-based model used by Chen *et al.* (2003) that incorporated climate change impacts (e.g., longer growing season, CO_2 fertilization, nitrogen deposition) yielded larger carbon stock estimates of aboveground biomass than inventory-based approaches. Modelling assumptions — such as increased productivity due to higher atmospheric CO_2 concentration, warmer temperatures, and longer growing seasons — can be poorly constrained (Girardin *et al.*, 2011; Kurz *et al.*, 2013), and the responses are regionally specific (Girardin *et al.*, 2016). An understanding of how soil carbon stocks respond to environmental conditions and disturbances is also limited by the need for increased regional measures and observations of soil carbon and biomass to inform models, and for soil carbon observations at depth (Jobbágy & Jackson, 2000), as evidenced by the impact of these on soil carbon stock estimates in Canada (Sothe *et al.*, 2022). Permafrost dynamics in the northern boreal forests increase the complexity of these model assumptions, resulting in large uncertainties in estimates of net carbon fluxes in Canada's unmanaged boreal forest (Kurz *et al.*, 2013; Hayes *et al.*, 2014).

The assessment of carbon stored in HWPs is subject to debate

The treatment of carbon stored in HWPs is a further source of uncertainty and debate in forest carbon accounting (Dymond, 2012). During the processing of biomass into products (e.g., timber), carbon is released to the atmosphere, with losses of harvested biomass ranging from approximately 20–60% at harvest and more at processing, depending on conversion efficiency (Bergman & Bowe, 2008; Ingerson, 2009; NASEM, 2019). The remaining carbon is stored temporarily in the manufactured HWPs. The appropriate accounting of carbon in this pool, however, is debated. Selecting which carbon pools to consider in an accounting framework has significant implications for the kinds of incentives and practices that would be considered to yield additional sequestration benefits.

The 2006 IPCC reporting guidelines assumed carbon in harvested biomass was emitted during the year of harvest (i.e., instantaneous emission) (Pingoud *et al.*, 2006); in the *National Inventory Report*, however, the HWP pool is treated as a "carbon transfer related to wood harvest and hence does not assume instant oxidation of wood in the year of harvest" (ECCC, 2022a). Carbon accounting analysis has expanded to different end-of-life pathways, including postponing carbon emissions through the storage of HWPs in landfill, which must be considered in calculations to accurately estimate carbon effects (Larson *et al.*, 2012). Solid wood products placed in landfills experience a slow rate of decay (Ximenes *et al.*, 2008) and, therefore, a small emission of CO_2 to the atmosphere (Larson *et al.*, 2012). Carbon storage gains from HWPs discarded in landfills may be partly offset by the increased CH_4 emissions, which makes accounting even more complicated (Hennigar *et al.*, 2008; Larson *et al.*, 2012).

3.3.2 Estimating Forest NBCS Potential

International studies provide estimates of the amount of carbon per hectare that can be sequestered by selected forest NBCSs. Afforestation and reforestation globally provide an estimated net stock increase of 2.8–5.5 Mt CO_2e/yr, while improved forest management increases net stocks by 0.2–1.2 Mt CO_2e/yr (Griscom *et al.*, 2017). Such estimates provide an approximate range of the potential carbon sequestration benefits associated with these NBCSs; however, more accurate estimates would factor in the specific characteristics of forest lands in Canada. In the view of the Panel, global estimates are subject to significant uncertainty based on variability in forest characteristics and approaches for measuring forest carbon stocks and emissions. Additional information on specific forest NBCSs, including their effects on carbon stocks and potential benefits, is summarized below.

Improved forest management activities can result in short-term emissions reductions as well as longer-term changes in forest carbon sequestration

Forest NBCSs vary in the timing of their impact and their effects on different carbon pools. In the short term, many interventions related to forest management have immediate mitigation potential before declining. *Reducing the burning of logging slash*, for example, can result in immediate emissions reductions, since approximately 20–30% of pre-harvest biomass is typically left in the forest during harvesting (not including tree roots), and a smaller fraction of harvest residue is burned (Ter-Mikaelian *et al.*, 2016). Similarly, *increasing use of harvest residues in bioenergy or wood products* can yield immediate impacts in avoided emissions. However, clearcutting boreal forest for bioenergy to replace fossil fuels could result in net emissions of GHGs (Smyth *et al.*, 2017; Malcolm *et al.*, 2020). *Green-tree burial* (i.e., cutting fewer productive trees and burying the logs to prevent decomposition (Zeng, 2008)) could also sequester carbon by preserving it in woody biomass; this practice has an estimated global mitigation potential between 1.0 and 3.0 Gt CO_2/yr (Zeng *et al.*, 2013).[13]

Substituting wood products for other types of more energy-intensive construction (e.g., concrete, steel) may avoid emissions associated with the production of those materials and help ensure that carbon in wood products is sequestered in infrastructure for decades or longer. *Substitution*, however, has come under criticism in recent literature (e.g., Harmon, 2019; Leturcq, 2020; Howard *et al.*, 2021), primarily due to a number of associated assumptions. For example, that wood products are a direct substitute for concrete and steel in current building designs, overestimating the reduction of demand and use of non-wood products when replaced with wood.

The main potential climate benefit of increasing the use of HWPs is that they generally use less total energy in the overall production cycle and avoid emissions from the manufacture of other materials, such as cement (Sathre & O'Connor, 2010; NASEM, 2019). To that end, the *improved use and treatment of HWPs* means increasing the proportion of long-lived products and changing waste management strategies. HWPs have variable lifespans before they are discarded as waste; the IPCC estimated a 35-year half-life for sawnwood and other industrial roundwood, 25 years for panels, but only 2 years for pulp and paper (Pingoud *et al.*, 2006; ECCC, 2022a). Smyth *et al.* (2014) and Chen *et al.* (2018) noted that increasing the percentage of wood in HWPs for long-lived products reduces the timeframe needed to achieve net cumulative mitigation.

In Canada, conversion to longer-lived products (e.g., using more wood in construction and reducing the production of short-lived pulp and paper) was found to be a more effective mitigation strategy than using wood for bioenergy (Dymond *et al.*, 2010; Lamers *et al.*, 2014; Smyth *et al.*, 2014; Chen *et al.*, 2018). Improving preservative treatment methods of harvested wood (Song *et al.*, 2018), use of wood productions for bioenergy (Dymond *et al.*, 2010), and advanced landfilling could be significant CO_2 removal approaches, but these would not be credited under current reporting guidelines (NASEM, 2019; ECCC, 2022a). Implementing strategies to increase the uptake of long-lived HWPs, however, would be complicated; usage changes depend on market dynamics, consumer preferences, and a range of underlying socioeconomic factors, including

13 Agricultural land, protected areas, inaccessible forests, and wood for other uses were excluded from this estimate.

"population, economic growth, education, urbanisation, and the rate of technological development" (Ter-Mikaelian *et al.*, 2021).

Extending forest rotations can also lead to mitigation benefits

Based on U.S. and global estimates, longer timber harvest rotations (along with other management actions benefitting forest productivity) are estimated to be able to store an additional 0.2–2.5 t C/ha/yr for several decades (NASEM, 2019). Decreased harvesting frequency — coupled with practices that improve the retention of structural components, such as fallen logs and ground vegetation — has been shown to significantly increase mean carbon storage in models of northern hardwood-conifer forests, including biomass carbon stock (Freeman *et al.*, 2005; Hyvönen *et al.*, 2007; Nunery & Keeton, 2010). Conversely, increased harvesting has been estimated to lead to lower forest carbon stocks and higher net atmospheric GHG emissions in Ontario's boreal forests (Ter-Mikaelian *et al.*, 2021). Studies of extended rotations indicate that they tend not to coincide with constant levels of harvesting rates, and instead lead to either increased or decreased levels of harvesting relative to rotation length or tree retention (Nunery & Keeton, 2010; Santaniello *et al.*, 2017). Increases or decreases in carbon stocks from extended rotations only include carbon stored in the forest stand; the consideration of other carbon pools (e.g., wood products) generates more uncertainty about strategies to maximize overall mitigation (e.g., Hennigar *et al.*, 2008). Reducing wood harvest levels may, in turn, lead to leakage (Section 2.3.2) that would negate at least a fraction of the expected carbon sequestration benefit.

Thinning and other silvicultural treatments can encourage higher stand growth compared to untreated stands (NASEM, 2019). Commercial thinning has not been widely adopted in western Canada; however, studies have found that commercially thinning stands of lodgepole pine decreased rotation length and increased individual tree size and stand volume — thereby increasing carbon sequestration and decreasing the length of time needed between harvests (e.g., Das Gupta *et al.*, 2020). The impact of thinning on soil carbon and other carbon pools is uncertain; it has been found to reduce carbon stocks when accounting for removed biomass (Mayer *et al.*, 2020), but impact in other sites in the boreal forest may be minimal, although it has been shown to increase soil temperature and respiration (Zhang *et al.*, 2018; Jörgensen *et al.*, 2021). Commercial thinning may also mitigate mid-term timber supply shortages due to mountain pine beetle outbreaks and fire, and is most effective in stands younger than 60 years old (Das Gupta *et al.*, 2020).

Other silvicultural approaches can also benefit forest ecosystems and carbon sequestration, including *variable retention harvesting* and *continuous-cover forestry*, which are significant for retaining soil carbon inputs. Strategic planning that includes functional zoning approaches,[14] for example, can minimize the negative impacts of forest management on ecosystem function while maintaining timber supply (Côté *et al.*, 2010), although the potential carbon benefit requires additional research. Alterations to areas prioritized for conservation and high retention harvesting techniques can result in more stands with old-growth forest attributes (e.g., diverse stand ages, carbon stocks) as well as benefits to biodiversity and ecosystem services (Côté *et al.*, 2010; Price *et al.*, 2021).

More effective strategies for regenerating forest areas after harvesting or natural forest disturbance can also potentially lead to enhanced carbon sequestration over the longer term. Some forest stands may be better suited to current climate conditions and do not regenerate after consecutive natural disturbances; these have resulted in areas now classified as open woodlands (<25% canopy cover) in Canada's continuous boreal forest (Boucher *et al.*, 2012; Brown & Johnstone, 2012). Ecosystem-based management draws inspiration from natural disturbances, and replicating these after a silviculture treatment may be the best way to conserve natural aspects of the forest (Kuuluvainen *et al.*, 2021); the Panel noted, however, that the functional impact of commercial harvesting is nowhere near the same as historical wildfire — the predominant disturbance regime. Species that have a high survival and growth rate under changing climatic conditions may be prioritized for the replanting of productive forests for harvesting (Saxe *et al.*, 2001). In areas vulnerable to disturbances such as fire, fire-resistant species may be planted to preserve carbon storage, especially where harvesting may not be economically viable.

Avoiding the conversion of forest area to other land uses prevents the loss of carbon stored in these ecosystems

Preventing the conversion of forests to non-forested land through conservation can also avoid CO_2e emissions in the short term, most notably in areas that are consistent with other conservation objectives (e.g., old-growth forests). Globally, deforestation and associated land-use change are major sources of GHG emissions. Canada's forest area is relatively stable, though some deforestation continues (~35,000 ha/yr, or approximately 0.01% of total forest area) (NRCan, 2020a). Mining along with oil and gas development were the leading causes of recent forest conversion in Canada (~15,000 ha in 2019), followed by agriculture, infrastructure development (e.g., industry, transportation, municipal development, recreation), hydroelectric dams and reservoirs, and forestry roads (ECCC, 2021a). Preventing deforestation avoids both immediate emissions

14 Zoning refers to the practise of dividing the landscape into areas with different management objectives and uses.

associated with harvesting activity as well as residual emissions from ongoing decomposition of biomass in vegetation and soils. For example, the conversion of forest to agricultural land in Canada in 2018 led to immediate emissions of 0.9 Mt CO_2e, and residual emissions from conversion in previous years of 1.5 Mt CO_2e (ECCC, 2020c). Conservation preserves the ongoing ability of growing forests to sequester carbon, though rates of carbon sequestration in aboveground biomass decline as forests mature (Framstad *et al.*, 2013). Forest conservation initiatives are often accompanied by substantial co-benefits, such as species habitat and ecosystem services (Section 3.6).

Restoration of forest cover could potentially lead to long-term increases in carbon sequestration

By restoring degraded forest cover and creating new forests, reforestation and afforestation could have some of the greatest NBCS impact globally (Griscom *et al.*, 2017). Much of the North American carbon sink has been attributed to reforestation following agricultural abandonment associated with younger or mid-aged eastern forests (Birdsey *et al.*, 2006). However, the benefits of these NBCSs occur over longer timeframes, since their efficacy is constrained by forest growth rates (Forster *et al.*, 2021a). The carbon sequestration potential of agroforestry (i.e., the simultaneous presence of trees or shrubs with crops and/or livestock on a land management unit), as well as its uncertainties, is discussed in Section 4.1.

As forest stands mature and grow, carbon sequestration rates increase but gradually taper off when natural limits to growth are reached and tree mortality occurs (Kurz *et al.*, 2013). For conifer-dominated stands in the boreal forest, carbon sequestration peaks and then begins to decrease after approximately 150 years (Goulden *et al.*, 2011; Gao *et al.*, 2018). Carbon accumulation over time, after restoration of forest cover, depends on previous land use, soil type, site preparation technique, and planted tree species (Ma *et al.*, 2020; Mayer *et al.*, 2020). In the boreal region, model simulations suggest that the afforestation of open woodlands requires around 8–12 years to reach a net positive carbon balance (Boucher *et al.*, 2012). In contrast with the results of Boucher *et al.* (2012), simulations by Fradette *et al.* (2021) showed gains of carbon when restoration of forest cover takes place on boreal open woodlands.

Reforested areas benefit from the fact that they are historically suited to forest cover; planting native forest species on previously converted land is more likely to succeed because they are adapted to the site, with strong survival and growth rates suitable for wood products (NASEM, 2019). Determining lands suitable for afforestation is more difficult, requiring consideration of both environmental and anthropogenic pressures that could affect long-term success. In the Canadian context, a cost-benefit model for afforestation of hybrid poplar, hardwood, and softwood stands found that the most important variables related to carbon sequestration were site suitability, the conversion factors from biomass to carbon equivalent, and wood density (McKenney *et al*., 2006).

Since 1990, Canada has experienced almost no afforestation (ECCC, 2022b), although data are limited. Global studies have estimated large areas of opportunity (i.e., the area over which forest NBCSs can be deployed) and mitigation potentials for this NBCS in Canada, given the breadth of hypothetically suitable land (Roe *et al*., 2021). The reversion of agricultural lands back to forest cover could contribute to both regional and national carbon sequestration. For example, abandoned agricultural land reverting to forests naturally or through planting may have a significant impact on carbon budgets; one analysis of abandoned cropland in Ontario found that, over a 15-year period, a reforested site consistently sequestered approximately 1 t C/ha/yr (Voicu *et al*., 2017). The feasibility of restoration of forest cover, especially in eastern Canada, is limited on cropland due to the lack of area of opportunity and prohibitive costs (Section 3.5.1). In western Canada, agricultural land opportunity costs are generally lower; wood density is a more important variable there than it is in eastern Canada (McKenney *et al*., 2006). It is also worth noting that most research has focused on measurements of carbon in aboveground biomass; uncertainties remain about the impacts on belowground biomass and soils despite the size and longevity of these carbon pools (Noormets *et al*., 2015).

Urban tree canopy cover can help sequester carbon, though benefits are modest relative to other NBCSs

According to estimates in Canada's *National Inventory Report*, urban trees removed an average of 4.3 Mt CO_2e/yr between 1990 and 2018 (ECCC, 2022b). Urban forests can also contribute to GHG emissions reductions by reducing the use of air conditioning (City of Toronto, 2010). The climate impact of increased urban canopy cover varies from city to city depending on the carbon storage ability of selected species, the energy used for planting, maintenance, irrigation, and the potential net effect of trees on local air temperature (Ryan *et al*., 2010). Urban trees have been found to store an average of 76.9 t C/ha/yr in the United States (Nowak *et al*., 2013). Drever *et al*. (2021) estimated that urban trees in Canada annually sequester 2.12 t C/ha of canopy cover based on the results of US studies (e.g. Nowak *et al*. (2013)), which were adapted to reflect Canada's shorter growing season. Other studies have found that the carbon sequestration benefits of increasing urban canopy cover tend to be modest, especially when the relatively intensive costs of urban planting and maintenance are factored in (McGovern & Pasher, 2016). Carbon sequestration may be a secondary objective in this case, but urban trees are associated with other co-benefits linked to biodiversity, climate adaptation, and mitigation of urban heat-island effects (City of Toronto, 2010) (Section 3.6.1).

3.3.3 Forest NBCS Carbon Sequestration Potential in Canada

The area of opportunity for forest NBCSs in Canada is limited by feasibility constraints

The implementation of forest NBCSs is constrained by the size of the area over which they can feasibly be deployed. Reforestation potential is limited, for instance, by the extent of historically forested land that has been converted to other uses. The theoretical potential for restoration of forest cover is large in Canada, given the land area, but conflicts with other land management priorities which constrain implementation. Notably, it may not be any more feasible to practise afforestation in grasslands (Bárcena *et al.*, 2014) or peatlands (Zerva & Mencuccini, 2005) — which are strong carbon sinks — than, for example, cropland (Section 4.3). Regeneration deficits in previously forested lands (due to the frequency and intensity of fires) can limit the potential of forest-cover restoration (Kurz *et al.*, 2013).

Opportunities for conservation are also limited by the extent of forest at risk of deforestation and conversion to other uses. Theoretically, all managed forest area could be converted to other uses. In practice, however, most forest area is not at risk of being converted. Annual deforestation rates are low in Canada (NRCan, 2020a), and overall forest area is stable, leaving relatively small areas at risk for land conversion. However, Drever *et al.* (2021) noted that, although the rate of deforestation in Canada is low compared to tropical countries, there is nevertheless ample mitigation potential from avoided conversion that dwarfs, in the near term, the potential available from restoration of forest cover.

Most available data pertaining to area of opportunity are derived from managed forests. The forest areas suitable for these practices are limited by both biophysical and socioeconomic constraints, and the area of opportunity for forest restoration used in global studies that include Canada may consider areas of unmanaged forests not currently accounted for in modelling processes. On the other hand, Drever *et al.* (2021) conservatively estimated only 3.8 Mha could feasibly be restored through the restoration of forest cover after accounting for potential biophysical constraints (i.e., limiting area of opportunity to sites within 1 km of a road for ease of access, and excluding sites with low potential growth rates).

Changes in albedo offset some of the climate change mitigation benefits of expanding forest area

The overall effect of the restoration of forest cover on CO_2e can be significantly impacted by changes to *albedo* — the proportion of light reflected from Earth's surfaces — particularly in Canada; increases in forest cover reduce surface reflectivity (especially over snow cover), causing more surface warming (NASEM, 2019). In boreal zones, afforestation may have a warming effect that negates the cooling effects of the reduced CO_2 emissions of forests. In temperate zones, the effects depend on a multitude of factors, including vegetation type (e.g., deciduous, which has higher albedo in winter than coniferous), extent and timing of snow cover, slope, and aspect (the direction of the slope face) (NASEM, 2019). Drever *et al.* (2021) "estimated the CO_2e flux consequences of albedo-changes caused by forest harvest[; that is,] changes in albedo from full forest to newly cleared forest to regrowing forest and from old growth conservation relative to" business as usual. In the years immediately after a harvest, albedo effects are more substantial, persist longer for land-use changes, and are more dramatic following changes to conifer stands above the snow line (Cherubini *et al.*, 2012; Holtsmark, 2015).

Recent estimates suggest forest NBCSs could cumulatively sequester up to 783 Mt CO_2e in Canada between now and 2050, factoring in albedo changes

Drever *et al.* (2021) assessed the national potential of four general categories of forest NBCSs: improved forest management; avoided conversion; restoration of forest cover; and maintaining and increasing urban canopy cover (Table 3.2). These estimates clearly indicate some potential for these categories, though net sequestration would mostly occur only cumulatively after 2030 within some large ranges of uncertainty, with the exception of avoided conversion of forest. The *improved forest management* scenario combined the modelled impacts of a 10% reduction in annual total harvest,[15] a 10% increase in growth rates after harvest, and a 10% reduction of slash burning following clearcutting, while assuming a use of up to 50% of post-harvest residues for bioenergy production. The emissions reduction potential of this modelled change in forest management is approximately 7.9 Mt CO_2e/yr in 2030 (Drever *et al.*, 2021).

The same study estimated an *avoided conversion* "of 20,143 ha/year until 2030 against a [business as usual] scenario, accounting for changes in [both] albedo [and] emissions from all forest ecosystem pools due to conversion and forgone sequestration." Factoring in avoided GHG emissions, avoided loss of forest carbon sequestration, and changes in albedo due to land-cover change, this NBCS could provide mitigation of 26.3 Mt CO_2e cumulatively between 2021 and 2030 (Drever *et al.*, 2021).

15 This was achieved by saving the oldest stands scheduled for harvest. It is not just a reduction of harvest in old-growth forests, but reduction in harvest overall.

With respect to restoration of forest cover, Drever *et al.* (2021) included the "conversion of non-forest (<25% tree cover) to forest (>25% tree cover) where forests historically occurred [and excludes] planting of trees after forest harvest (a legal obligation in Canada)." The restoration of forest cover (by the establishment of native tree species only where trees are the natural vegetation) has a limited mitigation potential in 2030 of <0.1 Mt CO_2e/yr, but will be more impactful after several decades of growth (Drever *et al.*, 2021).

Table 3.2 Forest NBCS Sequestration Potential, as Estimated by Drever *et al.* (2021), and Panel Confidence

Type of NBCS	Present to 2030		Present to 2050		Panel Confidence	
	Annual (at 2030) (Mt CO_2e/yr)	**Cumulative** (2021–2030) (Mt CO_2e)	**Annual** (at 2050) (Mt CO_2e/yr)	**Cumulative** (2021–2050) (Mt CO_2e)	**Flux**	**Area of opportunity**
Improved forest management practices[16]	7.9 (-15.6 to 31.4)	-9.7 (-95.3 to 381.3)	27.9	471.4	Limited	Moderate
Avoided conversion of forests	3.8 (3.0 to 4.5)	26.3 (24.0 to 28.7)	1.1	63.3 (60.5 to 66.2)	Limited	Moderate
Restoration of forest cover	0.05 (-2.0 to 2.0)	-2.9 (-5.6 to -0.1)	24.9 (-11.5 to 61.0)	242.7 (168.2 to 317.1)	Moderate	High
Maintaining and increasing urban canopy cover	0.2 (0.1 to 0.6)	0.9 (-0.4 to 2.2)	1.6 (1.1 to 2.2)	18.5 (9.8 to 27.2)	High	High

Data source: Drever *et al.* (2021)

Avoided conversion of forests is estimated at a rate of 30,689 ± 2,085 ha/yr based on a business as usual scenario. The forest management estimate assumes: "(i) 10% reduction in harvest of old forest relative to" business as usual; (ii) "a 10% increase in growth rates of forests regenerating after harvest"; (iii) "avoidance of burning post-harvest residues in the forest;" (iv) "use of up to 50% of harvest residues for bioenergy" (Drever *et al.*, 2021). Reforestation is planting "where forests historically occurred and excludes planting of trees after forest harvest" (Drever *et al.*, 2021). Estimates were originally reported as Tg CO_2e/yr. The Panel indicated its level of confidence in these estimates by providing ratings for both the GHG flux and area of opportunity used by Drever *et al.* (2021) to calculate the mitigation potential. See the Appendix for Panel Confidence scale.

16 Drever *et al.* (2021) simulated implementation of improved forest management from 2021–2050, while implementation of other NBCSs stopped in 2030. Therefore, their results for annual sequestration in 2050 and cumulative sequestration for 2021–2050 are not comparable among NBCSs.

Recent national estimates of mitigation potential have some underlying uncertainties

There are uncertainties underlying recent estimates by Drever *et al.* (2021). Factors not considered in the uncertainty of the dataset include regional responses to climate change, ecosystem interactions, and the broader range of NBCS actions available for implementation. Future climate change effects were excluded, as well; changes in temperature and precipitation may be less of an issue when modelling effects on forest growth in the short term, but natural disturbances such as fires and insect outbreaks are expected to shift substantially. Differences in temperature and water availability have been noted to impact forest growth and soil carbon accumulation on decadal scales (D'Orangeville *et al.*, 2016; Ziegler *et al.*, 2017). Potential losses during planting due to drought are not fully assessed in the measurements. Drever *et al.* (2021) relied on an average wildfire area estimated using data for 2007–2017, and did not simulate insect outbreaks despite the large area of forest disturbed by insects each year (CAT, 2021) (Figure 3.3).

The *improved forest management* scenario modelled by Drever *et al.* (2021) combined the impacts of conservation, regeneration, and increased wood utilization, and did not include proposed management actions such as increased harvest rotations and thinning. While simulating the reduction in harvest level, Drever *et al.* (2021) did not include a drop in harvest below 10% of historical levels, in part to avoid the issue of leakage. For example, the amount of leakage from global forests based on a meta-analysis of 46 studies by Pan *et al.* (2020) was 40%. Therefore, the sequestration potential in the conservation portion of the *improved forest management* scenario in Drever *et al.* (2021) could be reduced by about 40% due to the negative effects of leakage.

Estimated sequestration potential for the *improved forest management* scenario includes avoided emissions due to the substitution of steel and concrete with long-lived HWPs, and of fossil fuels with bioenergy from harvest residue; the avoided fossil fuel emissions were maximized by selecting from nine different candidate bioenergy facilities as substitutes for fossil fuel burning (Drever *et al.*, 2021). This is a commonly used methodological approach, but it may result in an overestimation of substitution benefits due to the so-called rebound effect (defined as "the gap between the decreased use of resources that is expected from increased 'eco-efficiency' and the actual utilisation" (Holm & Englund, 2009)).

Global models are likely to overestimate forest NBCS mitigation potential in Canada

The estimations for some NBCSs in the forestry sector were modelled in global aggregation studies using a sectoral approach. Afforestation and reforestation in Canada, for example, were estimated to have a sequestration potential of approximately 102 Mt CO_2e/yr between 2015 and 2050 in a cost-effective modelling scenario (Austin *et al.*, 2020; Roe *et al.*, 2021), and a forest management potential of 30 Mt CO_2e/yr over the same period. While the global models used a similar cost-effective scenario (up to $100/t CO_2e) as Drever *et al.* (2021), the estimates are not easily comparable to the latter study — the global review was unable to consider local context, including policies and regulations, funding, technical and geophysical barriers, and co-benefit potential. Additionally, the aggregation of potentials across sectors or NBCSs did not always account for challenges related to land allocation and competition, nor the possibility of double-counting impacts (e.g., emissions from land-use change) (Roe *et al.*, 2021).

3.4 Stability and Permanence

Few biophysical limits constrain ongoing forest carbon sequestration, though rates of sequestration decline over time as forests mature

Some improved forest management practices (e.g., improved use of harvest residues) can be used indefinitely and provide continued benefits in avoided emissions. Others are constrained by the dynamics and stages of forest growth and carbon uptake. Sequestration rates of older boreal forests (>90 years) allow the forests to serve as carbon sinks beyond normal harvest age, but biomass accumulation rates decrease with age (Framstad *et al.*, 2013; Prescott *et al.*, 2020). Older forests have greater SOC and dead organic matter stocks; the variations in SOC stocks due to age require additional research, and it is not yet known if the carbon stocks accumulate indefinitely rather than reaching a steady state (Framstad *et al.*, 2013). Stimulation of tree growth can lead to canopy tree mortality in the future, eventually offsetting carbon gains (Brienen *et al.*, 2020). While rising atmospheric CO_2, global temperature, and nitrogen deposition, as well as longer growing seasons, have increased tree growth, these factors may also eventually result in greater tree mortality (Erb *et al.*, 2016; Körner, 2017). Limits on water availability, moreover, are present in some regions but less so in others (D'Orangeville *et al.*, 2016). Nutrient limitation controls on forest productivity can also be regionally controlled by soil and its geological parent material (Augusto *et al.*, 2017) with SOC storage impacted by weathering rates (Slessarev *et al.*, 2022).

Climate change impacts threaten the stability of forest carbon sinks, especially in the boreal forest

Threats to forest carbon pools are likely to intensify in coming decades due to climate change impacts such as a heightened risk of fire and drought, biotic agents such as insect infestations, and other disturbances (Gauthier *et al.*, 2015; Anderegg *et al.*, 2020); fire risks around Hudson Bay and the northwestern extent of the boreal forest will be especially acute (Girardin & Terrier, 2015). Anticipated increases in the frequency, extent, and severity of high-latitude disturbances in the North American boreal forest, as well as climate-mediated changes in productivity, may limit its potential to serve as a terrestrial carbon sink, and in fact represents a carbon climate feedback liability (Hicke *et al.*, 2012; Bradshaw & Warkentin, 2015; Dymond *et al.*, 2016; Creutzburg *et al.*, 2017; Wang *et al.*, 2021b). A greater understanding of deeper soil carbon pools and their response to climate change is needed, given their importance as carbon stocks with potential longer-term stability; there is uncertainty about their responses to climate change given shifts in carbon sources and hydrology (Kramer & Chadwick, 2018; Bowering *et al.*, 2022; Slessarev *et al.*, 2022; Weiglein *et al.*, 2022).

Boreal wildfires will play a key role in shifting the carbon balance as they continue to increase in size, frequency, and intensity (Walker *et al.*, 2019; Mack *et al.*, 2021). Pools of soil carbon have accumulated in forests by avoiding combustion beneath the burned layer across multiple fire events over millennia. These legacy pools are now at risk, as young forests (<60 years) have experienced an increase in legacy carbon combustion (Walker *et al.*, 2019). An additional climate change-induced effect of wildfires on carbon stocks is the length of wildfire season: Turetsky *et al.* (2011a) found that when the annual burn area was small in Alaskan black spruce stands, the depth of burning in ground biomass increased as the fire season progressed. There is notable regional variation in the possible risk of climate impacts to carbon stocks in Canada (e.g., the risk of more intense wildland fire is higher in western Canada than eastern Canada). In the Panel's view, limitations in the research on possible impacts of increased fire frequency and intensity, as well as less abrupt but impactful shifts in precipitation regimes, complicate estimates of the carbon sequestration potential of forest NBCSs.

Forests are vulnerable to natural disturbances and may adapt to growing stressors

Forest vulnerability to climate-driven natural disturbances varies across regions and is impacted by the effects of interactions among ecosystem processes (Forzieri *et al.*, 2021). Fire activity is driven by the vegetation composition of boreal forests and influences it in turn. Shifts in dominant species due to severe fire — from slow-growing conifer species such as black spruce to deciduous stands, for example — may offset the increased combustion of soil carbon (Mack *et al.*, 2021). While dry conditions and short fire intervals can overwhelm the resilience of coniferous boreal forests, deciduous forests are more resistant to such disturbance due to rapid asexual regeneration (Whitman *et al.*, 2019). They can support longer fire-free intervals, lower fire severity, and reduced fire spread across the landscape. These forests could potentially be a negative or stabilizing feedback to climate warming by maintaining carbon pools longer and increasing albedo associated with any shift from coniferous to deciduous growth (Mack *et al.*, 2021).

Storms and wind-driven events can also impact carbon cycling in forests as these disturbances weaken the impact of the forest carbon sink (Seidl *et al.*, 2017). The frequency, duration, and intensity of wind events have a direct effect on forest disturbance, as do snow and ice duration and intensity; however, while ice and snow events could generally be reduced due to warmer conditions, the frequency and duration of wind events are likely to persist or even grow (Cheng *et al.*, 2007; Peltola *et al.*, 2010; Seidl *et al.*, 2017). Natural disturbances can have a more immediate impact on forest biomass and carbon storage while the restoration of forest cover enhances carbon sequestration over a longer timeframe.

Insect disturbances are equally significant as a growing risk to forest carbon pools. Since 1990, outbreaks of mountain pine beetle, spruce beetle, eastern hemlock looper, and aspen defoliators have resulted in major impacts on managed forests in Canada (Stinson *et al.*, 2011) (Figure 3.3). Insect infestations lower the average age of forests and result in a decreased rate of carbon accumulation in biomass (ECCC, 2020c). Low-level insect infestations can increase tree mortality over large areas; this, in turn, increases emissions from decomposition (ECCC, 2020c), although impact on soil carbon pools requires additional research.

3.5 Feasibility

Changes in land use face more implementation barriers than changes in forest management practices

Feasibility challenges for forest NBCSs stem from a variety of factors, including access to land, consistency with current timber harvesting and forest management practices, and potential conflicts with other public land management objectives (Gaboury *et al.*, 2009; Gauthier *et al.*, 2015; NASEM, 2019). The limited availability of land for conversion, leakage, risk of disturbances, and economic and behavioural barriers can all impede the full adoption of forest NBCSs (NASEM, 2019), but the degree of feasibility varies across type. Many relevant forest management practices, including forest regeneration and tree planting, have been widely deployed, and knowledge about their implementation can be applied in a variety of contexts (City of Toronto, 2010; Austin *et al.*, 2020). Forest NBCSs involving changes in land use (e.g., restoration of forest cover), however, are likely to face more significant barriers in implementation than those associated with land available for conversion (NASEM, 2019).

Other barriers to implementing forest NBCSs relate to HWPs, such as the construction industry's inclination to use steel and concrete rather than wood products for structural purposes (Gosselin *et al.*, 2016; Howard *et al.*, 2021). Important motivating factors include the use of a sustainable resource to help mitigate climate change (Himes & Busby, 2020). Meanwhile, barriers to using wood include building codes, engineers' and architects' limited expertise with wood use in tall structures, concerns about material durability, and lack of supply of cross-laminated timber or other advanced wood-building material (Gosselin *et al.*, 2016). In the Panel's view, the ability of wood producers to address these barriers and encourage the use of these materials, along with global socioeconomic factors, will ultimately determine whether the use of wood in construction increases or decreases.

3.5.1 Forest NBCS Costs

Different methods are available to estimate the costs of implementing forest NBCSs

The costs of implementing NBCSs in managed forests may be over- or underestimated due to numerous factors, including the method of estimation (Box 3.1), harvesting requirements, leakage, and dynamic effects (e.g., changing prices of forest products over time). All models exploring these costs involve assumptions, including the costs of base products, implementation timescales, and future market-feedback effects. Cost studies in Canada's forestry sector that use a *bottom-up* approach may be underestimations because they exclude price and intersectoral market effects (Lemprière *et al.*, 2017). Bottom-up models may overestimate the costs of carbon per tonne in implementation models with a multi-year timescale as the cost of base products shifts from a demand for pulp and paper to longer-term HWPs (Lemprière *et al.*, 2017).

Box 3.1 Approaches to Cost Analysis

The costs of adopting forest NBCSs can be estimated using three general approaches:

- **Bottom-up approaches** rely on the calculation of costs for proposed management changes by simulating the increases in costs from a baseline that would arise from a proposed strategy (Richards & Stokes, 2004). This approach can factor in regional variations in costs and was used by Drever *et al*. (2021).
- **Optimization studies** optimize the net present value of operations if operators are given a payment for GHG reductions from the baseline (e.g., assumes a price for carbon to be paid and allows the firms to optimize given that price). The optimization approach should yield the level of carbon sequestration that can be achieved for a given price, and can be re-optimized over time, but strategies are not comparable across different land uses and regions (Richards & Stokes, 2004).
- **Econometric approaches** involve the analysis of specific case studies of landowner and user demands (Richards & Stokes, 2004). These studies reveal how landowners and managers have historically adjusted land use based on carbon prices, unlike the optimization approach, which models assumed profit maximization. Econometric studies have been used to estimate forest NBCS costs internationally; in the Panel's view additional Canadian research is required for analysis.

> "There is a potential to mitigate forest emissions by 2030 at a cost of less than \$70/t CO_2e, though uncertainty in the mitigation potential is quite large."

Long-term forest management practices could cost less than \$70/t CO_2e by 2030

Lemprière *et al.* (2017) estimated that long-term forest emissions mitigation strategies in Canada could result in an average reduction of 16.5 Mt CO_2e/yr at costs estimated to be below \$50/t CO_2e. Elsewhere, Drever *et al.* (2021) estimated a total cost of \$2.6 billion, or approximately \$260 million per year on average; the average cost is \$16/t CO_2e for improved forest management practices between 2021 and 2030,[17] reducing emissions by 9.7 Mt CO_2e/yr. According to the latter analysis, there is a potential to mitigate forest emissions by 2030 at a cost of less than \$70/t CO_2e, though uncertainty in the mitigation potential is quite

17 See Table 3.2 description.

large (95% confidence interval spans <0 to >30 Mt CO_2e/yr (Drever *et al.*, 2021). Improved forest management practices led by Indigenous communities — such as changing harvesting practices and decreasing deforestation — can generate carbon credits, which these communities can then sell to buyers, offsetting emissions and enhancing Indigenous investment in ecosystem management (Box 3.2). This opportunity may also represent a viable pathway to increasing the area of opportunity for these NBCSs.

Box 3.2 Indigenous-Led Forest Carbon Credit Programs

Many Indigenous communities in Canada are interested in the economic co-benefits of advancing NBCSs in their traditional territories (Townsend *et al.*, 2020). The profits from the sale of carbon credits — developed by Indigenous communities in collaboration with provincial and territorial governments — can be reinvested in these communities to help fund land stewardship and management practices. While such agreements are a relatively new development in Canada, there are several cases where First Nations have successfully implemented forest management practices aimed at generating economic benefits while simultaneously improving sustainability and forest health.

The Coastal First Nations in British Columbia have signed an Atmospheric Benefit Sharing Agreement with the Government of British Columbia that gives them ownership of, and the ability to sell, carbon credits (Coastal First Nations, 2020). The sale of carbon credits advances economic self-sufficiency within the First Nations. Carbon credits are generated through ecosystem management practices in the Great Bear Rainforest, such as avoided deforestation or degradation; protecting more trees by logging less frequently or more carefully; afforestation; and replanting forests where they have been removed (Coastal First Nations, 2020). The sale of carbon credits and the notion of commodifying nature and ecosystem services is an ethical question that each Nation considers.

Similar initiatives are underway in other provinces. In Manitoba, Poplar River First Nation has a carbon-sharing agreement with the provincial government along with ecosystem carbon accounting (Townsend *et al.*, 2020). In the Northeast Superior region of Ontario, Wahkohtowin Development GP Inc. was created by three First Nations to advance strategic economic opportunities, including the implementation of climate action strategies that focus on forest carbon (Townsend *et al.*, 2020; Wahkohtowin Development GP Inc., n.d.).

The costs for reforestation and avoided forest conversion are higher than those for improved land management. While most avoided forest conversion is focused on agricultural land, other avoided conversion — including constraints on infrastructure development and extractive industries — is likely to cost more than \$100/t CO_2e due to a range of economic, social, and regulatory factors (Drever *et al*., 2021). Drever *et al.* (2021) calculated that the average cost of converting forest to cropland is approximately \$2,000/ha and \$2,500/ha in western and eastern Canada, respectively. Additional costs for the management of unconverted forests (e.g., thinning, pest and fire control) were not included. By 2030, approximately 2.3 Mt CO_2e/yr, or about 97% of the total mitigation from avoided conversion to agricultural land, could be achieved at a cost below \$50/t CO_2e, while the cost of avoided conversion to non-agricultural land is assumed to be more than \$100/t CO_2e (Drever *et al*., 2021). Decisions related to restoring forest cover can be affected by the value of maintaining land in a more flexible state; assessing land-use change decisions at the agriculture-forestry interface can be complex (Yemshanov *et al*., 2015).

Excluding areas from harvest for the purposes of conservation could result in increased costs due to a dispersal of cutting sites across larger areas, decreasing transportation efficiency, and increasing the average time spent loading harvested wood (Lemprière *et al*., 2017). Costs for management actions also depend on their location and accessibility. For example, the costs for mitigating natural disturbances in remote areas of boreal forest are often not economically viable (Gauthier *et al*., 2015), yet ecosystem management practices in remote areas may play an important role beyond our current understanding of economic feasibility (Box 3.1).

Regional variation in initial investment costs impacts the mitigation potential of restoration of forest cover

Restoration of forest cover is considered to be among the least economically intensive GHG mitigation measures (Nabuurs & Masera, 2007), but the initial economic investment required can be an important decision-making factor (Boucher *et al*., 2012). Ensuring access to areas targeted for restoration of forest cover, including road construction and maintenance, may also require significant expenditures while generating emissions that would lessen the overall benefits of the increased tree coverage (Gaboury *et al*., 2009; Boucher *et al*., 2012). Restoration of forest cover has both upfront costs of implementation and subsequent costs of opportunity and land value (Drever *et al*., 2021). Based on average costs provided by provinces and territories, Drever *et al.* (2021) estimated that upfront costs include site preparation costs for restoration of forest cover at \$700/ha, tending costs at \$600/ha, and seeding costs from \$900/ha (for evergreen needleleaf forests) to \$2,000/ha (for deciduous broadleaf forests). In evergreen needleleaf forests, planting costs were estimated to be between \$730–1,200/ha, increasing with change in slope. Likewise, in mixed forests, planting costs are estimated to range from \$865–1,100/ha, while deciduous broadleaf forest costs were estimated at \$1,000/ha throughout (Drever *et al.*, 2021). While restoration of forest cover costs are subject to regional variation, a 2005 study found that carbon prices of \$10/t CO_2 or higher would encourage investment in afforestation in most regions of Canada (Yemshanov *et al.*, 2005). This estimate is close to but smaller than the estimate of \$15–20/t CO_2 based on the above estimates of the individual costs and the average biomass of 165 t CO_2 in mature forests in Canada (Penner *et al.*, 1997).

The costs for increasing urban canopy cover are high relative to other forest NBCSs

In the analysis by Drever *et al.* (2021), increased urban canopy cover was not found to be a cost-effective carbon sequestration strategy, with the average marginal abatement cost (MAC) calculated at \$150 (Cook-Patton *et al.*, 2021). Planting and maintaining urban forests can be resource-intensive and require heavy management, including pruning (Ryan *et al.*, 2010; McGovern & Pasher, 2016). Drever *et al.* (2021) did not find any mitigation opportunities with this NBCS costing less than \$100/t CO_2e, once initial costs for saplings and ongoing tree pruning and maintenance were included. This does not account for the value of other co-benefits of urban trees and greenspace, however, such as the mitigation of urban heat-island effects and heatwaves. Thus, this NBCS could still be an important strategy in some urban areas.

Forest NBCS costs include property rights, carbon leakage, and other considerations

Many complicating factors are often excluded from models estimating the costs of changes in forest harvest and management practices. A full assessment of NBCS costs in the forestry sector would look at production or *even-flow* requirements for mills (which require stable flows of timber to remain economically viable), forest carbon property rights, dynamic effects such as changing prices of forest products over time, and the transactional cost for the development, implementation, contracting, and monitoring of NBCSs (Boyland, 2006; Lieffers *et al.*, 2020). In the view of the Panel, it is not clear how the measurement of costs reported in Drever *et al.* (2021) are affected by even-flow requirements; linkages between mills and forests suggest that mill requirements constrain the ability of forest managers to implement NBCSs, thus increasing their costs.

Emissions leakage across regions or countries is another complicating factor that can substantially increase the cost of forest NBCS carbon sequestration. Carbon leakage — the unintentional increase or decrease in GHG emissions, both temporally and spatially — can be considered at the project level as well as regionally, nationally, and globally (Watson *et al*., 2000; Atmadja & Verchot, 2012; Pan *et al*., 2020) (Section 2.3.2). Leakage can occur, for example, when a reduction in harvest levels in one area is offset by an increase in harvest levels in another area to meet demand; this has been found to represent about 40% of offsets, on average, in the forestry sector (Pan *et al*., 2020). Such impacts can also have dynamic effects; a reduction in timber and HWP output can lead to price changes, which then make future reductions more difficult and costly. Forestry sector carbon policies are potentially more vulnerable to leakage than other sectors due to global markets for HWPs (Kallio & Solberg, 2018). Though such risks could be managed through harmonized climate policies and carbon prices, as well as long-term and integrated land-use planning in forestry (Pan *et al*., 2020), these impacts are not fully considered in most existing cost estimates.

3.5.2 Policy and Regulatory Challenges

Policy options and constraints are largely beyond the scope of this report; however, the Panel considered some approaches for addressing policy gaps in forest carbon mitigation. Uncertainties remain over the design of effective policies and programs to implement NBCSs, and the regulations of forest management practices generally do not explicitly account for carbon (Hoberg *et al*., 2016). However, the scale of mitigation that can be reached by implementing policy and regulation changes is vast compared to carbon offsets. For example, the Cheakamus Community Forest Offset Project in British Columbia takes place on 33,000 ha (CCF, 2019). A policy change that affects all forest harvest would be implemented on ~750,000 ha every year across Canada (NRCan, 2020a).

The implementation of forest NBCSs in Canada may be hindered by limitations in current forest management policies and frameworks. Policies (e.g., the Government of Canada's *National Forest Strategy*) and voluntary agreements (e.g., *Canadian Boreal Forest Agreement*) have sometimes been characterized as long-term management regimes that may not meet the dynamic challenges facing boreal forests (Thorpe & Thomas, 2007). Additionally, industry-oriented policies may be challenging to reverse without social and economic discomfort due to the reliance on investments in forest industries and infrastructure (Moen *et al.*, 2014; Skene & Polanyi, 2021). Policy implementation could become more effective in Canada, however, by better integrating forest-based resources into the climate policy framework (e.g., increasing use of wood for construction) (Moen et al., 2014; Himes & Busby, 2020; Ter-Mikaelian *et al.*, 2021). Standard forest management practices in the boreal region could be used to meet global climate targets more effectively through the application of new incentives, improved measurement of forest sector impacts on climate, and the development of reporting requirements that align with other sectors (Moen *et al.*, 2014).

Federal programs, including the Low Carbon Economy Fund, can provide funding to support the implementation of NBCSs at the provincial and territorial level. For example, in British Columbia, federal funding from the Low Carbon Economy Leadership Fund has combined with provincial investment to commit $290 million to managing forest carbon between 2017 and 2022 (Gov. of BC, n.d.).

The forest sector operates primarily on public land in Canada, unlike the United States, and subsequently the development of forest policies can have international implications. A review of the forest management policy in British Columbia found one of the numerous feasibility issues for climate action in forests is the tenure system, which allows the transfer of specific rights for a designated time period so the forestry sector can operate and manage timber on public land (Hoberg *et al.*, 2016). Any policy that proposes payments for altered harvesting, or management practices to sequester carbon, may have international trade implications due to the public nature of forestry in Canada. For example, since the 2006 Softwood Lumber Agreement expired in 2015, the United States and Canada have continued to dispute the import of Canadian lumber products due to claims that Canadian softwood lumber producers were being subsidized (GAC, 2022). These disputes add to the uncertainties in designing programs and policies to aid the implementation of NBCSs. Policies and programs that would effectively provide NBCSs could be challenged under trade agreements and subsequently prove to be unproductive or even impossible to implement.

Monitoring and accounting can help establish the effectiveness of a forest NBCS

Monitoring the forest sector in Canada to meet international reporting requirements relies on the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3); due to the nature of that accounting, an NBCS that focuses on avoided actions to enhance sequestration will not impact national reporting of emissions reductions (Drever *et al.*, 2021). Monitoring and accounting frameworks can coincide with the implementation of NBCSs to encourage adaptation in land management practices (Drever *et al.*, 2021). The inclusion of all belowground carbon sources (e.g., degradation of peatlands) and carbon emissions from forest management could impact the creation of carbon management policy (Carlson *et al.*, 2009). However, there may be associated costs if the NBCS approach leads to increased wildfire risk and associated impacts and/or a reliance on single species for reforestation (Seddon *et al.*, 2020a).

> “Monitoring is needed to establish the effectiveness of any implemented NBCS, while accounting frameworks should be clear and consistent with *National Forest Inventory* protocols and work done across the provinces and territories.”

In the view of the Panel, monitoring is needed to establish the effectiveness of any implemented NBCS, while accounting frameworks should be clear and consistent with *National Forest Inventory* protocols and work done across the provinces and territories (i.e., the data used to implement CBM-CFS3). This would capitalize on the tremendous resources the *National Forest Inventory* has to both assess and later reduce uncertainties in forest NBCSs.

Further, Indigenous Guardians can combine the technical environmental monitoring skills drawn from Traditional Knowledge with western scientific protocols to provide valuable monitoring as the land changes, including impacts from climate change and industrial development activities (SVA, 2016). With sufficient funding, Guardians can enhance the quality of monitoring activities on their traditional lands; water and wildlife monitoring can inform decision-making on how natural resources are used, conserved, and developed. Additionally, monitoring and protecting lands provide cultural benefits, including meeting cultural obligations to care for land and water (SVA, 2016).

3.6 Co-Benefits and Trade-offs

3.6.1 Co-Benefits

Forest restoration reduces fragmentation, preserves biodiversity, and has measurable benefits on air and water quality

Forests contribute to a wide variety of environmental and social benefits, as well as ecosystem services, which NBCSs can amplify. Restoration of forest cover has demonstrated long-term co-benefits, including impacts on biodiversity, air and water quality, flood control, soil erosion, and soil fertility (Griscom *et al.*, 2017). It can connect fragmented forests, which can mitigate carbon lost to fragmentation and reduce the vulnerability of forest edges (Putz *et al.*, 2014). Generally, boreal species are less impacted by fragmentation than temperate forests, possibly due to the frequency of natural disturbances. The biodiversity benefits of NBCSs only hold true to the extent that species benefit from increased undisturbed forest cover; species that thrive on recently disturbed forest may suffer (McCarney *et al.*, 2008) while other specialized species can be sensitive to fragmentation or change in habitat (Gauthier *et al.*, 2015; Harper *et al.*, 2015). The restoration of forest cover can help create corridors and buffer zones for wildlife, allowing species to travel between more established sections of forest (Harrison *et al.*, 2003).

Improved forest management and conservation practices can decrease fire intensity, as well as provide habitat for species dependant on old-growth forests and interior forest species (Price *et al.*, 2020). Fire management practices may include transitioning from complete fire suppression back to Indigenous burning practices, with associated cultural impacts and benefits (Box 3.3). NBCSs that retain 70% of stands have effectively preserved the biodiversity of most forest bird species in northern coniferous forests because they maintain landscape corridors (Price *et al.*, 2020). Improved urban canopy cover benefits biodiversity, as well; natural forest remnants in cities contribute to the conservation of native bird and plant species, while intensively managed components of urban forest — such as street trees — provide further bird habitat (Filazzola *et al.*, 2019; Wood & Esaian, 2020). Some forest NBCSs can also improve air quality, benefiting nearby communities. The reduced burning of harvest residue and slash piles, for example, avoids adverse air quality impacts (Nowak *et al.*, 2014).

Box 3.3 Indigenous Fire Management

Indigenous Peoples have a long history of using fire as a land management practice in a variety of contexts. Prescribed burning can preserve carbon stored in larger trees by burning brush and removing potential fuel for larger-scale, uncontrolled fires (Wiedinmyer & Hurteau, 2010). This practice can significantly contribute to sustainable forest management and carbon sequestration, depending on the ecosystem and fire-return interval (PICS, 2020b). That said, Indigenous knowledge-holders have often been denied the opportunity to develop research questions or control subsequent decision-making related to forest management (Miller *et al.*, 2010; Christianson, 2015).

Several examples of Indigenous-led fire management programs exist across the country. In 2006, the Pikangikum First Nation in northwestern Ontario signed the Whitefeather Forest Land-Use Strategy with the Ontario Ministry of Natural Resources, undertaking a community-based land-use planning process for the 1.3 Mha of Whitefeather Forest (Miller *et al.*, 2010). One component of this approach was creating a climate in which Elders felt comfortable sharing their expertise and perspectives on historic controlled burning traditions, including fire suppression, prescribed burning, and the role of fire as both a source of renewal for the land while also being a potential detriment to lives, property, and land values (Miller *et al.*, 2010).

Following the Elephant Hill forest fire in 2017 — which burned almost 192,000 ha — eight Secwépemc bands formed the Elephant Hill Wildfire Recovery Joint Leadership Council in British Columbia, with the aim of executing a three-year plan to restore damaged Secwépemc territory (Wood, 2021). This Indigenous-led restoration project focuses on protecting the diversity of forests as living infrastructure and bringing cultural burning practices back to the land. The Joint Leadership Council aims to create a model of forest restoration that other First Nations can replicate in the wake of fires in their own territories (Wood, 2021).

Indigenous nations are actively involved in fire management and emergency response services. The development of decision tools, including geo-referenced mapping products, currently support the First Nations' Emergency Services Society, including emergency management and wildfire training initiatives (FNESS, 2022).

Many forest NBCSs yield climate adaptation benefits as the climate warms

Forest health and its associated ecosystem services are threatened by the speed and magnitude of climate change in many regions (Gauthier *et al.*, 2015) (Section 3.3.2). However, modifying forest structures and compositions through forest management and regeneration practices can temper their sensitivity to changes in temperature and precipitation as well as other disturbances (Seidl *et al.*, 2017). Helping forests adapt by increasing their heterogeneity and species diversity may bolster resilience while aiding long-term conservation of carbon (Pukkala *et al.*, 2014; Gauthier *et al.*, 2015).

Benefits to biodiversity and forest resilience could become increasingly valued given the stresses created by climate change. Evidence from the boreal forest suggests the range of some charismatic species, such as woodland caribou and grizzly bears, will decrease in the long term (Venier *et al.*, 2014). Canada may face an extinction debt whereby cumulative effects from management practices and climate change contribute to species losses. Impacts of forest change on biodiversity are predominantly studied at stand and landscape scales, so a greater understanding of regional and ecosystem-wide change is needed to assess overall impacts across the boreal forest (Venier *et al.*, 2014) and reduce climate change liabilities associated with Canada's boreal forest.

3.6.2 Trade-Offs and Other Impacts

Increasing harvest productivity can be detrimental to carbon stocks in the short term

Not all forest NBCSs benefit biodiversity. A focus on maximizing wood production has meant that forest management practices historically reduced forest biodiversity and resilience in many contexts (Venier *et al.*, 2014). Many of them have decreased species diversity in boreal forests, and shifts to more intensive harvesting regimes (e.g., to increase carbon stored in HWP pools or support the increased use of bioenergy), or to planting practices that reduce species diversity relative to native forests, are likely to amplify these impacts (Venier *et al.*, 2014). Forest management practices beneficial to forest health (i.e., increased productivity) can also be detrimental to carbon stocks in the near term. Thinning of forests, for example, can reduce the risk of fire and insect outbreaks, and increase the growth of the remaining individual trees, but generally decreases carbon stocks compared to un-thinned stands (Ryan *et al.*, 2010). However, some modelling suggests thinning could maintain or enhance carbon stocks and sequestration over multiple decades (Collalti *et al.*, 2018).

Timescales for NBCSs should be taken into consideration, including the use of harvest residue for bioenergy. The evidence to support investment in HWPs or biofuels, however, is inconclusive. The classification and accelerated use of forest biofuels to reach renewable energy targets in the European Union has generated criticism that the practice could result in two or three times the amount of carbon to the atmosphere by 2050 per gigajoule of final energy (Searchinger *et al.*, 2018). Biofuel used in Europe is often harvested as wood pellets from North American forests; increasing these exports may in turn increase net global GHG emissions and diminish carbon sequestration (Birdsey *et al.*, 2018a). For near-term reductions in emissions (i.e., 2030–2050), investment in biofuel (except for harvest residue) is not feasible, as the substitution of biomass for fossil fuels will initially increase emissions. Increased use of longer-lived HWPs may achieve greater benefits than bioenergy when substituted for current products (Birdsey *et al.*, 2018a). Reducing harvest levels in Canada can enhance CO_2 removal by forests, but this reduction will decrease the availability of HWPs, subsequently impacting the benefits from other NBCSs, such as replacing more emissions-intensive materials (e.g., cement, steel) with HWPs (Smyth *et al.*, 2020).

“Improved forest management may increase employment opportunities and socioeconomic benefits for forest-dependent communities if long-term, regionally differentiated strategies are implemented.”

Forest NBCS implementation may have socioeconomic impacts

Local and regional socioeconomic impacts from NBCSs could include direct effects on employment in the forestry and logging industries, wood product manufacturing, transportation, and bioenergy generation, as well as on labour intensity in those industries, depending on the solutions deployed (Xu *et al.*, 2018b). Reduced forest harvesting has a potentially high socioeconomic cost due to local communities’ reliance on the forestry industry; there may be public opposition, though carbon credits could be offered to landowners for avoided conversion and reforestation activities (Galik *et al.*, 2012; Smyth *et al.*, 2020). However, improved forest management may increase employment opportunities and socioeconomic benefits for forest-dependent communities if long-term, regionally differentiated strategies are implemented (Elgie *et al.*, 2011; Xu *et al.*, 2018b). Some studies suggest that forest carbon credits may provide an economic incentive to reduce harvests and extend rotation lengths, even at relatively low carbon value — a result mainly due to the inclusion of a time value of carbon (Elgie *et al.*, 2011).

3.7 Conclusion

The successful implementation of NBCSs in Canada's forested areas will depend on the timescale of the proposed emissions reduction or enhanced sequestration of carbon. The interactive effects between short-term interventions (e.g., improved forest management practices) and long-term actions (e.g., restoration of forest cover) should be considered. Additionally, the impacts of climate change, such as fire intensity and frequency as well as warming temperatures and shifting precipitation regimes, will affect forests' ability to regenerate after disturbances and adapt to NBCSs. Uncertainties in the scope of soil carbon pools and the magnitude of forest carbon fluxes in managed and unmanaged forests, as well as forests' responses to climate change and changes in albedo, indicate a need for additional regionally focused research to assess the feasibility of implementing NBCSs in forested areas of Canada. Regional representation is required in measurements of forest carbon stocks, fluxes, and their controls across Canada in order to reduce these uncertainties. There is also a need for dependable, forward looking models to better estimate NBCS costs, including transaction and monitoring, as well as market effects of leakage. Indigenous expertise, design, and oversight of NBCSs on their lands is a critical element in addressing the feasibility challenges of implementing forest NBCSs, particularly within the large unmanaged forest regions of Canada.

4

Agriculture and Grasslands

Chapter Findings

- Cropland management and avoided grassland conversion hold the greatest potential for carbon sequestration in agriculture and grasslands. Uncertainties in estimating mitigation potential primarily stem from feasibility considerations, where uptake of NBCSs is affected by costs, policies, and behavioural barriers that can drastically change the area of opportunity for their implementation.
- Realizing the sequestration and emissions reduction potential of agriculture and grasslands requires an ongoing management effort together with long-term planning and policy incentives to prevent regression.
- Nutrient management is important not only for providing farm-level emissions reduction, but also for reducing eutrophication and related GHG emissions in adjacent and downstream aquatic systems.
- Engaging with Indigenous communities and recognizing Indigenous knowledge and management practices are essential for the long-term success of certain NBCSs, including the reintroduction of buffalo to grasslands as a component of grassland restoration and conservation. These NBCSs also foster reconciliation through the promotion of Indigenous self-determination.

Agricultural lands and grasslands contain large stocks of carbon in their soils, and exchange significant amounts of carbon with the atmosphere. There are approximately 47 Mha of cropland in Canada, while managed grasslands, used for pasture or rangeland, occupy approximately 6.2 Mha. The exact extent of natural grasslands in Canada is currently unknown (ECCC, 2022b). In Canadian grasslands, herbaceous species are the dominant form of vegetation. These are found mainly in the prairie regions of southern Alberta and Saskatchewan, as well as in the dry, interior mountain valleys of British Columbia. Grassland systems absorb and release carbon in response to environmental conditions and land management practices, offering a range of opportunities for enhancing carbon sequestration or reducing GHG emissions.

4.1 Opportunities for Enhancing Sequestration and Reducing Emissions in Agricultural and Grassland Systems

Agricultural and grassland NBCSs involve the sequestration of additional carbon or a reduction in GHG emissions: CO_2, CH_4, and N_2O. Most carbon is stored in soil organic matter (SOM), although above- and belowground vegetative biomass also contributes to carbon stocks in the case of agroforestry NBCSs. Carbon in soils is assessed through soil organic carbon (SOC) levels and is released to the atmosphere as either CO_2 or CH_4 (Hristov *et al.*, 2018; Paustian *et al.*, 2019). Carbon is added to soils via manure, crop residues, and root exudates (fluids emitted through the roots of plants) and is removed through erosion (which can also redistribute carbon) as well as microbial decay.

NBCS practices to sequester additional carbon in soils either increase the rate of carbon input or reduce the turnover rates of carbon already present in the soil (Paustian *et al.*, 2019). Beyond carbon sequestration, limiting emissions of other GHGs (N_2O in particular) is also an objective. N_2O has 298 times the global warming potential of CO_2 and is a significant component of agricultural systems, released as a by-product of nitrogen input to soil (IPCC, 2012; Équiterre & Greenbelt Foundation, 2020). In 2020, agricultural soils in Canada were estimated to emit an average of 21 Mt CO_2e of N_2O compared to an estimated net cropland carbon sink of 9.6 Mt CO_2e (ECCC, 2022b).[18] GHG emissions from grasslands also occur but are minor in comparison, accounting for less than 0.05 Mt CO_2e in 2020 (ECCC, 2022b).[19] These emissions are due, in large part, to the occurrence of naturally caused, prescribed, or human-induced fires (ECCC, 2022b).

Tables 4.1 and 4.2 identify agricultural and grassland NBCSs that could be implemented in Canada. Many of these NBCSs (sometimes referred to as agricultural *beneficial management practices*) have been well researched, leading to a number of key recommendations for wide implementation in Canada (Groupe AGÉCO *et al.*, 2020; Équiterre & Greenbelt Foundation, 2020; Drever *et al.*, 2021; Meadowcroft, 2021).

18 To convert non-CO_2 gases into CO_2e, ECCC (2022b) used GWP100 values from IPCC (2012) where CH_4=25 and N_2O=298.

19 Ibid.

Table 4.1 Agricultural NBCSs

Definition of NBCS	Mechanism
Crop Management	
Cover crops are planted in the fallow season or between rows of primary crops to function as protective cover, to maintain living roots, and to increase the carbon input to soils.	Additional biomass input to the soil increases the rate of carbon sequestration, while covering the soil reduces erosion (Équiterre & Greenbelt Foundation, 2020). Cover crops implemented in the shoulder season or over winter maintain living roots in the soil for longer, further increasing carbon. If crops are leguminous, they reduce the need for fertilizer application, thereby reducing N_2O emissions (Yanni *et al.*, 2018; Drever *et al.*, 2021).
Crop diversification includes the use of crop rotations (some of them cover crops), intercropping, and perennial cropping systems (perennialization) to move away from monocultures. Crop rotation involves varying the types of crops grown in the same field over successive growing seasons (or during the shoulder or winter season in the case of cover crops), while intercropping involves growing more than one cash crop simultaneously. Perennial cropping strategies include the replacement of annual crops with perennial ones (e.g., fruits, nuts, hay, perennial cereals).	Diversifying annual crop rotations to include perennial crops and legumes increases the carbon input (perennials) or reduces the need for nitrogen fertilizer (legumes) (McDaniel *et al.*, 2014). Perennial crops have extensive root systems, which increase SOM, add soil cover to reduce erosion, and remove the need for tillage, preserving soil carbon (AAFC, 2008). Perennial crops lower GHG emissions by reducing the need for tillage (thereby also reducing emissions from machinery), decreasing fertilizer application rates, and allowing for more efficiency in nutrient cycling (Yanni *et al.*, 2018). Increasing the percentage of legume crops will reduce the total need for external nitrogen fertilization, thereby avoiding N_2O and CO_2 emissions.
Soil Management	
No-till or **reduced tillage** practices involve completely halting or reducing soil turnover through tilling.	No-till avoids soil disturbance and leaves crop residue on the surface, reducing decomposition by soil microorganisms and thereby increasing carbon sequestration (Équiterre & Greenbelt Foundation, 2020; Drever *et al.*, 2021).
Biochar is produced by converting crop residue or other organic inputs (e.g., bone) to recalcitrant carbon (i.e., charcoal), which is added to soils.	Recalcitrant carbon in biochar is resistant to decomposition and therefore stable over long timescales (Lehmann, 2007; Song *et al.*, 2016); amending agricultural soils with biochar therefore increases the storage of CO_2 (Drever *et al.*, 2021).

Definition of NBCS	Mechanism
Nitrogen Management	
Promising practices for reducing the amount of nitrogen are known as the **4Rs**: limit the rate **(Right Rate)** of nitrogen application to more closely match crop requirements, adjust the timing **(Right Time)** of application relating to when a crop is actively growing and taking up nitrogen, vary the placement of fertilizer **(Right Place)** at depth (injection), and/or choose alternative fertilizer types **(Right Source)** that delay release or use inhibitors that prevent quick transformation (De Laporte *et al.*, 2021a).	Application of 4R practices can reduce the amount of nitrogen available in the soil for loss through (de)nitrification or leaching and volatilization, immediately reducing GHG emissions. Certain practices, such as right source, allow plants to access nitrogen more easily (De Laporte *et al.*, 2021a).
Agroforestry	
Alley cropping (also known as tree intercropping) sequesters additional CO_2 through the planting of trees between row crops and hay lands.	Carbon is stored in above- and belowground biomass, including through increased litter and root exudates (Baah-Acheamfour *et al.*, 2017). Variability in carbon storage estimates depends on the type of tree selected for planting, the density of tree planting, and the variety of cash crop (in the case of alley cropping) (Baah-Acheamfour *et al.*, 2015; Drever *et al.*, 2021).
Shelterbelts are rows of annual or perennial trees and shrubs that have traditionally served as windbreaks, but more recently have been observed to sequester carbon in soils and in both above- and belowground biomass.	
Riparian tree planting increases CO_2e sequestration when trees are planted in 30 m "buffers around all water bodies in agricultural zones where forests are the natural land cover" (Drever *et al.*, 2021).	
Silvopasture involves the integration of trees with pasturelands, simultaneously managed for livestock grazing, forage, and tree crops (Drever *et al.*, 2021).[20]	

20 For the purposes of this report, the Panel chose to focus on the expansion of silvopasture through the planting of trees in existing pastures. Silvopasture can also involve the grazing of understory in existing treed areas (e.g., Baah-Acheamfour *et al.*, 2014), but expansion of silvopasture in these areas was not modelled by Drever *et al.* (2021) and therefore not included in mitigation potential calculations.

Table 4.2 Grassland NBCSs

Definition of NBCS	Mechanism
Maintaining and Restoring Grasslands	
Avoided grassland conversion preserves SOC and above- and belowground biomass.	By reducing the area of grasslands converted into cropland each year, the emissions associated with clearing and tilling the land can be reduced, current soil carbon stocks are maintained, and emissions due to carbon oxidization are avoided.
Grasslands are restored on marginal and less productive agricultural lands.	Carbon storage has been observed to increase over time due to accumulation of root mass, and grasslands with higher root masses tend to accumulate SOC at greater rates (e.g., Jones & Donnelly, 2004; Soussana *et al.*, 2004; Lorenz, 2018; Yang *et al.*, 2019). Soil carbon is also increased by the deposition of material shed by plant roots (Soussana *et al.*, 2004; Lorenz, 2018).
Improved Grassland Management	
Improved grazing includes rotational grazing (described in recent literature as adaptive multipaddock grazing or AMP) and the introduction of bison to grassland systems. AMP employs longer rest periods between grazing and halting grazing during plant recovery, maximizing the active growth time of plants (Prescott *et al.*, 2021).	Improving grazing management (of any grazing animal) may affect carbon cycling in numerous ways, including through plant community alteration (Lyseng *et al.*, 2018), enzyme activity in plant litter (Chuan *et al.*, 2020), improved water infiltration (Döbert *et al.*, 2021), and production of excess carbon through root exudates (Prescott *et al.*, 2021). Introducing bison to grassland systems has the potential to alter carbon uptake by native plant species (Knapp *et al.*, 1999; McMillan *et al.*, 2019).
Producers can **introduce legumes** to pasturelands by including them in species mixes during sowing.	Legumes increase forage production in grasslands, leading to additional belowground carbon inputs and increased soil nitrogen, resulting in greater SOM produced by microbes and higher soil fertility, reducing the need for fertilizer (thereby reducing N_2O emissions) (Conant *et al.*, 2001; Bolinder *et al.*, 2007; Fornara *et al.*, 2016; Drever *et al.*, 2021; Prescott *et al.*, 2021).
Pastures can be sown with seed mixes targeted at **improved grass species selection** to enhance carbon inputs to the soil.	Improved grass species increase SOC by enhancing production via better adaptation to the local climate, increased resiliency to grazing and drought, and increased soil fertility as a result of high biomass production rates and deep rooting systems (Jones & Donnelly, 2004; Conant, 2012).

4.2 Indigenous Agricultural and Grassland Management

Indigenous Peoples have been stewards of grasslands and lands currently being used for agriculture since time immemorial. The diversity of plant and animal communities and their distribution across North America have been impacted by long-term Indigenous management (Turner, 2020). Furthermore, Indigenous Peoples have historically developed and engaged in agricultural practices, including forest gardens in the Pacific Northwest (Armstrong *et al.*, 2021; Fox, 2021) and widespread use of polyculture through the Three Sisters (corn, beans, and squash), the latter of which is still researched and practised today (AAFC, 2021). These traditions are precursors to some of the NBCSs discussed in this chapter. Three Sisters polyculture, for example, is a form of crop diversification and rotation. The inclusion of legumes provides nitrogen to the soil, while corn and squash provide structural support, weed control, and protection from erosion (Mt. Pleasant, 2016; Hill, 2020; Ngapo *et al.*, 2021).

As of 2016, Indigenous farm operators made up 2.6% of the national agricultural population, but the ratio of farmers to leasers is unknown (Gauthier & White, 2019). Data have previously demonstrated that the majority of land owned by First Nations in the Prairies is leased to non-Indigenous farmers (Pratt, 2004); this number may be an underestimate due to the shrinking overall number of family farms across the country (Arcand *et al.*, 2020; Sommerville, 2021).

Reintroduction of buffalo to the plains is an opportunity to foster reconciliation and restore prairie ecosystems

"Management of carbon stocks and fluxes is encompassed within, and not easily separated from, the overall Indigenous perspectives that holistically link human and ecological health" (McCarthy *et al.*, 2018). *Wahkohtowin*, the Cree word for the concept of kinship, describes this relationship; it is a worldview based on the idea that all of existence (including humans, plants, and animals) has spirit and is interconnected (Wildcat, 2018) (Section 2.4). "Elders would say we were in constant consultation with the spiritual realm that resides within the plants, soil, animals, water, and through living that way for millennia our people had opened up that spiritual access code which guided our governance and the way we conducted ourselves" (Philip Brass, personal communication).

Wahkohtowin encompasses both the natural laws of ecosystems and how Indigenous Peoples understood the consciousness of the ecosystems they inhabited and were part of. For the peoples of the plains, their relationship with buffalo exemplifies this consciousness:

> *We became buffalo chasers on the prairie and took direction from the buffalo spirit. Following the buffalo led us to clean water, medicines, acting as a tour guide to the prairie world. Life, and our survival and ability to thrive here, relied on the buffalo, and we moved them around to graze prairie grass over thousands of years, developing a massive carbon sink in the great plains.*
>
> Philip Brass (personal communication)

Widespread slaughter of buffalo in the nineteenth century and the expansion of agriculture led to deterioration of the prairie ecosystem, and with it the relocation of First Nations to reserves on marginal lands — mere fragments of their traditional territories (Corntassel & Woons, 2019). Efforts to reintroduce buffalo to the Prairies are ongoing and represent a critical opportunity for reconciliation and restoration of the prairie ecosystem, including Indigenous plains Peoples' relationship to the buffalo (Section 4.6.2).

Perennial plant cover is connected to First Nations land across the provinces

The conversion of grassland to cropland has been found to release large quantities of carbon to the atmosphere, significantly reducing natural carbon stocks (Janzen *et al*., 1998). Notably, however, many of the remaining pockets of conserved grasslands and aspen groves are connected to First Nations reserve land across the Prairies. Figure 4.1 highlights the fragmented nature of perennial plant cover across the region and the correlation of those areas to land managed by First Nations across the prairie provinces.

Data Source: GC (2021h, 2022a)

Figure 4.1 Relationship of Perennial Land and First Nations Reserves in Saskatchewan

This figure depicts land cover distribution in the northwest (left panel) and southeast (right panel) of the Grassland and Aspen Parkland regions of Saskatchewan. The two panels cover most home reserve lands of First Nations within the grain-growing region of Saskatchewan. Land-cover data were sourced from GC (2021h) and boundaries of First Nations lands were sourced from GC (2022a).

Although little evidence currently exists on why First Nations reserve land is so closely associated with perennial plant cover, the Panel believes that the ongoing success of prairie-parkland conservation on First Nations land may be potentially attributed to sociopolitical elements. The complex land-use history of these areas may be a key contributing factor to their preservation of perennial vegetation cover. The Numbered Treaties that span the contemporary agricultural regions of Alberta and Saskatchewan featured agricultural provisions and included reserve land that could be used to establish farming (e.g., Treaty No. 4 from 1874, Treaty No. 6 from 1876). Initially, many First Nations took up farming and broke reserve land for agriculture. However, historic barriers to First Nation participation in the agricultural sector (e.g., Buckley, 1992; Carter, 2019), combined with the high proportion of marginal land on reserves, likely contributed to conservation and the reversion of some cropland to perennial cover. Indigenous farmers continue to face institutional and structural barriers that hinder the implementation and growth of agricultural endeavours on First Nations-owned land and that may also contribute to the preservation of these grasslands (Pratt, 2006; Natcher *et al.*, 2011; Arcand *et al.*, 2020); farmers are less able to sustain long-term agricultural production on their own and would thus be incentivized to leave the land as it is. The Panel recognizes, however, that natural grassland ecosystems are integral to many plains First Nations communities, and their conservation may be linked to the protection and perpetuation of culture (e.g., LeBourdais, 2016).

"Recognizing the conservation linked to these communities is crucial in understanding not only how these practices can be implemented on a larger scale, but how many NBCSs are inherently Indigenous — tied to Indigenous knowledge and traditional practices that have been carried out by communities for generations."

However, no element is likely to be the sole explanatory factor underpinning the correlative relationship between First Nations land management and perennial plant cover on conserved grasslands. The Panel believes it is more likely the result of a combination of factors — including but not limited to those outlined above — that change and evolve within the cultures and contexts of each Nation and community. Nevertheless, this observed relationship makes clear that there is an ongoing need for recognition and support of First Nations in the implementation of NBCSs. Recognizing the conservation linked to these communities is crucial in understanding not only how these practices can be implemented on a larger scale, but how many NBCSs are inherently Indigenous — tied to Indigenous knowledge and traditional practices that have been carried out by communities for generations (Townsend *et al.*, 2020).

The Panel also notes that there is a need to actively support the conservation efforts of First Nations communities, in order to ensure that adverse economic development is not prioritized. These perennial landscapes represent carbon stocks that are at risk of becoming sources if lands are (re)converted into cropland. Push for further economic development, including increasing government supports for First Nations farmers, can potentially incentivize conversion of native grasslands, thereby releasing carbon to the atmosphere. On the Prairies, land-use change significantly impacts carbon sequestration and emissions reductions, and the potential to "lose carbon for cash" cannot be overlooked. However, any First Nations engagement must comply with the self-determination rights of these communities in land-based decision-making, ensuring that NBCSs do not end up dispossessing First Nations of their lands or knowledge.

4.3 Magnitude of Sequestration and Emissions Reduction Potential

Assessing how much additional carbon can be sequestered through agricultural or grassland NBCSs, or the amount of GHG emissions that can be avoided, requires understanding the impacts of changes in management practices or land use on carbon and other GHG fluxes in a given area. Such impacts have been widely studied in the context of improving agricultural productivity and sustainability, though there is substantial variation depending on environmental conditions and soil characteristics, and thus regional variation across Canada.

4.3.1 GHG Fluxes in Croplands

Variability in regional conditions and crop characteristics determines the potential of some agricultural NBCSs

Determining the national mitigation potential for most NBCSs is difficult due to the considerable variability inherent to agricultural landscapes. Myriad combinations of crop and soil types, climatic conditions, and management practices result in large uncertainties in estimating SOC accumulation and GHG emissions (Hristov *et al.*, 2018; Bradford *et al.*, 2019). Even NBCSs promoted as best management practices, such as cover crops, are subject to uncertainties and limitations relating to their suitability for certain climates. Though global and U.S. estimates of carbon sequestration for cover crop implementation are around 0.3 t C/ha/yr, values for Canada (adjusted for climate and timing of harvest for preceding cash crop) range from 0.025–0.64 t CO_2e/ha/yr, with the lowest in the west and highest in the east (Eagle *et al.*, 2012; Poeplau & Don, 2015; Drever *et al.*, 2021). For example, short growing seasons and water limitations have historically prevented widespread implementation of cover crops in the Prairies, though this trend is slowly starting to change, encouraged by uptake in neighbouring American states and eastern Canada (Morrison & Lawley, 2021).

Similarly, reduced or no-till practices (also known as conservation tillage) have been widely practised in Canada (especially in the Prairies), resulting in measurable increases in carbon inputs to soils (ECCC, 2022b). Land under conservation tillage increased by 18 Mha between 1990 and 2020 (ECCC, 2022b). Despite success elsewhere, there are still significant uncertainties related to the effects of reduced or no-till practices in eastern Canada, where impacts were inconsistent and highly dependent on climate and soil texture (Liang *et al.*, 2020). A synthesis of long-term experiments found that no-till led to an increase of 0.14 t C/ha/yr in western Canada over an average of 23 years, whereas an increase of only 0.06 t C/ha/yr was recorded in eastern Canada over an average of 18 years (VandenBygaart *et al.*, 2008).

Soil carbon and nitrogen mechanisms are linked, and can affect each other and soil biota

The carbon and nitrogen cycles within soils are intricately connected through in a series of complex interactions (Guenet *et al.*, 2021). Therefore, any actions to increase SOC in agricultural systems may also affect the nitrogen cycle and subsequent N_2O emissions. These interactions and effects are numerous: transformations of mineral nitrogen depend on SOC, plant dry matter production is limited by nitrogen availability, and turnover of SOM is determined by nitrogen availability to microorganisms (Guenet *et al.*, 2021). Microbes, which have been found to contribute substantially to SOC, depend on the availability of nitrogen to spur increased microbial biomass and thereby create SOM (Kogel-Knabner, 2017; Liang *et al.*, 2019; Kopittke *et al.*, 2020). The chemical balance of carbon and nitrogen in soils is therefore a critical consideration for the implementation of NBCSs, as high SOC contents have been shown to correlate to higher N_2O emissions (Stehfest & Bouwman, 2006; Henault *et al.*, 2012). This is particularly relevant to nutrient management, where the application rate of nitrogen to soils needs to take this relationship into account.

Crop type can also influence GHG fluxes

The interactions between carbon and nitrogen in soils also depend on the characteristics of the crops themselves. For example, the use of pulses in crop rotations has been touted as a method for reducing N_2O emissions due to their ability to fix nitrogen from the atmosphere, thereby reducing fertilizer requirements. Tests of four pulse types found that only two (pea and faba bean) reduced N_2O emissions when compared to continuous wheat crops, while others (chickpea and lentil) actually increased N_2O emissions (Liu *et al.*, 2021). Choice of cover crop type can also impact N_2O emissions; the magnitude of which relies on several factors, such as carbon to nitrogen ratios, decomposition rates, tillage practices, and additional fertilizer inputs (Guenet *et al.*, 2021). A low carbon to nitrogen ratio in the cover crop variety (like in legumes) increases the availability of nitrogen in the soil to microbial reactions, leading to a surplus of soil nitrogen if all leguminous biomass is incorporated (and any additional nitrogen input is not correctly adjusted). Nonetheless, a meta-analysis by Guenet *et al.* (2021) found that, while, on average, N_2O emissions from cover crops do not completely offset the gains made to SOC, the overall effects may be highly site-specific and are an important consideration when implementing NBCSs that increase SOC.

Uncertainties also stem from technical complexities and limited data

Some interventions, such as crop diversification, are difficult to study due to the number of variables in play during experiments. Perennial species may be introduced as a component of crop rotations; this complicates drawing conclusions on the ability of either one of these strategies to sequester additional carbon, and to attribute changes in flux to individual NBCSs. A review by Yanni *et al.* (2018) concluded that few studies have investigated the effects of crop rotations and crop diversification on carbon sequestration and GHG emissions in Ontario, though — in the Panel's view — this gap extends to other regions in Canada, as well. Experiments that do exist have found that rotating cash crops (e.g., corn) with other crops (e.g., alfalfa, oats) reduced emissions of N_2O, even when scaled to yield (Drury *et al.*, 2014).

Although agroforestry systems are widely employed across Canada, the precise extents of the different types of systems are uncertain. This lack of information contributes to uncertainty around the area of opportunity (i.e., the area over which a practice can feasibly be implemented) for increasing the uptake of these NBCSs (Baah-Acheamfour *et al.*, 2017). Furthermore, there are few studies reporting on the carbon storage capacities of these systems (An *et al.*, 2022); although agroforestry NBCSs have been repeatedly shown to have higher soil carbon content than adjacent croplands (e.g., Baah-Acheamfour *et al.*, 2014; Lim *et al.*, 2018), tree type and the NBCS itself will affect the carbon storage capacity (Baah-Acheamfour *et al.*, 2015). For example, Baah-Acheamfour *et al.* (2015) found that the use of *Populus* tree species resulted in the greatest increase in SOC when used in silvopasture, whereas *Picea* species were best used in shelterbelts. This variability contributes to uncertainties associated with the magnitude of sequestration potential for agroforestry NBCSs in Canada, along with the regional distribution.

4.3.2 GHG Fluxes in Grasslands

The carbon sequestration potential of improved grassland management is uncertain, as are the underlying mechanisms relating to improved grazing

As with agricultural systems, carbon fluxes in grasslands are influenced by land management strategies as well as environmental factors, such as mean temperature and precipitation (Ma *et al.*, 2021). Improved management is the most widely acknowledged soil carbon intervention for grasslands; however, its net effects on carbon sequestration are debated (Liu *et al.*, 2011; Lorenz, 2018; Bengtsson *et al.*, 2019; Iravani *et al.*, 2019; Ma *et al.*, 2021; Wang *et al.*, 2021a). Rotational grazing — identified by the Government of Canada as an agricultural climate solution (GC, 2022b) — has been associated with increased productivity and soil carbon sequestration (Lorenz, 2018), as has moderate grazing in general (Wang *et al.*, 2014; Hewins *et al.*, 2018; Bork *et al.*, 2020). However, recent research investigating all GHG fluxes from Ma *et al.* (2021) found no positive relationship between rotational grazing and reduced overall GHG emissions. Instead, carbon fluxes were found to be influenced by specific conditions, such as “cattle stocking rate, cultivation history, soil moisture content, and bulk density” (Ma *et al.*, 2021). This is supported by similar findings in Iravani *et al.* (2019) and Wang *et al.* (2021a).

Conflicting results may stem from the wide range of choices made by livestock producers when implementing grazing. This includes stocking rates and densities, as well as the pattern of grazing (e.g., timing, intensity, length of recovery period) (Teague *et al.*, 2013; Bork *et al.*, 2021). Furthermore, pastures are also generally grazed unevenly, with patterns dictated by proximity to sought-after resources such as water or minerals (e.g., salts), potentially affecting measurements (Wang et al., 2021a). Ecological limits, such as growing season and climate change, impact the efficacy of grazing NBCSs (e.g., increased or decreased grazing intensity) (Eldridge *et al.*, 2016; Ma *et al.*, 2021). As Wang *et al.* (2021a) highlight, “the plant recovery time [necessary for reducing carbon emissions] under rotational grazing depends on environmental conditions, such as the season of the year.”

The precise mechanism linking improved grazing practices to increased carbon sequestration (such as rotational or AMP grazing) is yet unknown. Grazing has been shown to convey positive effects on soil carbon through stimulation of plant productivity, especially in roots (Frank *et al.*, 2002). More recent research has shown that grazing alters the composition of plant communities (Lyseng *et al.*, 2018), the activity of enzymes released from roots and microbial cells (Chuan *et al.*, 2020), and increased water infiltration (Döbert *et al.*, 2021). Specifically allowing for adequate recovery time between grazing (a key tenet of rotational and AMP grazing) provides an avenue for increased productivity; longer rest periods between grazes paired with prohibited grazing during recovery time maximizes the time spent in active growth (Prescott *et al*., 2019). The increased soil carbon resulting from this has been hypothesized to result from exudation and excess carbon production during rest periods, but Prescott *et al*. (2019) noted more research is needed to understand this process fully. All of these mechanisms, along with external factors such as moisture availability and temperature, may affect the carbon sequestration capacity of grazed grasslands.

The introduction of bison instead of domestic cattle could also potentially yield carbon sequestration benefits, but this is also subject to significant uncertainty. Although there are notable differences in foraging patterns between cattle and bison, there is a lack of comparative data assessing the long-term effects of grazing while management practices are held constant (Knapp *et al*., 1999).

4.3.3 Estimating National Sequestration and Emissions Reduction Potential

At the global level, Roe *et al*. (2021) produced estimates of the magnitude of sequestration potential in Canada of several agricultural and grassland NBCSs, including technical and cost-effective (available below \$100/t CO_2e) potentials (Table 4.3). However, values are based on global datasets and were derived using assumptions that are unlikely to apply to the Canadian context; some estimates are quite high (e.g., no-till practices, biochar application) or quite low (e.g., nutrient management).

Table 4.3 Annual Sequestration Potential in Canada, 2020–2050

NBCS	Magnitude of Sequestration Potential (Mt CO_2e/yr) to 2050	
	Technical	Cost-Effective
Nutrient management	1.9	1.5
Cover crops + no-till[a]	27.6	24.9
Improved grassland management[b]	12.7	7.6
Agroforestry	44.8	9
Biochar	35.1	27.6

All values were extracted from supplementary information provided by Roe *et al*. (2021).

a No-till labelled as *soil carbon sequestration – croplands* in original document.

b Improved grassland management labelled as *soil carbon sequestration – grasslands* in original document.

In the study by Roe *et al.* (2021), the technical sequestration potential of agroforestry practices involved planting trees alongside crops in the total land area used for cropland. This, however, is an unlikely scenario for parts of Canada due to required use of large machinery and the related difficulties navigating around trees. Furthermore, tree growth is inhibited in most areas of the Prairies. That said, the cost-effective potential reduced cropland area to 20% of the total, and the potential uptake to only 10%, which may be more reasonable for the Canadian context (compare to Table 4.4). Estimates for the magnitude of potential for no-till and cover cropping are also likely overestimates; no-till is already extensively practised in Canada, and further expansion is limited by climate and technical constraints. Implementation of cover cropping is hindered by climatic constraints, and the assumption of 90% uptake in all cropland areas by 2050 is unlikely. These disparities demonstrate that a key determinant of total magnitude of sequestration potential is the area of opportunity, which in turn is influenced by both technical and socioeconomic factors (Section 4.5).

In the view of the Panel, more realistic estimates — ones that take greater environmental and regional detail into account, as well as additional constraints on NBCS implementation — can be found in Drever *et al.* (2021) (Table 4.4). These values were derived from calculating the relevant area of opportunity in Canada, as well as GHG fluxes in various cropland and grassland systems. The estimates are generally much lower than those presented by Roe *et al.* (2021). Mitigation potential was calculated based on various assumptions while accounting for several areas of uncertainty for each NBCS: productivity (scaling to ensure no reduction in crop yields), uptake (linear, and with errors reflecting over- and underestimation), regionality (reflecting climate and soil characteristics), additionality (building from a business as usual scenario), albedo trade-offs (applied to agroforestry NBCSs), logistics (technical constraints), and related emissions (upstream and concurrent effects on emissions).

Table 4.4 Agriculture and Grassland NBCS Sequestration Potential, as Estimated by Drever *et al.* (2021), and Panel Confidence

Magnitude of Sequestration Potential (Mt CO_2e/yr)			Panel Confidence to 2030	
NBCS	**Now to 2030**	**2030 to 2050**	**Flux**	**Area of opportunity**
Cover crops	9.78 (7.6 to 12.1)	9.78 (7.6 to 12.1)	Moderate	Low–Moderate
Crop diversification[a]	2.6 (2.4 to 2.8)	2.6 (2.4 to 2.8)	Moderate	Moderate
Crop management practices TOTAL	**12.38**	**12.38**	**Moderate**	**Moderate**
Reduced/no-till	0.9 (0.7 to 1.1)	0.6 (0.5 to 0.8)	High	High
Biochar application	6.9 (3.2 to 10.6)	6.9 (3.2 to 10.6)	Moderate	Low
Soil management practices TOTAL	**7.8**	**7.5**	**Moderate**	**Low–Moderate**
Nitrogen management (4Rs)	6.3 (5.0 to 7.6)	6.3 (5.0 to 7.6)	High	Moderate–High
Alley cropping	3.9 (0.5 to 14.4)	3.9 (0.5 to 14.4)	Moderate	Low
Silvopasture	2.8 (0.8 to 7.0)	2.8 (0.8 to 7.0)	Low	Low
Riparian tree planting	0.7 (-0.9 to 2.3)	1.6 (0.6 to 3.5)	Low	Low
Avoided conversion of shelterbelts	0.2 (0.0 to 0.4)	–	Moderate	Moderate
Agroforestry TOTAL	**7.6**	**8.3**	**Low**	**Low**
Avoided grassland conversion	12.7 (2.2 to 41.3)	4.1 (0.2 to 20.2)	Low	Moderate
Grassland restoration	0.7 (-0.1 to 1.5)	0.4 (0.0 to 1.8)	Low	Low
Improved grassland management[b]	0.22 (0.19 to 0.25)	0.22 (0.19 to 0.25)	Low	Moderate
Grasslands TOTAL	**13.62**	**4.72**	**Low**	**Low**

Data source: Drever *et al.* (2021)

This table presents the annual sequestration potential of agricultural and grassland NBCSs in Canada to 2030 and over the 2030–2050 period. The Panel has indicated its level of confidence in these estimates by providing ratings for both the GHG flux and area of opportunity used by Drever *et al.* (2021) to calculate the mitigation potential. See the Appendix for Panel confidence scale.

a Although this category includes crop rotations, perennial crop strategies, and legume crops, the value represented here only uses the magnitude of sequestration potential for legume crops, as estimates for crop rotation and perennial crop strategies were not considered by Drever *et al.* (2021).

b Several strategies are encompassed within this NBCS, but the values provided only represent avoided N_2O emissions from increasing legumes in pastures derived from Drever *et al.* (2021). Not enough information on area of opportunity exists for the other strategies.

Overall, the estimates of emissions and sequestration rates in Drever *et al.* (2021) represent current knowledge on the state of these NBCSs, though uncertainties associated with the area of opportunity used to calculate total mitigation potential in Canada are underrepresented. The extent of cropland and pastureland is relatively well known due to the managed nature of these regions, so the area of opportunity for implementing most agricultural NBCSs is based on feasibility considerations (both technical and economic, taking into account policy and behavioural barriers). Uncertainty relating to the area of opportunity for avoided grassland conversion is especially high; some reports indicate continued conversion of native grasslands in both Canada and the United States, while others indicate that, at least in some regions, grasslands are not being converted at a rapid rate (WWF, 2021; CAPI, 2022; Raven *et al.*, 2022). This uncertainty is compounded further when future market pressures related to global food shortages are considered, as these will likely increase grassland conversion to cropland (Section 4.4). Furthermore, Panel confidence in flux estimates for grassland NBCSs is low, reflecting relatively few data on GHG fluxes and high uncertainty when compared to cropland NBCSs.

One limitation to the above data is the assumption that uptake of these practices is linear instead of the more realistic S-shaped curve shown to generally characterize the uptake of innovations (Rogers, 1962; Pratt *et al.*, 2021). Drever *et al.* (2021) assume that, so long as an NBCS is proven to be economical, no further incentives are needed to promote implementation. When determining costs for cover crops, Drever *et al.* (2021) found that maximum adoption is profitable regardless of carbon price; if this is the case, additional barriers must be considered (Section 4.5.2) to understand why uptake has not already occurred. Similarly, there is limited detail on which incentives motivate the adoption of various levels of 4R management, making it difficult to assess the validity of the magnitude of emissions reduction.

In the view of the Panel, the estimates in Drever *et al.* (2021) provide a useful baseline to inform future policy decisions on agricultural NBCSs in Canada. Large uncertainties remain, however, and more research is needed to understand the longevity of these activities (Section 4.4) and how best to overcome social, economic, and technical barriers for implementation (Section 4.5).

4.4 Stability and Permanence

Terrestrial soils have a carbon storage limit

The conversion of natural forests and grasslands to agricultural lands resulted in historical soil carbon loss in Canada, making these areas amenable to carbon addition through improved management practices. Once such practices are implemented, stocks and fluxes will reach an equilibrium state after a few decades, however, and no more SOC will accumulate (Paustian, 2014; NASEM, 2019; Groupe AGÉCO *et al.*, 2020), as demonstrated by declining rates of accumulation in reduced and no-till cropland systems. Liang *et al.* (2020) found that no-till systems in western Canada sequestered 0.74 t C/ha/yr 3–10 years after implementation, 0.26 t C/ha/yr 11–20 years after implementation, and 0.1 t C/ha/yr in the very long term (>20 years after implementation). This limitation extends to grassland ecosystems, which cannot remain sinks in perpetuity (Smith, 2014).

> "While soil carbon stocks can remain stable (barring natural or anthropogenic disturbance), the sink function of grasslands cannot be considered indefinitely sustainable."

Analysis by Smith (2014) determined that, following land-use conversion or changes to land management regimes, grasslands will take up soil carbon but then reach equilibrium after a certain period of time, after which further increases in carbon stocks cannot be sustained. This equilibrium is the result of a steady decline in soil carbon absorption following rapid sequestration in the years immediately after the recorded change (Smith, 2014). While soil carbon stocks can remain stable (barring natural or anthropogenic disturbance), the sink function of grasslands cannot be considered indefinitely sustainable.

Adding biochar to soil can overcome this limitation, since biochar is resistant to microbial decay and, on average, remains in soils for hundreds of years or more, making it a long-lasting carbon storage vehicle (Santos *et al.*, 2012; Wang *et al.*, 2016). However, although SOC equilibrium may be achieved in agricultural systems, actions to reduce emissions of non-CO_2 gases such as N_2O can continue to accrue GHG mitigation benefits indefinitely (Paustian *et al.*, 2016).

Changes to Canada's climate can both help and hinder NBCS effectiveness

Future climate changes, especially in warming and precipitation, will affect SOC in both agricultural systems and grasslands. Significant uncertainties remain about the specific characteristics of soil carbon pools in grasslands, as well as the extent to which future warming will impact carbon sequestration trends in grassland soils (Jones & Donnelly, 2004). Temperature and precipitation rates play a significant role in soil processes and, as the climate changes, these variables will affect the rate and amount of carbon sequestered. Warming could prompt increased microbial respiration, causing loss of soil carbon in the short term. However, warming could also boost primary productivity, increasing soil carbon in the long term (Jones & Donnelly, 2004).

Future climate change scenarios could also exacerbate soil carbon destabilization, for example, where drought-induced soil drying coupled with extreme precipitation events can lead to disturbance of soil aggregates and fluctuations in soil redox (chemical reactions involving both oxidation and reduction) (Bailey *et al.*, 2019). Warming may extend the growing season of some crops and is expected to increase ecosystem respiration (Hristov *et al.*, 2018), while CO_2 fertilization will potentially enhance the growth of certain crops, leading to increased carbon input to soils. Warming will affect microbial metabolism, further enhancing soil destabilization and elevated CO_2 emissions (Bailey *et al.*, 2019). Increased precipitation could lead to increased sequestration of carbon in soils, but reduced precipitation could limit plant productivity and lead to drought.

As of 2019, there were no Canada-wide studies of future drought predictions, but models generally indicate that there is a higher likelihood of drought in the southern Canadian prairies and interior of British Columbia (Bonsal *et al.*, 2019). Dry conditions have already hindered adoption of cover crops in the Prairies, with 27% of farmers polled in a recent survey reporting establishment problems caused by a lack of moisture in the fall (Morrison & Lawley, 2021). Increased warming and drying in grassland regions can also contribute to greater probability of extreme fire conditions and wildfire occurrence (Cohen *et al.*, 2019). Although the emissions associated with the burning of grassland biomass in Canada are low (<0.05 Mt CO_2e/yr),[21] there is uncertainty associated with the estimated area burned per year, as well as the average fuel load per hectare and combustion efficiency of the areas (ECCC, 2022b).

NBCSs must rely on sustained efforts by landowners and producers if sequestration and emissions benefits are to last over the long term

NBCSs involving management practices require ongoing efforts to maintain both carbon sequestration and emissions reduction. Achieving these benefits requires sustained, repeated, and often seasonal implementation of NBCSs, such as planting of cover crops and legumes, maintaining no-till, applying 4R nitrogen fertilizer practices, and grazing management. Should management practices resulting in carbon accumulation revert to business as usual (e.g., resumption of intensive tillage), stored carbon will be lost, effectively undoing previous efforts. In contrast, reduced N_2O emissions due to 4R implementation are not erased; rather, those emissions increase only in the year when practices are

21 To convert non-CO_2 gases into CO_2e, ECCC (2022b) used GWP100 values from IPCC (2012), where CH_4=25 and N_2O=298.

reverted — even so, maintaining a trend of emissions reduction requires sustained application of the 4R method. Policies or funds to encourage uptake of NBCSs would consequently need to be maintained and enforced over the long term (Paustian *et al.*, 2019).

In the Panel's view, threats to the continued use of NBCSs include rising maintenance costs, the completion of landowner contracts, and changing market pressures — all of which are difficult to predict and therefore apply to mitigation potential calculations for the future. Market uncertainties are further tied to future pressures on food security; demands for land to grow crops can be directly at odds with efforts to mitigate climate change and may drive further demand for conversion of marginal lands, including grasslands and wetlands (Hasegawa *et al.*, 2018; Ma *et al.*, 2022).

4.5 Feasibility

Many agriculture NBCSs, such as no-till and cover cropping, are already widely practised in some regions of Canada. Barriers associated with their implementation are well documented, and the industry has considerable experience and knowledge about approaches to overcome them. Knowledge bases for other NBCSs are continually being developed; for example, the adoption of the 4R strategy across Canada is a significant topic of research and policy, and there is widespread awareness of benefits beyond emissions reduction (such as reduced pollution of waterways, discussed in Section 4.6.1). Expanding these NBCSs further will likely be easier than those less well studied. When considering the feasibility of implementing these NBCSs, it is important to note that most agricultural lands are privately owned, and therefore both costs and policies associated with implementing them need to balance private costs to landowners with primarily public benefits. As discussed in Section 2.3.2., not all policy options will be appropriate in all situations, and careful consideration of incentives and regulations will be critical for maintaining a balance.

4.5.1 Agricultural and Grassland NBCS Costs

Costs for the implementation of agricultural NBCSs vary depending on climate, soil characteristics, and crop types

Due to the inherent variability in climate, crop type, soil characteristics, and choice of farming methodologies, the range of costs for implementing agricultural NBCSs can vary widely across Canada. For example, individual cover crop types differ in their capacity to sequester carbon, in turn affecting the costs per tonne of carbon sequestered, with specific differences between grasses and legumes (De Laporte *et al.*, 2021b). Based on a survey of cover-crop studies in the United States and Canada, De Laporte *et al.* (2021b) found that — when tillage, seeds, planting, and termination are considered alongside fertilizer savings, compaction, and weed and erosion control benefits — costs outweighed the benefits in non-legume crops (i.e., a mean value of -$86/ha, ranging from -$314/ha to $44/ha for rye cover crops), whereas nitrogen credit conveyed a net benefit in legume crops (i.e., a mean value of $66/ha, ranging from -$107/ha to $255/ha). These ranges reflect uncertainties surrounding seed prices, nitrogen credits, and the value of weed control over time (De Laporte *et al.*, 2021b); along with limited timeframes for establishment, they also potentially deter producers from implementing cover cropping (Schipanski *et al.*, 2014; CTIC, 2020).

Furthermore, higher economic gains achieved through monoculture disincentivize farmers from using certain crop rotations — for example, replacing annual cash crops with perennial grass or legume hay on a short-term basis (NASEM, 2019). Although inclusion of winter wheat in corn and soybean rotations has been proven to be profitable over time, high initial costs and lower initial returns can deter implementation (De Laporte *et al.*, 2022). Based on calculations by Drever *et al.* (2021), Cook-Patton *et al.* (2021) estimated the mean marginal abatement cost (MAC) for adopting cover crops to be $63.01/t CO_2e. This estimate relies on 2011 data from the Statistics Canada *Census of Agriculture* and will therefore be affected by shifting costs for seeds, fertilizer, and weed control, both regionally and in the future.

Vegetation type also affects the costs for using biochar as a soil additive to enhance soil carbon. Drever *et al.* (2021) found that not all crop residues used in creating biochar were economically feasible. Wheat and oat/barley (which collectively comprise ~70% of available residue) were estimated to cost $88 and $92 per t CO_2e in 2050, respectively, which is below the commonly used threshold for cost-effective mitigation of $100/t CO_2e. However, the mean MAC calculated by Cook-Patton *et al.* (2021) is $150/t CO_2e in 2030, highlighting the variability in crop type and the temporal considerations for relatively novel NBCSs such as biochar.

While no-till agriculture is relatively prominent in areas of Canada already, Drever *et al.* (2021) assumed that market signals would be important for adopting reduced tillage, increasing no-till from the already high level of adoption, and for maintaining that high level. This is reflected in the relatively high average MAC of $74.44/t CO_2e (Cook-Patton *et al.*, 2021). Due to the uneven uptake of no-till across the country, regionality will be a key determinant of the costs for encouraging and implementing no-till or maintaining the current levels of uptake.

Costs for implementing nitrogen reduction depend on the intensity of adoption

Annual nitrogen monitoring costs have been estimated to range from $3–18/ha for basic to advanced scenarios, whereby monitoring moves from simple to detailed, from field level to sub-field, and from simply matching nutrient supply to manipulation of the timing and type of fertilizer (Drever *et al*., 2021). Advanced nutrient management implemented at a level beyond standard practices has a MAC of $55.79/t CO_2e (Cook-Patton *et al*., 2021). Assumptions about the level of adoption of 4R practices can have significant implications for cost. A study comparing two scenarios — one with 90% of fertilizer managed under 4R by 2030 (but with a lower percentage of advanced uptake) and another with only 70% managed under 4R by 2030 (with a higher percentage of advanced uptake) — found that costs for the latter were nearly three times greater on a cost-per-tonne basis than the former for nearly identical outcomes; the variation stems from the high costs for enhanced efficiency fertilizers used in the advanced scenario (Burton *et al*., 2021).

Despite being shown to be mutually beneficial to farmers and the environment, farmers are still not widely adopting the 4Rs (De Laporte *et al*., 2021a). Overapplication of fertilizer, for example, continues to occur, possibly due to the desire to maximize yields in good years and ensure there is always enough nitrogen available to crops (Rajsic & Weersink, 2008; De Laporte *et al*., 2021a). In the Panel's view, this demonstrates that costs are likely higher than the direct financial calculations; even in cases where practices are profitable, there is hesitancy to engage in them because of perceptions of risk reductions with higher applications, perceived benefits of higher rates of use beyond cost-effectiveness, and cultural factors (Section 4.5.2).

Agroforestry NBCSs can be deployed at relatively low cost beyond riparian areas

Mean MAC estimates for adding or maintaining trees in agricultural lands vary, depending on the species of tree selected, density of planting, and management strategies: $11.15 for alley cropping, $6.36 for avoided loss of shelterbelts, and $3.58 for silvopasture (Cook-Patton *et al*., 2021; Drever *et al*., 2021). However, in the view of the Panel the MAC for silvopasture may be an underestimate; Drever *et al.* (2021) assumed adoption at zero cost for the first third of the estimated area of opportunity, and only the cost of trees for the second third. Drever *et al.* (2021) also assumed that costs for establishing silviculture depend primarily on the price of trees and associated establishment expenses, and that uptake can be encouraged through partial or full compensation. Since most costs for agroforestry are low, the lack of current uptake indicates that considerations beyond costs must be contributing to the relative lack of establishment (Section 4.5.2).

Estimates for planting trees in riparian areas — in wetlands, or along the banks of streams or rivers — are considerably higher, with no opportunity at less than \$100/t CO_2e (Drever *et al.*, 2021) and a mean MAC of \$3,873.90 (Cook-Patton *et al.*, 2021). This includes costs for purchasing and planting trees, site preparation, herbicide application (estimated at \$3,920/ha), and maintenance costs (\$451/ha/yr), as well as long-term opportunity costs associated with land retirement from agricultural production. Opportunity costs contribute significantly to the total cost, particularly when high-value crops are removed and direct financial compensation to landowners is required (Drever *et al.*, 2021).

Grassland restoration and conservation costs are difficult to estimate

For avoided grassland conversion, Drever *et al.* (2021) estimated that the majority of mitigation potential would only be available at more than \$100/t CO_2e, with a MAC of \$144.31 calculated by Cook-Patton *et al.* (2021). In the Panel's view, using land values from Drever *et al.* (2021) may overestimate the costs, as they should reflect the difference in returns among land-use types. In contrast, an economic study by De Laporte *et al.* (2021b) found that avoiding the conversion of pasturelands to croplands would actually yield positive returns in comparison to converting them to row cropping, especially in the Prairies. This study assumed that any pastureland would be of lower quality, and that any converted land would therefore have a lower yield. After considering land costs, the authors found that the net benefit of maintaining pasture in the Prairies ranges from \$229.35–331.90/ha (De Laporte *et al.*, 2021b). These contrasting findings highlight issues around additionality and determining the true area of opportunity for avoided grassland conversion. If the costs derived by Drever *et al.* (2021) are overestimated, then avoided grassland conversion may be a more cost-effective option. However, if conversion to cropland, as proposed by De Laporte *et al.* (2021b), is of limited value, then this option may not actually be additional.

Similarly, Drever *et al.* (2021) analyzed the costs associated with grassland restoration in Canadian riparian areas and ultimately determined that 60% of the overall mitigation potential of this NBCS (0.4 Mt CO_2e/yr out of the total 0.7 Mt CO_2e/yr) will be available at a cost of less than \$100/t CO_2e. The mean MAC calculated by Cook-Patton *et al.* (2021) is just over that threshold at \$102. This estimate is limited, however, to the restoration of grasslands in riparian areas; the costs of grassland restoration in other areas were not estimated.

Grassland management strategies can have both negative and positive effects on profits, depending on strategy and region

Given that there are many options for managing grasslands and the potential for implementing multiple strategies at once, it is difficult to determine how upfront implementation costs will interact with potential long-term profits. For example, De Laporte *et al.* (2021b) determined that, despite initial costs for installing fencing and water sources, rotational grazing conveyed a net benefit, with an annual change in net return ranging from $3.54–47.95/ha. This variation reflects the level of adoption and its relationship to number of animals per unit — the more rotational grazing, the higher the number of animals on each hectare of land and therefore the higher the profit (Burton *et al.*, 2021).

Cook-Patton *et al.* (2021) estimated that adding legumes to pastures would have an average MAC of $40, which is relatively cost-effective when compared to some other agricultural NBCSs. However, other studies disagree that the use of legumes in pastures to fix nitrogen and reduce dependence on fertilizers can convey either a net benefit or cost. De Laporte *et al.* (2021b) found that increasing legumes in pastures resulted in net average returns — a mean of $34.65/ha in the Prairies — and a mean of -$29.73/ha in the rest of Canada. Whether a return is positive or negative depends on regional variation in fertilizer costs; a positive return correlates to high fertilizer costs since more money is saved by not buying and applying fertilizer.

Maintaining crop yields or compensating for crop-yield losses are important considerations when implementing NBCSs

Incorporating additional rotations of crops such as winter wheat into continuous cropping systems, such as the corn and corn-soybean rotations common in Ontario, can result in higher crop yields and reduction in yield variability (Yanni *et al.*, 2018). Incorporating rotations has further been found to produce higher yearly net returns in corn systems (Deen *et al.*, 2006a, 2006b). Once established, no-till systems without reductions in crop yield can have lower economic costs than intensively tilled areas, reducing the costs of labour and equipment relative to other tilling practices (Sørensen & Nielsen, 2005; Derpsch *et al.*, 2010). Reduced tillage does not generally result in higher yields and may produce higher yield variability in certain soils (Beyaert *et al.*, 2002; Dam *et al.*, 2005; Vetsch *et al.*, 2007; Munkholm *et al.*, 2013; Vanhie *et al.*, 2015). Similarly, decisions to reduce the use of nitrogen fertilizer warrant careful consideration so as not to reduce crop yields; while managing nitrogen inputs into soils helps to reduce N_2O emissions, it may also lead to a reduction of carbon sequestration in soils (Groupe AGÉCO *et al.*, 2020) (Section 4.3.1).

The impacts of NBCSs on profitability can be uncertain, and vary with changes in climate, soil conditions, and market demands. It can be difficult to determine in advance whether certain NBCSs will affect profits at all. In a recent survey on the use of cover crops in the Prairies, approximately 47% of respondents were unable to determine the impacts of cover crops on farm profit (Morrison & Lawley, 2021). However, 24% of farmers saw an increase in profit, 24% saw no change, and only 4% experienced a decline (Morrison & Lawley, 2021). Such variability highlights the difficulty in prescribing a one-size-fits-all approach when calculating the feasibility of NBCSs at the farm level.

Marginal lands with low crop yields are most attractive for planting perennial vegetation or trees. Once trees have matured, they can be harvested and used in a variety of ways, including as bioenergy to replace fossil fuels, or for more traditional products such as pulp, paper, and construction materials (Drever *et al.*, 2021) (Section 3.3.2). Species composition depends on climate, topography, and soil type, selected to provide a variety of other co-benefits, such as fruit or nut production. If these areas are agriculturally productive and occupied by high-value crops, then replacing this land with tree buffers will result in economic losses to landowners. Provision of financial compensation for tree establishment would then be critical to promoting adoption (Drever *et al.*, 2021). However, strategies such as alley cropping can still provide benefits, and will additionally reduce erosion in croplands (Yanni *et al.*, 2018).

4.5.2 Policy and Regulatory Challenges

Policies for encouraging uptake of agricultural NBCSs can involve "carrots" (e.g., subsidies or payments to those implementing NBCSs) or "sticks" (e.g., penalties or regulations). Canada has primarily used voluntary agri-environmental programs that provide monetary incentives to further environmental goals, while the use of regulations has been viewed as "a politically unattractive last resort" (Baylis *et al.*, 2022). A review of policies available for encouraging or mandating NBCS uptake is out of scope, but the Panel highlights some considerable uncertainties and barriers to implementation below.

Instability and inadequate compensation can stymy participation in agricultural carbon credit systems

Canada's only operational agricultural carbon credit system is in Alberta. It contains 19 offset protocols, such as 4R nutrient stewardship, and has previously included reduced tillage as part of conservation cropping (Gov. of AB, 2022b; Lokuge & Anders, 2022). Farmers have been reluctant to participate in this program, however, due to inadequate compensation through incentives and instability in the carbon market (Lokuge & Anders, 2022). A literature review on carbon credit systems in agriculture found that, "due to a history of regulatory risk the agriculture sector has seen the revocation of carbon credit eligibility for certain practices, and invalidated credits can lead to significant financial losses for farmers" (Lokuge & Anders, 2022). Research has indicated that reduced-till and no-till projects have the highest risk of being invalidated through changes to the Alberta offset system, which bore out with the closing of the conservation tillage credit stream in December 2021 (Tarnoczi, 2017; Gov. of AB, 2022b). To strengthen the carbon credit system in Alberta, Lokuge and Anders (2022) suggested emphasizing other efficiencies associated with carbon credit-accumulating activities (e.g., co-benefits associated with 4Rs), and not focusing solely on potential financial gains associated with participation in carbon credit programs. Increased stability and more significant rewards may potentially prompt higher farmer participation in carbon credit systems.

Effective implementation of agricultural NBCSs often relies on farmers' awareness of the potential benefits, and relevant policy incentives and supports

Implementing agriculture and grassland NBCSs can be slowed by a lack of awareness about specific NBCSs and relevant environmental relationships (Dessart *et al.*, 2019; Prokopy *et al.*, 2019; Groupe AGÉCO *et al.*, 2020). For example, a survey of producers in Saskatchewan found that many were unaware of the financial benefit of retaining shelterbelts; if any benefits were recognized, they were perceived to be non-economic and therefore not included in management decisions (Rempel *et al.*, 2017). This emphasizes the importance of improving farmers' understanding of the real costs and benefits of shelterbelts. Agroforestry NBCSs are also subject to considerations around reversibility; farmers may be reluctant to invest in actions that are permanent, or cost money to reverse, such as any NBCSs that involve planting trees (Yemshanov *et al.*, 2015). The costs associated with reversal are seldom included in cost calculations based on net present value (e.g., Drever *et al.*, 2021), resulting in further underestimation.

> "Increased stability and more significant rewards may potentially prompt higher farmer participation in carbon credit systems."

A focus on farm-level networks can be crucial for supporting the uptake of these NBCSs, as interaction among farmers (both informally in social settings and formally within industry organizations) is correlated with an increased acceptance rate of altered management practices (Prokopy *et al.*, 2019; Groupe AGÉCO *et al.*, 2020). Outreach initiatives to inform farmers and landowners about practices such as agroforestry, as well as the provision of expertise or maintenance equipment (Drever *et al.*, 2021), can foster increased awareness and knowledge within the sector, influencing the likelihood of long-term acceptance and implementation of NBCSs. Increased awareness of NBCSs does not always result in optimization, however. In the case of 4R nitrogen management, a survey cited in Burton *et al.* (2021) found that Ontario corn farmers who were familiar with the 4Rs applied 28% more fertilizer on average than those who were not aware. The Panel notes that, in these types of situations, investment in technical assistance and training may help achieve the intended benefits.

Improving nitrogen management and increasing the uptake of cover crops are priorities for the federal government, which included them as target projects for the Agricultural Climate Solutions program (AAFC, 2022). The value of conserving existing trees on farms (including shelterbelts and riparian buffers) has also been recognized by the federal government and supported with $60 million through the Nature Smart Climate Solutions Fund (GC, 2021d). These initiatives indicate the willingness of governments to support NBCS interventions where they are known to have environmental or economic co-benefits. Additional policy measures for reducing grassland conversion could include actions such as a moratorium on future conversion of native grasslands for agricultural purposes, the creation of incentives for avoided conversion of grasslands to cropland, and the expansion of protected areas in grassland zones (Nature Canada, n.d.).

Current programs and policies to reduce agricultural business risk may be incompatible with NBCSs

Risks linked to crop production (including yield and selling price) have been associated with suboptimal nitrogen application rates (Pannell, 2017). In short, policies intended to reduce risk for farmers (such as crop insurance) are "likely to result in increased use of nitrogen fertilizer overall, as they allow farmers to adopt more risky nitrogen application strategies without bearing the full consequences of those increased risks" (Pannell, 2017). In some cases, this strategy bears out; applying excess fertilizer to boost gains in good years is relatively cost-effective compared to the cost of under-application (Rajsic & Weersink, 2008). However, crop insurance programs may also incentivize conversion of intact ecosystems such as grasslands and wetlands, further increasing emissions (FCS, 2022).

NBCSs associated with land-use change on agricultural lands (e.g., agroforestry and mineral wetland restoration/conservation; see Chapter 5) have been disincentivized by existing agricultural business risk management (BRM) programs. A study by Jeffrey *et al.* (2017) demonstrated that net gains or losses associated with implementing certain NBCSs were amplified by participation in BRM programs. For example, benefits associated with the use of legumes or cover crops increased when paired with BRM participation, while, conversely, the net cost for implementation (i.e., disincentive to adopt) for buffer strips and wetland restoration increased. Consequently, "participation in public BRM programs may result in reduced uptake of many environmentally friendly production practices or land-use changes (e.g., buffer strips or shelterbelts) if they are costly for producers to adopt" (Jeffrey *et al.*, 2017). Participation in BRM programs has also been found to increase the use of fertilizer and pesticides, negatively impacting ecosystems and environmental goals (Eagle *et al.*, 2016).

> "In the absence of legal mandates, a landowner's decision to implement NBCSs is an individual one, in large part influenced by their personal beliefs and behavioural characteristics."

One way of dealing with this issue is *cross-compliance*, or "the linking of environmental conditions to agricultural support payments" (Rude & Weersink, 2018). Essentially, to receive income support, farmers must ensure an environmental target is met; success is dependent on combining income support and environmental programs, increasing effectiveness. However, cross compliance is unlikely to be applicable to Canada's current suite of BRM programs — the benefits available to farmers are fewer than compliance costs, leading to limited voluntary participation (Rude & Weersink, 2018).

Behavioural factors are a key uncertainty in assessing uptake of NBCSs

Even if NBCSs have demonstrated net benefits or relatively low costs, they are not uniformly accepted and implemented by farmers across the country. In the absence of legal mandates, a landowner's decision to implement NBCSs is an individual one, in large part influenced by their personal beliefs and behavioural characteristics (Groupe AGÉCO *et al.*, 2020). For example, Dessart *et al.* (2019) found that cognitive factors, including farmers' knowledge of NBCSs and perceptions of the possible outcomes associated with these practices, were most directly related to the adoption and implementation of improved land management practices. Most economic modelling for adopting best management practices (including some NBCSs) assumes that maximizing profit is the primary driver for farmers. It is, however, not the only objective; social influences and awareness of environmental effects can also influence adoption (Weersink & Fulton, 2020).

To better understand the influence of behavioural characteristics on agricultural practices, Huber-Stearns *et al.* (2017) undertook an analysis of enabling conditions — "factors that increase the likelihood of an intended change in… management regime" — in the successful implementation of payment for ecosystem services programs. They found that, alongside biophysical, economic, and governance-related conditions, sociocultural conditions (e.g., trust and transparency, stakeholder communication, proximity of a community to other like-minded actors) were required for the success of the policy and avoiding the development of additional policy barriers (Huber-Stearns *et al*., 2017). Every decision about agricultural NBCSs is made in relation to a variety of external influences, such as the age, experience, and expertise of a farmer; the farmer's attitudinal orientation toward environmental considerations and risk tolerance/aversion; and characteristics of the farm itself, including size, tenure, and vulnerability of the land (Groupe AGÉCO *et al*., 2020). The context-dependent nature of individual decision-making results in considerable uncertainty; while many NBCSs may have high technical and economic potential, there is no guarantee of high adoption rates due to these social-behavioural elements. The design of effective policy mechanisms would benefit from consideration of these behavioural factors.

Uptake of certain NBCSs has also been found to be affected by whether or not the land is owned or rented, and how long rentals are expected to last. A study of the implementation of conservation tillage and cover crops in southern Ontario found that activities with short-term benefits, such as conservation tillage, were equally likely to be implemented on both owned and rented lands (Deaton *et al*., 2018). Cover crops, where positive net benefits take longer to accrue, were 9.9% less likely to be implemented on rented land than on owned land, presumably because farmers are more reluctant to invest up front if there is a possibility that they will not be in a position to reap medium-term benefits. This applies to the time horizon of rented land, as well; farmers with long-term rental arrangements were equally likely to plant cover crops on both rented and owned land, whereas farmers with short-term rentals were not (Deaton *et al*., 2018). Thus, the ease of implementing certain NBCSs will depend on land ownership when benefits are estimated to arise.

4.5.3 Monitoring and Accounting

Determining optimal strategies for NBCS implementation requires local and regional information

Though some agricultural NBCSs are well established, identifying optimal strategies on a farm-by-farm basis requires detailed knowledge of environmental conditions, soil composition, topography, and land-use history (Groupe AGÉCO *et al*., 2020). There is no one size fits all strategy that can be universally applied; investment in research that monitors and tracks changes in stocks and emissions can help target actions in a variety of different regions (Meadowcroft, 2021). This need was identified in interviews conducted by Groupe AGÉCO *et al.* (2020), who noted,

> *Regional and farm level soil information is complementary and necessary to manage soil health effectively. Yet…there is a lack of such information on the current status of soil health. This data gap is problematic for researchers (as well as policymakers and producers) as it limits the ability to understand, identify, manage, and track improvements over time.*

Similar challenges apply to pasturelands. As a result of uncertainties around grazing practices and grassland management, many researchers call for site-specific grazing metrics (as opposed to larger-scale spatial data) to accurately track the complexities and variance across management practices (Bork *et al.*, 2021). Although they have merit in terms of accuracy (Smith *et al.*, 2012; Bork *et al.*, 2021), site-specific data often lead to issues of interoperability. For example, Maillard *et al.* (2017) noted that "the sampling depth recommended for SOC measurement varies according to project purposes, institutional preferences, [and] land uses" and, as a result, are often incomparable. Annual changes to grassland SOC are small, and cumulative result is only statistically detectable after several years (Maillard *et al.*, 2017). Measuring such changes can be difficult, however, due to the short-term nature of research projects, which may not capture the full extent of changes in an ecosystem over the required timescales.

Canada does not track or account for changes in soil carbon or GHG emissions associated with some NBCSs

Though monitoring is key to understanding the effectiveness of NBCSs, there are critical knowledge gaps related to tracking changes to carbon stocks around certain NBCSs in agricultural systems and grasslands. For example, there is no Canada-specific breakdown of total carbon sequestration rates and impacts for improved grassland management strategies. As Viresco Solutions Inc. (2020) pointed out, this lack of data results in the potentially inaccurate assumption in Canada's *National Inventory Report* that "grassland management has not significantly altered since 1990 and therefore does not account for any SOC stock changes on grasslands as a result of management or a changing climate." The Government of Canada is now required to address this omission, but the data needed to do so do not currently exist (Viresco Solutions Inc., 2020). As a result, significant uncertainty remains about the regionally specific benefits of different modes of land management across Canada's grasslands. Similarly, the *National Inventory Report* does not track adherence to (and thus the results of) the 4R method of nitrogen management. Although it assesses emissions related to nitrogen input (synthetic and organic), the lack of data on other spatially explicit management practices and their change over time (e.g., timing of fertilizer application) means the potential of these practices to affect emissions is overlooked (ECCC, 2022b). In the Panel's view, this is critical to incentivizing the uptake of NBCSs and evaluating their effectiveness.

4.6 Co-Benefits and Trade-Offs

Agricultural and grassland NBCSs have distinct co-benefits and trade-offs; they can all vary through time and often depend on the regional climate, local topography, crop species, soil characteristics, and market conditions, which can all vary through time. Some interventions proposed to sequester carbon in soils have been extensively studied and deployed in Canada (e.g., reduced or no-till), and others were originally employed to primarily offer other benefits, such as shelterbelts to protect soil from wind erosion (Mayrinck *et al.*, 2019; ECCC, 2022b). Most trade-offs in implementing these NBCSs are associated with costs and changes in land use; as such, they are largely discussed above in Section 4.5, while the following discussion mostly concerns co-benefits. Co-benefits can also be split to apply either privately (to the landowner or manager) or publicly; the discussion in this section encompasses both however, ideally, private benefits would be captured in MAC calculations.

4.6.1 Soil and Ecosystem Health

Higher levels of carbon in soils offer benefits to overall soil health

Cover crops confer other benefits beyond carbon storage and reduction of emissions, including drought resistance, reduction of erosion and leaching (leading to retention of soil nutrients), cheaper management of weeds and pests, and better soil structure (Morton *et al.*, 2006; Roesch-McNally *et al.*, 2018; Bergtold *et al.*, 2019). Soil health is also enhanced through an increase in microbial diversity and biomass, as well as improved water retention and nutrient cycling (Hristov *et al.*, 2018). Cover crops can reduce indirect N_2O losses as well, by capturing excess nitrogen after the harvest of the cash crop and reducing the required rate of nitrogen application; however, further research on the applicability of this co-benefit is needed (Yanni *et al.*, 2018). These benefits can offset initial costs of implementation (Roth *et al.*, 2018).

Soil health can also benefit from changes in tillage intensity. No-till practices lessen the effects of erosion, increase water retention, and improve soil health in general (Meadowcroft, 2021). The related practice of one-time deep inversion tillage could also act to bury surface soil layers high in carbon 60–80 cm deep, slowing decomposition (Paustian *et al.*, 2019). This practice is most effective in humid and sub-humid regions with poorly drained soils. However, the expansion of no-till practices, with associated rises in crop residue, has been found to increase phosphorus runoff (which contributes to eutrophication), particularly in the Prairies, where freeze-thaw cycles are a contributor. Incorporating occasional till cycles to break up topsoil has been found to reduce runoff; however, it reverses the positive gains of no-till for both carbon and nitrogen retention (Messiga *et al.*, 2010).

Adding biochar to soils can boost plant productivity and, in turn, enhance carbon input to the soil through plant residues, though this effect is highly dependent on soil and plant varieties, as well as management practices (Crane-Droesch *et al.*, 2013; Subedi *et al.*, 2017). One potential drawback to adding biochar to soil is the risk that toxic compounds (including heavy metals) might also be added (Subedi *et al.*, 2017). In general, agricultural NBCSs that increase SOC stocks also act to enhance the drought resilience of crops, which may become increasingly beneficial as Canada's climate changes (Banwart *et al.*, 2014; Bush & Lemmen, 2019; Oldfield *et al.*, 2019).

Trees in agricultural lands trap snow and promote biodiversity and animal health

In certain scenarios, agroforestry strategies can boost crop yields, enhance the quality of soils, and contribute to the conservation of biodiversity (Kort, 1988; Jose, 2009; Schoeneberger *et al.*, 2012). Adding trees to riparian areas can stabilize streambanks and limit nutrient runoff into water bodies (Schoeneberger, 2009). Beyond sequestering carbon, shelterbelts act to protect crops and livestock from wind and snow and can promote biodiversity in certain regions (Schoeneberger, 2009; Mayrinck *et al.*, 2019). Shelterbelts alongside roads can trap blowing snow, making for safer driving conditions and reducing the need for road maintenance (AAFC, 2009). Moisture from trapped snow is then redistributed to the soil in the spring, contributing to soil moisture retention (AAFC, 2009). Silvopasture has been used to provide habitat for wildlife and provide shelter for livestock (Baah-Acheamfour *et al.*, 2017). However, replacing pastures or croplands with trees can reduce albedo (Drever *et al.*, 2021), which needs to be taken into consideration when evaluating the benefits derived from carbon sequestration.

Intact grasslands reduce erosion, maintain water quality, and support biodiversity

Grassland vegetation conveys multiple benefits beyond carbon sequestration, including prevention of runoff and soil erosion through soil stabilization (Duran Zuazo & Rodriguez Pleguezuelo, 2008; Bengtsson *et al.*, 2019) and water filtration of pollutants ((DUC, 2006). Improved water quality can also benefit livestock production, as both the quality and quantity of plant biomass serving as fodder are important for meat and dairy production (Bengtsson *et al.*, 2019). Furthermore, intact grassland ecosystems support biodiversity by regulating services such as pollination (Bengtsson *et al.*, 2019; Viresco Solutions Inc., 2020). Nature Canada (n.d.) reported that, since 1970, populations of species dependent on native grasslands have fallen by 87%. In Alberta, the majority of identified species at risk are found in grassland regions (CPAWS, n.d.). Moreover, grassland cover offers pollinator species a place to live undisturbed, providing benefit to nearby agricultural fields (CPAWS, 2011).

Reducing nitrogen inputs to agricultural soils has positive downstream impacts

Fertilizer runoff from croplands has led to eutrophication of water bodies (Schindler, 2006). Increased availability of nutrients leads to greater algal productivity, consuming oxygen in the water column and creating anoxic (oxygen-poor) conditions in deep waters and sediments. Under anoxic conditions, the switch from aerobic (oxygen-consuming) to anaerobic (not oxygen-consuming) respiration leads to the production of CH_4, which in turn increases the warming potential of these ecosystems (Beaulieu *et al.*, 2019; Deemer & Holgerson, 2021). Wetlands in agricultural regions, such as the Prairie Pothole Region, are also observed to emit elevated levels of N_2O due to runoff from croplands (Bedard-Haughn *et al.*, 2006; Pennock *et al.*, 2010; Tangen *et al.*, 2015). These emissions have been linked to periods of inundation, prompted largely by spring snowmelt and runoff (Pennock *et al.*, 2010).

These impacts are further reflected in proximal real estate prices and losses in recreational profits; toxic algal bloom presence was found to convey 11–17% capitalization losses in near-lake homes in Ohio, with a loss of 22% in lake-adjacent properties (Wolf & Klaiber, 2017). Recreational damage estimates based on monthly fishing permits for Lake Erie demonstrated a 10–13% drop associated with harmful algal concentrations (Wolf *et al.*, 2017). Thus, addressing surface water eutrophication through reduced nutrient input can have demonstrable economic benefits in addition to reducing CH_4 emissions.

Reducing the use of fertilizers through 4R management could help to stymy, and possibly reverse, the eutrophication of water bodies by limiting the amount of reactive nitrogen available for removal by runoff and groundwater seepage (Beaulieu *et al.*, 2019; Groupe AGÉCO *et al.*, 2020). This is associated with the wider concept of *watershed management*, where decisions around land use take into account all downstream effects for rivers, lakes, and wetlands. Although watershed management is not considered an NBCS in this report, it is a crucial co-benefit of nutrient management.

4.6.2 Cultural Impacts

Maintenance of grasslands is associated with cultural benefits

The sociocultural services that grasslands provide centre mainly on tourism, recreation, and cultural heritage (Bengtsson *et al.*, 2019). Work done by CPAWS (2011) highlighted how, "for decades, the prairies have provided local residents [of Alberta] their livelihood while allowing them to enjoy nature through various recreational activities." Those activities, combined with the aesthetic value of the sprawling grassland ecosystem, are also a draw for tourists, providing economic benefit to local communities (CPAWS, 2011).

Recognizing the role of First Nations in the care and conservation of grassland systems is a form of decolonial justice

Maintaining grasslands is associated with reconciliation, decolonial justice, and the well-being of Indigenous individuals and communities — all vital cultural benefits. For example, bison are slowly being reintroduced to the Prairies after being hunted to near extinction in the late 1800s (Cecco, 2020; Tait, 2021). This effort has been undertaken not just as a means of increasing the ecological stability of the plains, but also as an "effort to heal relationships...between animals and the land" and between Indigenous communities and the state (Mamers, 2021). Bison are, for many plains Indigenous Peoples, central to ways of being and knowing, and "intimately bound to threads of reciprocity, morality, kinship relations, and sovereignty" (Hisey, 2021). They embody "all my relations" (Section 2.4), a fundamental tenet in which the interrelationship of all things is respected, conserved, and perpetuated (Buffalo Treaty, 2014). As such, their reintroduction also represents an ontological shift toward the "human-Creation" relationship (Hisey, 2021); the Buffalo Treaty, which explicitly focuses on returning bison to the land through collaboration with federal and provincial/territorial governments, is at the centre of this shift (Buffalo Treaty, 2014). Signed by 11 Indigenous nations, the treaty represents a vision of the future — one in which reconciliation is not merely an acknowledgement of the past but motivation for a better future (Mamers, 2021).

4.7 Conclusion

Many of the NBCSs discussed in this chapter are well studied and have either been implemented in the past or are currently being encouraged, lending an advantage to their more widespread use across Canada. Although uncertainties around the rates of SOC sequestration or emissions reduction for certain NBCSs remain, the more critical issue of estimating the magnitude of sequestration potential at any scale is linked to determining the area of opportunity — which is likely to vary regionally. Costs, policies, behavioural barriers, and technical impediments can all affect the implementation of NBCSs and require careful analysis and consideration to improve predictions about which NBCSs are the most promising for widespread use in Canada. There are opportunities to foster reconciliation by advancing self-determination and sovereignty over lands, while simultaneously conserving or restoring native grassland ecosystems by engaging Indigenous experts and recognizing Traditional Knowledge. Beyond the implementation of NBCSs, it is crucial to consider how to maintain their ongoing use, especially for those requiring sustained efforts to continue to reap benefits (e.g., nitrogen management, no-till practices). Long-term initiatives, policies, and funding programs, as well as extensive monitoring networks, will be important decision-making components for maximizing the potential of these NBCSs in agricultural areas and grasslands across Canada.

5

Inland Freshwater Ecosystems

Chapter Findings

- Avoided conversion of peatlands has the greatest mitigation potential due to the high carbon losses prevented on a per-hectare basis when they are protected from peat, oil, and gas extraction, and from mineral mining activities. However, this NBCS faces significant economic barriers based on the economic valuation of carbon alone.
- Protecting wetlands from conversion can be achieved through regulation, though current no-net-loss policies often allow for the loss of existing functional wetlands, instead favouring restoration and creation elsewhere; this results in at least a temporary loss of carbon.
- The ability of restored mineral wetlands to sustain carbon sequestration is subject to uncertainties and can be partly offset or even negated by increased CH_4 emissions. However, restoration of mineral wetlands has substantial co-benefits related to groundwater recharge, water quality, biodiversity, and flood protection, which are critical considerations for bolstering the case for both protection and restoration.
- Indigenous leadership and the creation of IPCAs can help protect wetlands from resource extraction while supporting reconciliation and restoring land claims. This is particularly critical in regions such as the Hudson Bay Lowlands and boreal Alberta, where proposed resource extraction is at odds with the conservation of carbon-rich peatlands. This type of trade-off will be a critical issue for decision-makers attempting to reach net-zero targets.
- Although most lakes and reservoirs in Canada are supersaturated with CO_2 (therefore acting as carbon sources), their sediments play a role in long-term carbon storage. The efficiency of these carbon sinks is likely to be reduced in the future due to warming, especially in small-sized lakes. Other perturbations, such as excess nutrients, are associated with an increase in CH_4 emissions. Nutrient management and conservation measures are key to avoiding these emissions and preserving carbon burial functions.

Inland freshwater ecosystems comprise wetlands (including peatlands), lakes, rivers, and reservoirs. Canada contains approximately two-thirds of the total 220 Mha of freshwater wetland area in North America (Kolka *et al.*, 2018), and at least a quarter of the world's peatlands (Tarnocai *et al.*, 2011; Xu *et al.*, 2018a). Northern peatlands in Canada alone are estimated to store ~150 Gt C (Joosten, 2009; Hugelius *et al.*, 2020). Several important wetland regions are found in

Canada, including the second- and third-largest northern peat-accumulating regions in the world: the Hudson Bay Lowlands and the Mackenzie River Basin (Packalen *et al.*, 2016; Hugelius *et al.*, 2020; Olefeldt *et al.*, 2021). Straddling Canada and the United States is the Prairie Pothole Region, which is dotted with millions of small (average <2 ha) marshes (colloquially referred to as potholes or sloughs) that provide a critical breeding ground for waterfowl (Badiou *et al.*, 2011; Tangen & Bansal, 2020; DUC, n.d.).

Wetlands, especially peatlands, can sequester significant amounts of carbon over long timescales, which, combined with their spatial extent, makes them a critical carbon sink in Canada. Other freshwater ecosystems, such as lakes and rivers, also play a role in the carbon cycle. Rivers are drivers of lateral carbon flux, transporting dissolved and particulate carbon among various ecosystems and eventually out to the ocean, but they are also emitters of both CO_2 and CH_4 (Cole *et al.*, 2007; Hutchins *et al.*, 2020, 2021). Globally, lakes are estimated to store 820 Gt C in their sediments (Cole *et al.*, 2007), accumulated over millennia; their annual rate of accumulation is modest, however, and they still emit both CO_2 and CH_4 (Ferland *et al.*, 2012; Raymond *et al.*, 2013; Mendonça *et al.*, 2017). The carbon balance of lakes and rivers is closely tied to the surrounding landscape, supplying carbon that can then be stored, emitted to the atmosphere, or transported to the ocean. These inland freshwater ecosystems offer a range of potential opportunities for enhancing CO_2 sequestration or reducing and avoiding emissions.

5.1 Opportunities for Enhancing Carbon Sequestration in Freshwater Systems

The Canadian Wetland Classification System defines *wetland* as "land that is saturated with water long enough to promote wetland or aquatic processes as indicated by poorly drained soils, hydrophytic vegetation and various kinds of biological activity which are adapted to a wet environment" (NWWG, 1988, 1997). Wetlands in Canada are first classified based on soil type, differentiating between organic and mineral soil wetlands. The Canadian Wetland Classification System then uses five classes of wetlands, further subdivided into more than 100 forms and sub-forms (NWWG, 1997). Organic soil wetlands include bogs, fens, and swamps, while mineral soil wetlands include marshes, swamps, and shallow water wetlands (NWWG, 1997).

Although lakes and reservoirs can share many ecological characteristics, the former are generally naturally occurring while the latter are human made. Both lakes and reservoirs simultaneously emit carbon gas to the atmosphere and store carbon in their sediments, though the balance of carbon sequestration to emission varies. For example, lakes in boreal regions have been calculated to contain up to 25% of landscape carbon stocks (Ferland *et al.*, 2012), but their emissions of CO_2 through sediment mineralization have also been measured to exceed carbon burial (Chmiel *et al.*, 2016). Due to this uncertainty, and because of their largely unmanaged nature, lakes are not great candidates for carbon burial enhancing measures; fertilization, which could potentially increase sedimentation by stimulating primary production, is associated with negative impacts (including eutrophication) and is therefore at odds with nutrient-reduction practices. As indicated in Section 4.6.1, eutrophication can lead to oxygen depletion in both the water column and sediments, causing the production of CH_4 via anaerobic respiration. As such, measures to reduce nutrient loadings could have a beneficial effect on the carbon cycling of lakes by reducing CH_4 emissions (Beaulieu *et al.*, 2019).

There are large uncertainties surrounding estimates of carbon storage and rates of sequestration with respect to lakes and rivers. As such, the Panel does not consider their restoration and conservation to be viable NBCSs due to these knowledge gaps (Box 5.1).

Box 5.1 Carbon Storage and Sequestration in Lakes and Rivers

The conservation of river and lake systems ensures their continued carbon storage and transport capacity. Lakes sequester carbon in sediments, keeping it out of the atmosphere for significant amounts of time (on the scale of 10,000 years or more) (Cole *et al.*, 2007). Rivers, in contrast, act as channels between oceanic and terrestrial carbon cycles (Maavara *et al.*, 2017). Anthropogenic disturbances within watersheds can affect lakes and reservoirs by increasing GHG emissions to the atmosphere from both sediments and the water column (Huttunen *et al.*, 2003).

There are a number of uncertainties around the current stocks and fluxes of carbon in lakes and rivers, both nationally and globally. Currently, there is no single estimate of carbon stored in Canadian lake sediment or river systems, though upscaling case studies can offer rough estimates. Using the average areal carbon stock of 230 t C/ha measured in several Quebec lakes (Ferland *et al.*, 2012) and applying it to the total surface extent of 86 Mha for Canadian lakes (Messager *et al.*, 2016) yields a conservative total stock of about 20 Gt C. It should be noted, however, that, although their potential for enhanced carbon sequestration is presently unknown, the conservation and restoration of lakes has been and continues to be practised to gain a range of biological and societal benefits (Jansson *et al.*, 2007; Vermaat *et al.*, 2016; Chausson *et al.*, 2020).

NBCSs associated with freshwater wetlands either avoid converting existing wetlands to other uses or restore previously existing wetlands that have been damaged or reduced. In Canada, wetlands are vulnerable to loss from many land-use developments, including resource extraction (e.g., minerals, oil and gas, peat), urban expansion, and the agriculture and forestry industries (Rooney *et al.*, 2012; Chimner *et al.*, 2017). Table 5.1 details potential NBCSs in various freshwater systems.

Table 5.1 Freshwater System NBCSs

Description of NBCS	Mechanism
Avoided Wetland Conversion	
Avoided wetland conversion prevents the release of carbon which has accumulated over hundreds to thousands of years. Wetland disturbances such as drainage (conversion to agricultural land, horticultural peat extraction), removal of material (horticultural peat, mines, and well-pads), compaction (seismic lines, temporary well-pads), and flooding (for dam construction) have the potential to cause rapid losses of GHGs to the atmosphere.	The process of draining wetlands interrupts anoxic (oxygen-poor) conditions prevalent during waterlogging, exposing the soils to air. This accelerates decomposition of organic material into CO_2, but also reduces the production of CH_4 (Silvola *et al.*, 1996; Bridgham *et al.*, 2006). Drainage can also lead to increased N_2O production (Tangen & Bansal, 2022). Peatland compaction can lead to wetter conditions and cause vegetation shifts, which can increase CH_4 emissions (Strack *et al.*, 2018). Peat removed for mining is stored in piles for reclamation but continues to emit CO_2. Wetlands can also be cut off from water sources through road construction or stream channelization (Kolka *et al.*, 2018), while the other side of the road experiences flooding, affecting vegetation and increasing CH_4 emissions.
Wetland Restoration	
In situations where wetlands have already been affected — through peat harvesting, mining, oil and gas extraction, or drainage/ conversion to agricultural lands — the **restoration of hydrological and biological regimes** can eventually re-establish carbon sequestration.	Restoration of freshwater marshes converted for agricultural purposes involves restoring hydrology (either by blocking drainage ditches or removing tile drains) and re-establishing vegetation, either passively or actively (Craft, 2016). Peatland restoration after peat extraction involves raising the water table by blocking or filling drainage ditches previously dug to allow peat to dry prior to extraction (Chimner *et al.*, 2017; Bieniada & Strack, 2021). Vegetation is also often transferred from a nearby donor peatland to jumpstart re-colonization of peat-forming species, such as *Sphagnum spp* (Graf & Rochefort, 2016).

Description of NBCS	Mechanism
Water-Level Management in Reservoirs	
Enhanced strategies for water-level management maintain sediment within reservoirs for longer timescales and prevent drawdown when water levels in reservoirs are low.	Reservoirs can accumulate and store significant amounts of organic material. However, when this material is exposed to air, accelerated decomposition results in an emissions-to-burial ratio of 2.02 (Keller *et al.*, 2021) — suggesting that reservoirs emit more carbon than they bury.
Lake Conservation	
Conservation of lake systems helps to protect their carbon stocks from release. While this carbon is generally considered to be permanently buried, its magnitude is such that caution should be exercised to maintain it.	Slowly accumulated lake sediments undergo minor decomposition over the initial decades post-deposition (Gälman *et al.*, 2008) but remain largely unaltered for millennia afterwards. Conservation can minimize its potential conversion to CH_4 by reducing the temporal and areal extent of anoxia induced by eutrophication and nutrient-loading.

5.2 Indigenous Freshwater System Management

Indigenous Peoples across Canada have been stewards of both the land and water for time immemorial. "Our people always said that we are the land, we are the water, the fish, the animals, and it's our responsibility to take care of this territory — we have to speak for the environment" (Vern Cheechoo, personal communication). In many regions of Canada, development has damaged the traditional lands and territories of Indigenous communities, and intact ecosystems, including extensive peatlands, continue to be at risk (Section 5.6).

As discussed in Section 2.4, IPCAs, or lands and waters over which Indigenous governments have primary authority (ICE, 2018), are key for advancing wetland conservation in Canada. IPCAs are also nation-to-nation agreements between the Crown and Indigenous governments (Indigenous Leadership Initiative, n.d.-a) that offer an opportunity to "achieve conservation and reconciliation concurrently" (Zurba *et al.*, 2019). However, the creation of IPCAs in regions where there is a low chance of wetland loss through development or mining would not be considered additional. In the Panel's view, in order for IPCAs to be as effective as freshwater NBCSs, they would need to be implemented in regions where industrial interests exist, such as the Hudson Bay Lowlands (Section 5.6).

An example of this is the Edéhzhíe National Wildlife Area and Dehcho Protected Area in the Northwest Territories. It comprises boreal forests and wetlands, and was declared an IPCA in 2018 (Galloway, 2018; Dehcho First Nations, 2018). In 2002, development was prohibited for eight years while the Dehcho First Nations negotiated for protection; however, in 2010, the federal government assessed belowground resources in the region and opened it up to mineral exploration.

A lawsuit followed, and the ruling declared that the government should not have allowed exploration without consultation; negotiations continued until the IPCA was officially established (Galloway, 2018). Although mines were never established on this land, the potential for wetland carbon to be lost was demonstrated.

Although three IPCAs have been created since 2018, there are challenges related to contrasting priorities among various stakeholders. For example, in May 2021, the Dene Tha' First Nation submitted an application for the development of an IPCA in the Cameron Hills (Nagah Y'i) of northwestern Alberta, covering thousands of hectares of wetlands, peatlands, and boreal forest, as well as Bistcho Lake (Mbecho) (Dene Tha' First Nation, 2021). The initiative sought to formally manage and conserve the vast wetlands in the area to "sustain balanced hydrological processes, and healthy, naturally sustaining wildlife populations," including numerous species-at-risk, such as the Bistcho caribou herd (Dene Tha' First Nation, 2021). However, the draft *Provincial Woodland Caribou Range Plan* released in April 2022 does not include any Indigenous-led conservation initiatives, despite unanimous recommendation from the two task force groups asked to provide input to the government (Gov. of AB, 2022a; Pedersen, 2022). The Dene Tha' First Nation and other conservationists voiced concern about the plan's allowances for further industrial development, including peat extraction and construction of permanent roads into the previously undisturbed region (Pedersen, 2022). "We found that we did not get what we needed and neither did the caribou, because the plan, at its heart, is a development plan," said Matthew Munson, a technician with the Dene Tha' First Nation at Bistcho Lake (Pedersen, 2022).

"Advancing Indigenous-led initiatives such as IPCAs will, through respecting and upholding communities' rights to land and water stewardship, also lead to the protection and enhancement of carbon sequestering systems."

Thus, the Panel notes that, at the heart of such land management disputes, rests the concept of and need for Indigenous land management. Advancing Indigenous-led initiatives such as IPCAs will, through respecting and upholding communities' rights to land and water stewardship, also lead to the protection and enhancement of carbon sequestering systems. As such, the following discussion about the potential of inland freshwater NBCSs is oriented around avoided conversion and restoration of ecosystems. However, it is critical to note that the primary goal of IPCAs is supporting Indigenous land rights; meeting GHG emissions reduction goals is secondary.

5.3 Magnitude of Sequestration and Emissions Reduction Potential

To determine the magnitude of the sequestration potential or emissions reduction potential of a freshwater system, both GHG fluxes and the area of opportunity (i.e., the area over which a practice can feasibly be implemented) must be estimated. When accounting for avoided emissions via the prevention of wetland conversion to other uses (e.g., mining, agriculture, peat extraction), fluxes for both undisturbed and disturbed sites must be understood. These differ widely, adding additional complexity to the task of estimating any gains made by restoration activities. Carbon fluxes in aquatic systems can be measured and extrapolated to cover larger areas, but decisions about the area of opportunity for an NBCS's implementation depend on judgments of feasibility. Understanding potential socioeconomic and technical barriers contributes significantly to developing realistic estimates of the area of opportunity.

5.3.1 GHG Fluxes in Wetlands

GHG fluxes in undisturbed wetlands are affected by many variables, and no single estimate can be made across wetland types

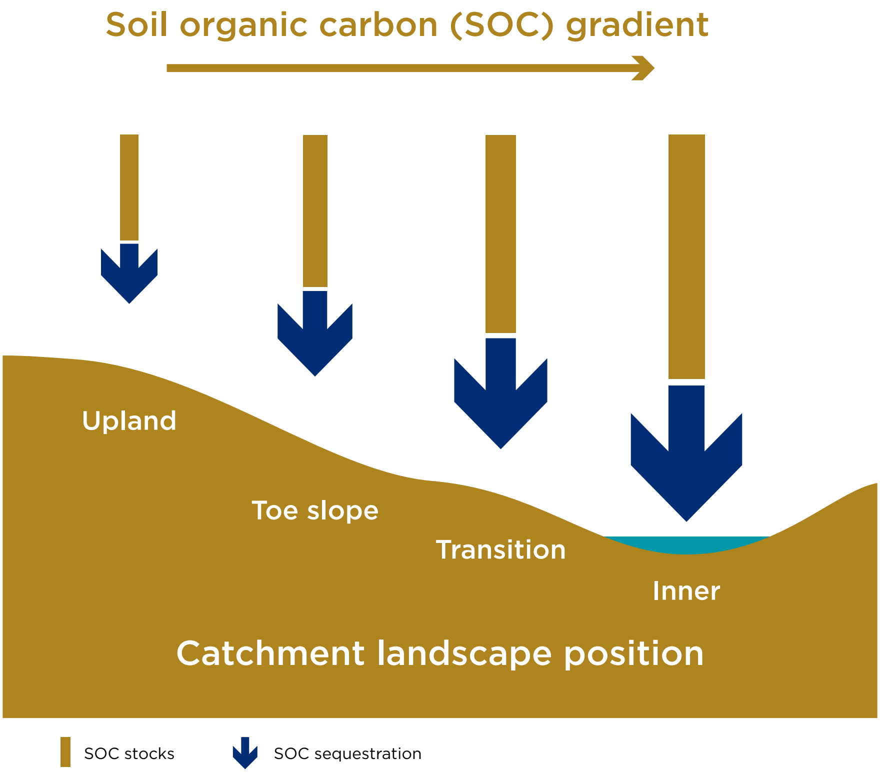
An accurate estimation of GHG fluxes is critical for calculating the sequestration potential of wetland NBCSs. In addition to CO_2 fluxes, it is also important to consider CH_4 and N_2O emissions from wetlands in order to understand the GHG balance. Around agricultural lands, runoff can lead to increased nitrogen load in wetlands and subsequent N_2O emissions (Tangen *et al.*, 2015; Tangen & Bansal, 2022) (Section 4.6.1). Significant research has been undertaken at a variety of intact, unrestored, and restored sites to catalogue the ranges in GHG fluxes and help guide conservation and restoration efforts (e.g. Waddington *et al.*, 2010; Badiou *et al.*, 2011; Strack *et al.*, 2016; Nugent *et al.*, 2018; Rankin *et al.*, 2018; Loder & Finkelstein, 2020; Tangen & Bansal, 2020).

Peatlands have a relatively well-known, long-term average rate of carbon accumulation (~0.23 t C/ha/yr), but regional (e.g., climate) and local (e.g., hydrological position in landscape) factors can influence the rate of carbon accumulation in individual peatlands (Loisel *et al.*, 2014). For example, peatlands in the permafrost region generally have lower rates of carbon accumulation than non-permafrost peatlands (Loisel *et al.*, 2021), while relatively dry conditions in warmer regions can lead to slower carbon accumulation (Charman *et al.*, 2015; Chaudhary *et al.*, 2017). At a local scale, adjacent beaver dams can raise and stabilize the water table of the peatland and increase the CO_2 uptake (Karran *et al.*, 2018). Peatland carbon accumulation rates also vary substantially from year to year, depending on weather conditions.

Peatlands are moderate sources of CH_4 (ranging from 0.01–0.15 t CH_4/ha/yr, or 0.45–6.75 t CO_2e/ha/yr), with generally lower emissions from bogs than fens (Treat *et al.*, 2018; Kuhn *et al.*, 2021). Wetland CH_4 emissions are primarily influenced by water table position, soil temperature, and vegetation composition; these factors are not independent of one another (Kuhn *et al.*, 2021). When considered over long timescales, the effect of CO_2 uptake dominates CH_4 emissions due to the shorter lifetime of CH_4 in the atmosphere; thus, peatlands in Canada have had a cooling effect on the climate (Frolking *et al.*, 2006). However, when peatlands are drained (e.g., for peat extraction), they become large emitters of CO_2, initially releasing ~16.3 t CO_2/ha/yr, then levelling off to ~7.9 t CO_2/ha/yr (Nugent *et al.*, 2019). In other words, every year post-drainage results in carbon losses that took ~70 years to accumulate.

The carbon balance of mineral soil wetlands is more variable than that of peatlands, owing to their large variability in the permanence of inundation (i.e., the length of time a wetland is flooded) (Bansal *et al.*, 2016). Dry periods allow for the decomposition of SOM (soil organic matter), thus marshes with greater permanence of inundation are generally found to have greater soil carbon storage. For example, freshwater marshes in wetter regions (e.g., Ontario) on average store significantly more carbon than marshes in the drier Prairie Pothole Region (1,420 ± 890 t C/ha and 62 t C/ha, respectively) due to their hydrological regimes (Byun *et al.*, 2018; Tangen & Bansal, 2020). Even within marshes, soil carbon storage is greater in the centre of the marsh than along the edges, which dry out more frequently (Figure 5.1). Research by Tangen and Bansal (2020) demonstrated that edges of wetlands sequester significantly less carbon than central areas, ranging from 0.35 t C/ha/yr (1.3 t CO_2e/ha/yr) for edges to 1.1 t C/ha/yr (4.04 t CO_2e/ha/yr) for inner basins (an average of 0.66 t C/ha/yr or 2.4 t CO_2e/ha/yr). Prairie Pothole Region marshes generally have high CH_4 emissions while they are inundated; after being drained, CH_4 emissions stop and atmospheric losses of CO_2 occur (Strachan *et al.*, 2015; Bansal *et al.*, 2016; Tangen & Bansal, 2020).

“Every year post-drainage results in carbon losses that took ~70 years to accumulate.”



Adapted with permission: Tangen and Bansal (2020)

Figure 5.1 Gradient of Soil Organic Carbon Storage by Landscape Position

Basins in the prairies were found to have differing soil organic carbon (SOC) storage, depending on the catchment landscape position. There are greater carbon stocks, and greater sequestration of SOC, in the inner areas of basins than the outer toe slope and upland areas.

Carbon fluxes in restored wetlands will be variable, and depend on the rapidity of restoration

Peatlands drained for horticultural peat extraction (or other uses, such as forestry and agriculture) decompose and release large amounts of CO_2 (Waddington & Price, 2000; Waddington *et al.*, 2010; Rankin *et al.*, 2018). Restoration, which re-establishes water level and reintroduces *Sphagnum* mosses, can revert the peatland into a CO_2 sink (Strack *et al.*, 2016). In some cases, however, it can take decades before the peatland turns from CO_2 source to sink. In Europe, peatlands re-wetted after extraction were found to be net sources of CO_2 after 29 years, but other sites restored 42 and 51 years prior became net sinks of CO_2 (Samaritani *et al.*, 2011). Another study in Canada demonstrated that peatlands restored after horticultural peat extraction resumed CO_2 sequestration within 14 years (Nugent *et al.*, 2018), which is within the timeframe for achieving the Government of Canada's goal to reach net-zero GHG emissions by 2050 (GC, 2021a). In order to yield higher certainty in the rates of carbon accumulation following restoration of various types of disturbance, investments in monitoring and data collection are critical (Section 5.5.3).

The timing of restoration is also significant. Excluding the carbon lost by removed peat, peatlands restored immediately after extraction were projected to attain pre-disturbance levels of carbon stocks 155 years earlier than those left unrestored for 20 years (Nugent *et al.*, 2019). These results highlight the damaging effects of abandoning drained peatlands that continue releasing CO_2. It is also important to note that, even with rapid restoration, the centuries to millennia of stored carbon lost to disturbance will never be regained (Noon *et al.*, 2022) (Section 2.1.5).

The long-term cooling benefits of peatlands outweigh short-term warming from CH_4 emissions

Climate change responses and long-term carbon balances are uncertain, and restored wetlands may not have the intended effect on emissions reductions when non-CO_2 emissions are considered. The balance between carbon sequestration and CH_4 emissions is a key trade-off when wetlands are restored, since the waterlogged conditions of most freshwater wetlands result in significant CH_4 emissions (Bansal *et al.*, 2016; Bieniada & Strack, 2021). In some restored peatlands, CH_4 emissions were found to be higher than in undisturbed, unrestored, and even actively mined sites (Bieniada & Strack, 2021). The magnitude of these emissions depends on several factors, including water-table depth and fluctuation, type of vegetation, soil temperature, and soil porosity (Bieniada & Strack, 2021). In other situations, restored mineral wetlands subject to fluctuating water levels may continue to emit CH_4 while never sequestering enough carbon to become a sink (Badiou *et al.*, 2011; Bansal *et al.*, 2016); the relationship between temperature and wetness is complicated, and further discussed in Section 5.4.3 in the context of future climate change. Peatlands converted to agricultural fields can also release N_2O when re-wetted and restored (Schrier-Uijl *et al.*, 2014).

Despite the trade-off between carbon sequestration and CH_4 emissions, researchers still advocate for the restoration of peatlands, because benefits (reducing long-lived CO_2 emissions impacts) can outweigh the relatively short-lived radiative effect of CH_4 (Lemmer *et al.*, 2020). Beyond balancing emissions and sequestration, considering other co-benefits makes restoration even more attractive (Section 5.6). Models of radiative forcing for northern peatlands have demonstrated that — although CH_4 emissions dominate in the first few decades of peatland formation, causing a net warming effect — increasing carbon sequestration will have a continuously increasing net cooling effect (Frolking *et al*., 2006).

5.3.2 GHG Fluxes in Reservoirs

There is significant uncertainty around measuring carbon fluxes in reservoirs

Recent data on the ratio between carbon emissions and burial in reservoirs indicate that reservoirs, globally, act as a net source of carbon to the atmosphere, with emissions of ~773 Mt CO_2e/yr (Deemer *et al*., 2016).[22] Much of these are in the form of CH_4 production and release from areas of high, long-term sedimentation (Maeck *et al*., 2013). Drawdown areas (where sediment is exposed) have been calculated to emit ~96.2 Mt CO_2/yr (~12% of total emissions), indicating a pool of preventable emissions (Keller *et al*., 2021). These estimates are subject to great uncertainty, however, because fluxes in freshwater systems remain difficult to measure and there is no single, widely agreed-upon accounting methodology for freshwater carbon measurements (Prairie *et al*., 2018). Nonetheless, a rough estimate of carbon emissions from Canadian reservoirs can be derived from GHG reservoir (G-res) model data; using an emissions rate of 3.9 t CO_2e/ha/yr, and an area of 5.4 Mha, Canadian reservoirs can be estimated to emit 21.1 Mt CO_2e/yr, most of which is in the form of CO_2 (Harrison *et al*., 2021). On average, it is estimated that about 69% of reservoir CO_2 emissions are sustained by allochthonous (i.e., external) organic inputs over the lifetime (100 years) of reservoirs (Prairie *et al*., 2021).

At the global scale, reservoirs have been shown to bury carbon at higher rates than natural lakes (Dean & Gorham, 1998), highlighting the potential role of water-level management in avoiding drawdown and associated emissions where possible, as well as the need to maintain the sediment within the reservoirs over longer timescales. However, no single estimate of carbon stored in reservoirs exists for Canada as a whole; this knowledge gap is compounded by the fact that carbon burial estimates tend to be poorly constrained and often provide data that do not take sediment focusing into account (i.e., the movement of sediment by water turbulence) (Anderson *et al*., 2020). Further uncertainty results from the issue of additionality. The amount of sedimented carbon that is rightfully considered an offset depends entirely on its origin, and on what its fate might have been in the absence of the reservoir (Prairie *et al*., 2018). Only sedimented

22 Conversion to CO_2e by Deemer *et al.* (2016) used an emissions factor of 34 for CH_4 and 298 for N_2O.

carbon that would have otherwise not been stored can be considered a carbon offset — anything else is simply carbon burial that has been displaced. Ensuring that estimates of sedimented carbon are additional is complex and can be considered another significant knowledge gap needing to be addressed (Prairie *et al*., 2018).

5.3.3 Areal Extent and Area of Opportunity for Wetlands

Although the mapping of peatland extent has improved in recent years (e.g., Hugelius *et al*., 2020; Olefeldt *et al*., 2021), detailed knowledge of peat depth, peatland type, and disturbed areas on a local level is more uncertain (Harris *et al*., 2022). A lack of adequate mapping data is especially problematic for mineral wetlands; Loder and Finkelstein (2020) highlighted the lack of publicly available reports on the areal extents of freshwater marshes and other mineral wetlands, which are critical components for determining the area of opportunity for conservation. In addition, knowledge of the extent of drained wetlands, especially marshes, is lacking. In the Prairie Pothole Region, estimates of wetland loss range from 40–90% (Rubec, 1994; GC, 1996; Watmough & Schmoll, 2007; DUC, n.d.). which restricts the ability to determine the area of opportunity of wetland restoration beyond no-net-loss. Changes in wetland extent and permanence are also dependent on long-term precipitation trends, which will be affected by climate change (McKenna *et al*., 2017).

The area of opportunity for avoided conversion crucially depends on judgments about the future of resource extraction in peatlands (e.g., mining, peat, oil and gas), including associated disturbances such as roads, seismic lines, well-pads, drainage for agricultural lands or forestry, and other land uses. Extrapolating from past trends is one method of determining the area of opportunity, but it is difficult to say how future demands for oil and gas, minerals, and horticultural peat will change. The area of opportunity for restoration will be constrained by feasibility considerations to do with costs, policies, and technical barriers, as well as certain behavioural barriers (Section 5.5.4).

5.3.4 Areal Extent and Area of Opportunity for Reservoirs

Although no published estimates for the number or areal extent of Canadian reservoirs exist, information extracted from the Global Reservoir and Dam Database (GRanD) provides an estimate of 229 reservoirs with volumes of 100,000 km^3 or greater (excluding Lakes Ontario and Winnipeg), covering a total of about 5.4 Mha (Lehner *et al*., 2011; GDW, n.d.). This uncertainty contributes to an inability to calculate the magnitude of sequestration potential of implementing water-level management in reservoirs.

5.3.5 Estimating National Sequestration Potential for Wetlands

Regarding the potential of wetland restoration and avoided conversion in Canada, the most comprehensive estimates of carbon sequestration potential come from Drever *et al.* (2021). This study considered both organic and mineral soil wetlands and provided estimates of sequestration potential at a variety of price points out to 2030 and 2050. Table 5.2 summarizes these findings.

Table 5.2 Freshwater Wetland NBCSs Sequestration Potential, as Estimated by Drever *et al.* (2021), and Panel Confidence

<table>
<tr><th>Type of NBCS</th><th colspan="2">Additional Sequestration Potential (Mt CO_2e/yr)</th><th colspan="2">Panel Confidence</th></tr>
<tr><th></th><th>Now to 2030</th><th>2030 to 2050</th><th>Flux</th><th>Area of Opportunity</th></tr>
<tr><td>Avoided conversion of peatlands (horticultural peat extraction)</td><td rowspan="2">10.1 (2.2 to 29.7)</td><td rowspan="2">3.7 (0.9 to 10.3)</td><td>Moderate</td><td>Moderate</td></tr>
<tr><td>Avoided conversion of peatlands (oil and gas extraction, mineral mining)</td><td>Moderate</td><td>Limited</td></tr>
<tr><td>Avoided conversion of mineral wetlands</td><td>3.1 (0.5 to 5.7)</td><td>0.0 (-3.5 to 0.4)</td><td>Moderate</td><td>Limited</td></tr>
<tr><td>Avoided conversion TOTAL</td><td>~13.2</td><td>~3.7</td><td>Moderate</td><td>Limited</td></tr>
<tr><td>Restoration of peatlands (horticultural peat extraction)</td><td>0.2 (-0.3 to 0.7)</td><td>0.2 (0.0 to 0.8)</td><td>Moderate</td><td>High</td></tr>
<tr><td>Restoration of peatlands (oil and gas extraction, mineral mining)</td><td></td><td></td><td>Limited</td><td>Moderate</td></tr>
<tr><td>Restoration of mineral wetlands</td><td>0.4 (-1.6 to 2.4)</td><td>0.4 (-1.6 to 2.4)</td><td>Limited</td><td>Moderate</td></tr>
<tr><td>Restoration TOTAL</td><td>~0.6</td><td>~0.6</td><td>Limited</td><td>Moderate</td></tr>
</table>

Data source: Drever *et al.* (2021)

The Panel has indicated its level of confidence in these estimates by providing ratings for both the GHG flux and area of opportunity used by Drever *et al.* (2021) to calculate the mitigation potential. See the Appendix for Panel confidence scale. Includes estimates for both organic (peatland) and mineral soil wetlands. Estimates originally reported as Tg CO_2e/yr.

Drever *et al.* (2021) based their undisturbed peatland flux estimates on Webster *et al.* (2018), resulting in a mean uptake (±SD) of 0.78 ± 3.74 t CO_2/ha/yr for bogs and 0.34 ± 2.65 t CO_2/ha/yr for fens. Similarly, they adjusted the values for CH_4 flux from Webster *et al.* (2018) to reflect more real-world measurements for non-growing season flux, based on Saarnio *et al.* (2007), culminating in estimates of 0.06 ± 0.08 t CH_4/ha/yr for bogs and 0.08 ± 0.1 t CH_4/ha/yr for fens. In the Panel's view, these values are similar to other measurements from peatlands and are likely representative of undisturbed fluxes.

To estimate the extent of peatlands at risk of being disturbed, Drever *et al.* (2021) combined data on the magnitude of annual peat extraction for horticultural purposes with land-use change information from the Wall-to-Wall Human Footprint Inventory and Canada's *National Inventory Report* for mining, road, and seismic-line disturbances. This resulted in an estimate of 11,069 ha/yr of peatlands at risk. Drever *et al.* (2021) incorporated estimates for peatlands at risk from conversion to settlement derived from the assumption that 30% of the forest-to-settlement change category in the *National Inventory Report* is representative of real-world values. However, the peatland areas at risk for disturbance depend on the assumption that the past rate of peatland disturbance will remain unchanged. For example, determining the rate of peatland conversion to mine area relied on Alberta-specific data from 2010–2017; this trend may not hold to 2030 and beyond. Future demand for materials is tied to many socioeconomic factors, which increases uncertainty over the extent of peatland disturbance and, with it, the area of opportunity for avoided conversion.

For restoration of peatlands following horticultural peat extraction, Drever *et al.* (2021) used the total area of peatlands currently or previously affected (~34,000 ha) from the *National Inventory Report* and assumed 3,400 ha would be restored per year for 10 years. This, however, ignores regulations stipulating that companies must restore peatlands to their previous conditions, implying that at least some of the calculated area of opportunity is not additional. This is further complicated by certain provincial regulations allowing companies to restore to alternative land uses (e.g., Alberta and New Brunswick), and by the relatively recent establishment of some policies (2015 and 2016 in Manitoba and Alberta, respectively), meaning that any peat extraction prior to this did not mandate restoration (Gov. of NB, 1991; Gov. of MB, 2014; Gov. of AB, 2016). Furthermore, in New Brunswick, although the law requiring restoration has existed since 1991, it only applies to Crown land, which comprises 70% of peatland viable for extraction, with no laws pertaining to private land (Gov. of NB, n.d.). Thus, it is difficult to determine precisely how much of the proposed area of opportunity calculated by Drever *et al.* (2021) would not be additional. Furthermore, once a peatland area has been opened for extraction, it can be used for several decades before all harvestable peat is depleted. In the Panel's view, the 10-year timeframe for complete restoration seems short, as many current fields may not be depleted within 10 years.

For restoration following mining activities (including oil and gas extraction), Drever *et al.* (2021) assumed that activity would be minimal between 2021 and 2030 and therefore did not include it. This ignores legislation stating companies have an obligation to restore (e.g., in Alberta); however, if this practice were being followed already, such an activity would not be considered additional. Further complication arises when considering the technical difficulty of restoring wetlands in regions with extensive mining and their ability to resume carbon sequestration (Section 5.5.4). The Panel notes that some extraction activities leading to lesser impacts — compared to complete peatland loss when mines are established (e.g., well-pads, seismic lines, access roads) — may be more feasible to restore to a carbon-accumulating ecosystem.

To estimate the avoided loss of SOC following drainage of mineral wetlands, with loss occurring evenly over 20 years, Drever *et al.* (2021) used a rate of 16.3 t CO_2e/ha/yr over 20 years based on Badiou *et al.* (2011). When extending beyond 20 years to 2050, a long-term sequestration rate of 5.7 t CO_2e/ha/yr based on rates from Loder and Finkelstein (2020) was used to account for the ongoing presence of wetlands. This may be an overestimate; the rates of sequestration determined by Tangen and Bansal (2020) are also less than half of those determined by Badiou *et al.* (2011) (2.4 t CO_2/ha/yr and 9.9 t CO_2/ha/yr, on average, respectively), indicating significant uncertainty in the magnitude of wetland sequestration potential in the Prairie Pothole Region (PPR). To account for CH_4 emissions in avoided conversion, Drever *et al.* (2021) used an emissions factor of 136 kg CH_4/ha/yr for natural temperate wetlands from IPCC (2014b). They then applied flux values, derived from the PPR, to the perceived area of opportunity for avoided conversion across Canada. In the Panel's view, this is a key uncertainty, which may underestimate the potential for carbon loss from other regions, such as the Great Lakes, which may store much more carbon per area at risk (e.g., Loder & Finkelstein, 2020).

When calculating the area of opportunity for the implementation of avoided mineral wetland conversion, Drever *et al.* (2021) focused primarily on freshwater marshes in the PPR. They assumed that wetlands bordered by croplands on at least 65% of their edges would be most at risk of conversion to agricultural lands, totalling 355,813 ha. To account for mineral wetlands at risk of conversion outside of the PPR, Drever *et al.* (2021) considered 24% the PPR area (84,210 ha), resulting in a national estimate of ~440,023 ha. In the Panel's view, the process for assessing the area of opportunity is highly uncertain and dependent on the location of the wetland; the actual area of at-risk wetlands close to expanding urban areas may be higher than accounted for, whereas wetlands in agricultural regions may not actually be highly vulnerable to drainage, given their continued existence through the intensification of drainage in the 1960s, 1970s, and 1980s.

For restoration of mineral wetlands, Drever *et al.* (2021) used 2.2 ± 0.5 t C/ha/yr (8 ± 1.8 t CO_2e/ha/yr) as the annual increase of sequestration for 40 years following restoration, and an emissions factor of 0.315 t CO_2e/ha/yr for avoided emissions from croplands that would occur without restoration, based on the Agricultural Greenhouse Gas Indicator from Agriculture and Agri-Food Canada. The former value is less than that given by Badiou *et al.* (2011), but not as low as that found by Tangen and Bansal (2020). This is especially important when considering CH_4 emissions. Drever *et al.* (2021) subtracted CH_4 emissions based on an emissions factor of 153 ± 76 kg CH_4/ha/yr for the first 40 years post-restoration, then the emissions factor for natural temperate wetlands from IPCC listed above. The Panel notes that, if the sequestration of CO_2 is closer to the values calculated by Tangen and Bansal (2020), then the CH_4 emissions in that same time period may not result in overall net climate cooling, instead conveying a short-term warming effect to restored wetlands in the PPR. As with peatlands, the warming effect of CH_4 emissions may initially overwhelm lower CO_2 gains but, over time (decades to centuries), this will shift to a net cooling (even if annual fluxes remain unchanged).

Evaluations of sequestration potential can also be aided by global estimates. An assessment of the potential for NBCSs to mitigate climate change by Roe *et al.* (2021)[23] projected that, between 2020 and 2050, the avoided conversion of peatlands in Canada could prevent the release of 199 Mt CO_2e/yr (134 Mt CO_2e/yr at <US$100/t), and that restoration could sequester a further 25 Mt CO_2e/yr (23 Mt CO_2e/yr at <US$100/t). This substantial deviation from Drever *et al.* (2021) (Table 5.2) likely results from an overestimation of the area of opportunity for avoided conversion. To determine the country-level magnitude of sequestration potential, Roe *et al.* (2021) used peatland degradation and restoration modelling by Humpenöder *et al.* (2020), who estimated future peatland dynamics based on projected changes in agriculture and forestry. Since most land-use change in Canada affecting peatlands is related to horticultural peat extraction and mining, these results do not apply as well to the Canadian context. Furthermore, when determining the technical magnitude for restoration, Roe *et al.* (2021) assumed that all degraded peatlands will be re-wetted. This may be unrealistic for Canada, due to the difficulties in restoring peatlands degraded by mining (Section 5.5.4).

23 To convert non-CO_2 gases into CO_2e, Roe *et al.* (2021) used GWP100 values from IPCC (2014a), where CH_4=28 and N_2O=265.

5.3.6 National GHG Mitigation Potential for Lakes and Reservoirs

The national sequestration potential of NBCSs involving other water bodies, such as lakes and reservoirs, is unknown — no research has been conducted on the potential of water-level management on a Canada-wide scale. The uncertainties detailed above contribute to this gap, and although there is potential for these NBCSs in the future, further research is warranted to understand their benefits. As a result, the strongest role that lakes and reservoirs can play in GHG mitigation involves reducing the magnitude of their GHG emissions, particularly CH_4, through nutrient-load management.

5.4 Stability and Permanence

5.4.1 Sustained Sequestration in Wetlands

The effects of future climate change are uncertain for both permafrost and non-permafrost peatlands. Some studies predict that non-permafrost peatlands that remain undisturbed will likely continue to sequester carbon for the long term in "all but the very worst climate change scenarios" (Qiu *et al.*, 2020) while others model a switch from sinks to sources in regions with reduced precipitation (Chaudhary *et al.*, 2017). In permafrost zones, colder climates that would normally impede peat production are modelled to become warmer and wetter, increasing productivity (Chaudhary *et al.*, 2017).

The long-term sustained carbon sequestration ability of restored mineral wetlands is lesser than that of peatlands, but likely also more variable and dependent on local hydrological conditions (Tangen *et al.*, 2015). Once carbon sequestration ability has been restored, the carbon dynamics of marshes in the PPR will likely be driven by changes in precipitation and temperature (Millett *et al.*, 2009; Werner *et al.*, 2013). Given the influence of hydrology on the rate of accumulation and total soil carbon storage, it is difficult to verify, monitor, and scale up the amount of CO_2 that can be taken up.

5.4.2 Sustained Emissions Reduction in Reservoirs

The reduction of emissions from reservoirs through water-level management is still untested, and therefore the ability of this intervention to sustainably reduce emissions is unknown. However, efforts to reduce eutrophication in reservoirs and lakes have the potential to greatly reduce emissions of CH_4 from aquatic systems (Section 5.1). Eutrophic reservoirs (i.e., high nutrients, low oxygen) emit, on average, about 15 times more CH_4 than oligotrophic ones (i.e., low nutrients, high oxygen) (Lovelock *et al.*, 2019).

5.4.3 Permanence of Carbon in Wetlands

Carbon sequestered in freshwater wetlands is vulnerable to climatic change

The permanence of carbon stocks in wetlands is a critical consideration for the implementation of wetland NBCSs, since the value of avoided conversion depends on the future ability of those saved wetlands to continue to accumulate or store carbon. The changing climate poses several threats to carbon pools stored in freshwater wetlands through impacts on water balance, growing season, permafrost thaw, and wildfire.

Warming will increase the growing season length, encouraging plant productivity that, in turn, may also increase sink potential (Charman *et al.*, 2013); however, rising temperatures may also spur increased microbial activity in wetlands, resulting in greater production of CH_4 and CO_2 (Yvon-Durocher *et al.*, 2014; Knox *et al.*, 2020). Permafrost thaw in some peatlands may accelerate the anaerobic decomposition of organic material in these soils, producing CH_4, though ranges of present-day CH_4 emissions values are still ill constrained, adding to the uncertainty in estimating future CH_4 flux (Tarnocai *et al.*, 2009; Olefeldt *et al.*, 2021). In contrast, enhanced plant growth (spurred by warmer temperatures and longer growing seasons) may result in increased carbon uptake (Zhu *et al.*, 2016), but there is little agreement among experts about expected biomass changes (Abbott *et al.*, 2016).

Responses to thaw have also been proposed to vary by region; analysis of a series of peat cores in western Canada demonstrated that carbon losses post-thaw (over 200 years) were offset by rapid peat accumulation during the same period (Heffernan *et al.*, 2020). This study concluded that there was no long-term net impact of permafrost thaw on carbon stocks, in contrast to other studies that found either rapid losses of carbon, or rapid uptake post-thaw (Heffernan *et al.*, 2020). Regional response variation is therefore a critical consideration when attempting to predict the effects of future warming on permafrost peatlands, and the assessment of potential gains from implementing avoided conversion or restoration in these regions.

In peatlands, future reductions in water-table depth may result in further declines in vegetation while increasing susceptibility to wildfires (Thompson *et al.*, 2019). Changes in fire frequency and intensity are expected to have a considerable impact on peatlands, increasing carbon emissions from immediate combustion as well as through continued emissions post-fire, until the peatland can re-establish vegetation and carbon sink processes (Wieder *et al.*, 2009). Weather conducive to extreme fire has been increasing in recent decades due to decreasing humidity and rising temperatures, and this trend is expected to continue (Jain *et al.*, 2022).

Increased risk of drought will affect the ability of wetlands to store carbon; more frequent droughts in the southern prairies and the B.C. interior will lead to soil drying and subsequent decomposition of the existing carbon stock, affecting restoration activities focused around carbon sequestration (Bush & Lemmen, 2019). The flux of CH_4 in PPR marshes is also affected by both temperature and moisture. Bansal *et al.* (2016) found that rising water depth and temperature contributed to increased CH_4 emissions, with the largest effects observed under both warmer and wetter conditions. Drying has the opposite effect, reducing CH_4 emissions but, in the case of ephemeral wetlands, also resulting in CO_2 emissions, complicating projections for the carbon balance of these wetlands in a changing climate (Badiou *et al.*, 2011; Bansal *et al.*, 2016). Changes to the vegetation composition of wetlands can also have a strong influence on CH_4 emissions, particularly in seasonal wetlands (Emilson *et al.*, 2018; Bansal *et al.*, 2020). Fluxes of N_2O are similarly affected by moisture, where exposed wetland soils were found to emit significantly more N_2O than inundated ones (Tangen & Bansal, 2022).

Uncertainty about how vegetation and hydrology will react to future climate change poses challenges for effective wetland restoration

There are challenges associated with quantifying how various species will respond to future temperature and precipitation changes, and how, in turn, ecosystems can be restored and become resilient to these changes (Harris *et al.*, 2006; Hobbs *et al.*, 2009; Chimner *et al.*, 2017). When restoring wetlands, a key question is whether to return a wetland to historical conditions or restore it to a novel state by employing alternative plant communities or hydrological regimes better adapted to future climatic conditions (Harris *et al.*, 2006; Wiens & Hobbs, 2015). Palaeoecological reconstructions of past species compositions during warmer periods may help guide decision-making in this sphere (Gorham & Rochefort, 2003).

5.4.4 Permanence of Carbon in Lakes and Reservoirs

Carbon emissions from lakes and reservoirs will likely be affected by rising temperatures

Climate warming will affect the fluxes of CH_4 from lakes, as CH_4 production is particularly dependent on temperature (Yvon-Durocher *et al.*, 2014; Rasilo *et al.*, 2015; DelSontro *et al.*, 2016). Climate warming will also alter the temperature regime of lakes: a longer thermal stratification period will increase the likelihood of anoxia in the deepest layer and favour larger CH_4 accumulation and its potential release at fall turnover (Zimmerman *et al.*, 2021). The extent and magnitude of this phenomenon is still contested (Zimmerman *et al.*, 2021).

There is uncertainty surrounding the permanence of carbon storage in reservoirs depending on sediment management strategies. It is also likely that sediment mineralization rates may accelerate overall in the coming decades due to rising temperatures, thereby increasing emissions (Prairie *et al.*, 2018; Harrison *et al.*, 2021). Research has suggested that rising temperatures enhance primary production in eutrophic reservoirs, potentially leading to anoxic conditions and higher rates of CH_4 emissions; however, further research is needed to substantiate this effect (Harrison *et al.*, 2021). Actions to reduce emissions, such as water-level management, could theoretically help to mitigate some of these emissions, but there is little evidence to support (or refute) the effectiveness of appropriately managed reservoirs, particularly in cold climates such as Canada, where deep water CH_4 rarely reaches high levels.

5.5 Feasibility

The feasibility of NBCSs in freshwater systems depends on many variables, though costs and policy considerations are the most significant. Monitoring the effectiveness of NBCSs once implemented (i.e., accounting for carbon) poses further challenges with respect to feasibility. The Panel notes that, since water-level management in reservoirs has not yet been implemented in Canada or even globally, there is a lack of information on the potential costs or policy barriers associated with this particular NBCS, hindering a full discussion of the feasibility of water-level management in reservoirs.

5.5.1 Inland Freshwater Ecosystem NBCS Costs

Determining the costs associated with avoided wetland conversion and restoration is critical for assessing the feasibility of any NBCS. Avoided conversion costs will comprise primarily opportunity cost — stemming from the forgone returns associated with the new land use — while restoration costs will rest on opportunity, maintenance and engineering, and nuisance costs (Yang *et al.*, 2016; Drever *et al.*, 2021) (Section 2.3.1). These costs may, in turn, be affected by the level of degradation in a wetland and the choice of restoration method.

Costs for conserving and restoring wetlands are often prohibitive under current policies and carbon-pricing schemes

Drever *et al.* (2021) estimated that peatland loss through horticultural peat extraction could not be avoided at $100 or less per t CO_2e, with an average marginal abatement cost (MAC) of $363.42 calculated by Cook-Patton *et al.* (2021). The costs of avoided conversion for other types of disturbance, including mining, seismic lines, and roads, were not calculated; however, in the Panel's view, this exercise is still worthwhile, since the energy sector can spatially substitute some activities, preserving soil organic stock in valuable peatland soils (e.g., Hauer *et al*., 2018). A study by Hauer *et al.* (2018) demonstrated a methodology for constructing implicit land values associated with energy sector activities in order to calculate the net-present-value loss associated with reduced use that would be necessary to achieve caribou conservation in Alberta. This study was based on maps and calculations for valuing natural gas, conventional oil, bitumen, and forestry resources, and used two different price regimes to reflect the impact that world energy prices would have on the implicit land values (Hauer *et al*., 2010, 2018). This methodology demonstrates the potential for constructing implicit land values but, in the Panel's view, would require refining and further research to be applied to wetland NBCSs.

Since peat extraction takes place on both private and public land, Drever *et al.* (2021) assumed that the cost of conservation would need to cover lost income to peat mining companies as well as lost tax revenues and government royalties; the final per-hectare present value of peatlands was estimated at $217,000. According to the analysis in Drever *et al.* (2021), "carbon prices in excess of CAD $1,560/t CO_2e (2030 horizon) and $550/t CO_2e (2050 horizon) would be required to achieve competitiveness with peat extraction." The Panel notes, however, that the cost functions used for horticultural peat extraction are derived from a 1999 study that may not reflect present-day costs; further, it is only based on one operation in New Brunswick (Dufournaud *et al*., 1999) and then applied uniformly across the area of opportunity. These costs are therefore highly uncertain in the Panel's view and point to a lack of available data on the operating costs and land values used for horticultural peat extraction across Canada. For peatland restoration following peat extraction, Drever *et al.* (2021) estimated average restoration costs at $3,750/ha using data from the Canadian Sphagnum Peat Moss Association. After applying discounts for carbon mitigation, the authors determined that only 0.06 Mt CO_2e/yr of mitigation would be available at $100/Mt CO_2e or less, with the average MAC calculated at $403.15 (Cook-Patton *et al*., 2021).

In contrast, Roe *et al.* (2021)[24] estimated that avoided conversion of Canadian peatlands between 2020 and 2050 could provide 134 Mt CO_2e/yr at <US$100/t, and that restoration could sequester a further 23 Mt CO_2e/yr at <US$100/t. These are likely overestimates —Roe *et al.* (2021) relied on modelling by Humpenöder *et al.* (2020), which assumed that land-use change for peatlands is dominated by agriculture, pasture, and forestry conversion. This may be the case in other countries, but most modern peatland degradation in Canada comes from horticultural peat extraction and removal for mining and related activities (Harris et al., 2022). Lost revenue and land values for mining and peat extraction far outstrip the values for avoided conversion and restoration estimated by Humpenöder *et al.* (2020), which Roe *et al.* (2021) used to determine the cost-effective mitigation potential.

Drever *et al.* (2021) estimated that avoided conversion of mineral wetlands could be achieved at $50 or less per t CO_2e (mean MAC of $29.19) (Cook-Patton *et al.*, 2021). Conversely, a case study by Asare *et al.* (2022) from Alberta calculated the cost of avoided conversion to be $187/ha/yr or $2,404/ha (at net present value); this deviation from Drever *et al.* (2021) may stem from their use of 2011 land values. Asare *et al.* (2022) also concluded that there is a high level of heterogeneity in opportunity costs across the watershed, and that larger avoided conversion costs are correlated with the greatest environmental benefits. This has implications for policies, suggesting that conserving those wetlands with the lowest opportunity costs will not necessarily convey high benefit. In other words, not all wetlands are equal in the benefits they provide. The values for avoided conversion of mineral wetlands vary significantly from those estimated for avoided conversion of peatlands; this stems from the much higher costs of lost revenue for both peat extraction and mining on peatlands. The avoided conversion of mineral wetlands to agricultural uses is therefore a more cost-effective NBCS per hectare, though the volume of carbon stored in these marshes is also significantly less. Estimates of mitigation potential by Drever *et al.* (2021) assumed that 29,335 ha/yr of mineral wetlands are at risk of conversion, therefore making the area of opportunity for avoided conversion of mineral wetlands greater than that of peatlands (11,069 ha/yr), as well.

24 To convert non-CO_2 gases into CO_2e, Roe *et al.* (2021) used GWP100 values from IPCC (2014a), where CH_4=28 and N_2O=265.

Regarding mineral wetlands, a high mean MAC (\$496.80/t CO_2e) largely stemming from habitat management costs (\$278/ha/yr) precluded restoration as a feasible pathway below \$100/t CO_2e when only the value for carbon is included (Cook-Patton *et al.*, 2021; Drever *et al.*, 2021). This estimate ignores the economic implications of co-benefits, which have been demonstrated to be significant, especially for wetlands in the PPR. For example, Gascoigne *et al.* (2011) modelled a social welfare loss of over US\$4 billion when considering the benefits of native prairie elements (including grasslands and wetlands) in the PPR of North and South Dakota. However, there are few economic valuation studies on the ecosystem services of Canadian prairies, making it difficult to calculate the true costs of marsh retention and restoration in the context of co-benefits (Lloyd-Smith *et al.*, 2020).

Other studies provide cost breakdowns for restoring wetlands in the PPR. Yang *et al.* (2016) modelled annual economic costs for wetland restoration in the South Tobacco Creek watershed of Manitoba, arriving at an overall cost range between \$20.90/ha/yr and \$409.90/ha/yr, with an average of \$132.40/ha/yr. The driving components for cost were the forgone agricultural returns, due to variations in productivity across the landscape (Yang *et al.*, 2016). Beyond the restoration of hydrology, there are also concerns about returning appropriate vegetative communities to wetlands, which can incur even greater costs. Strehlow *et al.* (2017) implemented three wetland vegetative restoration methods in North Dakota and found that the more components were included, the costlier it became, ranging from US\$1,909–5,072/ha. Conversely, additional vegetation components have led to higher biodiversity and fewer invasive species five years after marsh restoration (Salaria *et al.*, 2019); weighing the costs against co-benefits beyond carbon sequestration is an important consideration for decision-makers.

5.5.2 Policy and Regulatory Challenges

Due to the high costs of wetland restoration and retention, government policies are a critical pathway for implementing these NBCSs. Such policies can focus on minimizing disturbances to peat stocks, maintaining existing carbon stocks, and supporting the restoration of wetlands on the local scale (Harris *et al.*, 2022). Due to the long-term nature of most wetland restoration activities, policy mechanisms to preserve existing carbon stocks held in wetlands will be crucial land-use strategies for minimizing carbon emissions in the coming years (Harris *et al.*, 2022). Existing policies around wetland conservation and restoration, however, may fall short of providing the desired effects; restoration of peatlands damaged through oil and gas extraction may not succeed in reinstating carbon sequestration functioning (Section 5.5.4), and the concept of *compensatory restoration*, as a component of no-net-loss policies, does not account for irrecoverable carbon losses in certain regions (see below).

No-net-loss policies rely too heavily on offsetting, bypassing avoidance measures and losing valuable wetland area in the process

The mitigation sequence of "avoid, minimize, and compensate" is commonly used in North America, most notably in the no-net-loss strategy employed in the United States and Alberta. Despite being the first word in this sequence, research has demonstrated that avoidance of impacts is largely ignored in favour of compensation for wetland loss after the fact (Race & Fonseca, 1996; Hough & Robertson, 2009; Clare *et al.*, 2011). Seeking to explain this pattern, the literature review and key-informant interviews conducted by Clare *et al.* (2011) found:

> *(1) a lack of agreement on what constitutes avoidance; (2) current approaches to land-use planning do not identify high-priority wetlands in advance of development; (3) wetlands are economically undervalued; (4) there is a "techno-arrogance" associated with wetland creation and restoration that results in increased wetland loss, and; (5) compensation requirements are inadequately enforced.*

This is a critical gap in governance; to achieve net-zero emissions and keep rising temperatures below 2°C, preserving existing wetlands, especially peatlands, is necessary to avoid emissions. Increasing wetland area elsewhere as a compensatory action to wetland loss will not replace the lost carbon and may also not adequately provide other intended ecosystem services; Taylor and Druckenmiller (2022) found no discernible effect of wetland area increases on flood insurance claims, possibly indicating that created wetlands do not offer the same flood protection service as conservation of intact ones. If existing legislation does not prioritize avoidance as a strategy to mitigate wetland loss, the intended benefits of wetlands may be lost.

> "If existing legislation does not prioritize avoidance as a strategy to mitigate wetland loss, the intended benefits of wetlands may be lost."

Weak policy enforcement harms wetland protection and restoration

Even wetlands currently designated for protection can be at risk. In 2020, for example, the Government of Ontario issued a ministerial zoning order allowing development on the Duffins Creek wetland in Pickering (Crawley, 2021). When environmental groups launched a lawsuit in response, the provincial government proposed amendments to Ontario's *Planning Act* to remove a clause limiting the scope of ministerial zoning orders (Crawley, 2021). As a result, all remaining freshwater mineral wetlands in southern Ontario are at a relatively high risk of conversion and could be considered as such when calculating the mitigation potential of conservation. To put it in context, modelling by Byun *et al.* (2018) indicated that the remaining 138,100 ha of intact marshes store 196 (±123) Mt C, a significant carbon pool in non-peatland wetlands outside of the PPR. This area of opportunity far exceeds the estimate by Drever *et al.* (2021).

5.5.3 Monitoring and Accounting

Canada's current GHG inventory does not adequately account for wetland losses

Canada only accounts for wetland losses due to horticultural peat extraction; the loss of forested peatlands exploited for mining or oil and gas extraction is considered to be deforestation (ECCC, 2022b). Deforestation losses do not factor in organic soil loss, thus masking the true carbon cost of peatland damages (ECCC, 2022b; Harris *et al.*, 2022; UNFCCC, 2022). The national GHG inventory therefore does not account for many human-driven disturbances to peatlands, and there is no policy mechanism to account for GHG fluctuations in peatlands outside of human influences (Harris *et al.*, 2022). This lack of reporting "in the national GHG inventory is hindered by a lack of [records for] the total area of disturbed peatland across Canada, and [it is likely that] total GHG emissions from disturbed peatlands are [...] much greater than those presently accounted for" (Harris *et al.*, 2022).

Long-term monitoring of restored wetlands is critical to understanding restoration success and informing future restoration initiatives

Success for wetland restoration can be assessed through a variety of metrics such as the return of natural vegetation, hydrological processes, peat accumulation, or even fulfillment of policy mandates. Regardless of the choice of metric, long-term monitoring of restored wetlands is required to understand whether a wetland is on the correct pathway to regain carbon sequestration ability (Ketcheson *et al.*, 2016). This information is critical to recognizing the manner in which these systems may change in the future, in order to better guide any further adjustments. For example, reconstructed wetlands in regions such as the Athabasca oil sands in Alberta are subject to unique conditions stemming from mining by-products and processes, including changes in substrate composition, hydrology, salinity, vegetal composition, and others (Biagi *et al.*, 2019, 2021).

Continuous, long-term monitoring is essential to understanding these effects and how they may change over time (Nwaishi *et al.*, 2016). Some key components of a monitoring system include an assessment of the region's substrate and topography to better predict the results of restoration; monitoring evapotranspiration due to its critical role in the functioning of wetlands, achievable through installation of eddy covariance (i.e., in situ atmospheric gas measurement) towers; and long-term groundwater monitoring to assess changes outside of the decadal wet-dry cycles that dominate the Athabasca oil sands regional climate. Each of these tools is valuable for understanding hydrologic responses to anthropogenic changes (Volik et al., 2020).

"Understanding the natural, disturbed, and restored carbon balances across different climatic regions and among various hydrological settings is key to determining the ability of NBCSs to accumulate and store carbon in the future."

Given the currently large uncertainty of the rate of carbon accumulation in both undisturbed and disturbed wetlands, substantial effort would need to be put toward establishing monitoring networks to fully understand the outcome of conservation and restoration actions in terms of GHG emissions. Infrastructure such as flux measurement towers comes with a high cost for both establishment and maintenance and can act as a barrier to collecting critical data for determining carbon exchange in various NBCSs (Novick *et al.*, 2022). In the Panel's view, the issue of monitoring goes beyond restoration activities and ties in with the large variability in carbon balance for both peatlands and mineral wetlands (Section 5.3). Understanding the natural, disturbed, and restored carbon balances across different climatic regions and among various hydrological settings is key to determining the ability of NBCSs to accumulate and store carbon in the future. Calculating the net gains of NBCS implementation is critical, especially for assessing the accounting of avoided peatland conversion.

5.5.4 Other Barriers to NBCS Implementation

Ecological and hydrological complexities constrain the ability to restore certain wetland types, as do certain types of disturbance

Ease of restoration varies significantly among classes of wetlands. For example, the rain-fed nature of bogs means that water movement is generally low-energy, making ditch restoration easier (Chimner *et al.*, 2017). In contrast, fens, which are fed by groundwater or surface water, can be sloped (sometimes steeply), making it more difficult to restore ditches (Schimelpfenig *et al.*, 2014; Chimner *et al.*, 2017). Decisions to restore certain types of wetlands also depend on the type of disturbance that has taken place. Although restoration from horticultural peat extraction is well studied and often practised, knowledge of carbon accumulation in recreated peatlands in former mines (both oil sand mines and mineral mines) is not as extensive; there are no outlined promising practices for restoration following mining, as there are for restoration following peat harvesting (PERG, n.d.).

Initial tests to reclaim peatlands in oil sands mines have demonstrated that certain peatland plant communities can be re-established, and found the beginnings of peat accumulation (Borkenhagen & Cooper, 2016); monitoring is required, however, to assess long-term sustainability (Volik *et al.*, 2020). More recently, however, these study sites are becoming novel saltmarsh-like ecosystems — for which carbon accumulation is unknown — rather than moving toward the intended fen ecosystem (Biagi *et al.*, 2021). Issues around establishing peat stratification stem from the use of salvaged and compressed peat, resulting in problems regulating water-table depth, which is needed for developing normal peatland function (Biagi *et al.*, 2021). The high salinity of these sites also stymies the growth of key peat-building species such as mosses (Vitt *et al.*, 2016). These are serious problems for the restoration and recreation of peatlands removed for mineral and oil and gas exploration, since there is no demonstrable ability to replace any of the carbon lost by destruction. In the Panel's view, peatland recreation in mining areas is therefore not currently a feasible NBCS from a carbon sequestration perspective and will require more research and next-generation pilot projects to be considered viable in the future.

Behavioural barriers can inhibit wetland conservation, even if proven to be financially sound

Wetland loss to agricultural production is a frequent occurrence in the prairie provinces; there is a common perception that wetland drainage is associated with financial benefit because it expands land use for crops (Clare *et al.*, 2021). Although this is true in some cases, in others these lands have led to overall financial losses when compared to non-wetland cultivated areas. Although producers expected losses, the magnitude of these losses came as a surprise. Despite these findings, the producers interviewed in this study maintained they would continue to drain wetlands. According to Clare *et al.* (2021),

> *while the producers generally expressed the opinion that wet areas are financially risky and can produce lower yields, there was still a general sense that draining and consolidating wetlands as a management practice leads to higher productivity on average and over the longer term, despite an acknowledgement that the increasingly unpredictable weather has elevated the risk and uncertainty of cultivating within or near a wetland.*

These decisions are indicative of social dimensions beyond just the financial considerations of wetland drainage, highlighting the necessity for policy-making that goes beyond financial incentives.

5.6 Co-Benefits and Trade-Offs

Restoring damaged or altered freshwater ecosystems, or protecting existing ones, can yield many co-benefits and trade-offs. These co-benefits vary depending on wetland type, location, vegetation composition, and hydrological processes. Any accounting for the implementation of activities or policies to protect or restore wetlands therefore requires careful consideration of local conditions and effects on adjacent or connected ecosystems.

Maintaining and restoring peatlands reduces the risk of wildfires and provides habitat for endangered species

The restoration of drained wetlands through re-wetting can reduce the extent of peat fires, which negatively impact air quality and release large amounts of carbon to the atmosphere (Turetsky *et al.*, 2011b; Reddy *et al.*, 2015). Particulate matter from wildfires is increasingly being recognized as a human health risk, with potential for long-term implications for respiratory health and even death (Black et al., 2017; Orr *et al.*, 2020). Between 1900 and 2016, Canada experienced 101 wildfire-related disasters, resulting in damages in excess of $5.8 billion (PS, 2022). As discussed in Section 5.4.3, future drying and warming have been predicted to increase the severity and extent of wildfires, especially in the boreal region. Drained and mined peatlands have been shown to be significantly more at risk of burning than intact and undrained wetlands (Granath *et al.*, 2016).

Peatlands across Canada are home to endangered species such as woodland caribou, and provide rare and medicinal plants to Indigenous communities in the region (GC, 2019; Latimer, 2021). Intact boreal bogs may act as critical climate change refuges for wildlife and vegetation in future, where high water tables and soil moisture may provide defence against drought and wildfires (Hokanson *et al.*, 2016; Stralberg *et al.*, 2020). NBCSs for wetlands can involve trade-offs, however. Wetland restoration can be initiated for a variety of reasons, some of which may be at odds with each other. For example, maximizing the potential for carbon sequestration could limit a wetland's ability to support natural biodiversity or other ecosystem values in some contexts (e.g., Chimner *et al.*, 2017).

Freshwater marshes offer benefits to biodiversity, flood mitigation, and groundwater recharge

Wetlands in the PPR are critical habitats for migratory birds, and much of the conservation and restoration effort has been centred on re-establishing this capacity (DUC, n.d.). Waterfowl, such as northern pintails, mallards, canvasbacks, redheads, gadwalls, blue-winged teals, and northern shovelers, all migrate to breed in the wetlands of the PPR (DUC, n.d.). A synthesis of research by Baulch *et al.* (2021) concluded, with a high level of certainty, that wetland habitat loss through drainage and conversion to agricultural land directly impacts the abundance and diversity of all wetland biota, including plants, macroinvertebrates, and amphibians. The diversity of wetland size and permanence classes in the PPR is a critical support for the biodiversity of the region; activities such as consolidating natural wetland mosaics into larger, deeper, and more permanent water bodies can lead to a loss of biodiversity, favouring certain species while inhibiting others (McLean *et al.*, 2020). The drainage of wetlands in the PPR negatively affects the availability of groundwater for domestic uses, especially for municipalities and residents in remote areas (Baulch *et al.*, 2021). Decreased surface water storage in wetlands reduces the recharge of groundwater, highlighting the importance of conserving and restoring wetlands in the prairie provinces (Baulch *et al.*, 2021).

Intact wetlands offer protection from flooding, acting as sponges to soak up and later release excess water (Antolini *et al.*, 2020). Conversely, widespread drainage of wetlands in the Prairies has increased runoff and flooding caused by excess snowmelt and rainfall (Dumanski *et al.*, 2015). Using flood insurance claims and land-use data, researchers found that wetlands converted to other uses between 2001 and 2016 cost an average of US$1,840 per hectare annually in the United States, and over US$8,000 in developed areas (Taylor & Druckenmiller, 2022). This spatial heterogeneity reflects greater exposed capital in developed areas (therefore relating to greater potential for wetlands to reduce damage to infrastructure resulting from flooding), though the higher land values in populated areas would increase the cost of conserving wetlands. The Taylor and Druckenmiller (2022) study found that the societal benefits of conserving wetlands for flood protection outweigh the cost of conservation within six years; since they do not take non-flood mitigation into account, these benefits may actually be underestimated.

Achieving climate goals through the conservation of existing carbon stocks can be directly at odds with mineral extraction

In areas such as the Hudson Bay Lowlands, there is a need to balance the protection of extensive carbon stocks with efforts to extract the materials required to support decarbonizing transportation and electricity production (e.g., electric vehicles, solar panels, and wind turbines). Global demand for these minerals is projected to increase sixfold, with the Government of Canada announcing a list of critical minerals on which to focus future mining operations (GC, 2021e; Lawton, 2021). The "Ring of Fire" region within the Hudson Bay Lowlands has been targeted for development by the Government of Ontario, in part due to interest in exploiting deposits of these valuable minerals (Semeniuk, 2021). Experts estimate that anywhere between ~130 and ~250 Mt C (477.1 to 917.5 Mt CO_2e) could be directly lost as a result of the implementation of all mining claims in the region (Harris *et al.*, 2022). Conserving the peatlands of the Hudson Bay Lowlands would contribute to Canada's target of conserving 25% of the land by 2025 (GC, 2021g).

5.7 Conclusion

The greatest sequestration potential for wetland NBCSs lies in avoiding peatland disturbances, such as peat extraction, mining, and oil and gas development, along with associated infrastructure. That said, there is great uncertainty in the assessment of the area of opportunity for avoiding peatland conversion in Canada because it is difficult to anticipate what the demand will be for industrial developments within peatlands over coming decades. When compared to lost potential revenue, avoided conversion is not economical, with most mitigation costs exceeding \$100/t CO_2e. Furthermore, there are knowledge gaps surrounding current and future rates of GHG fluxes, along with variation among different peatland classes in different settings, including the GHG balance of restored peatlands. Despite these challenges, preserving current carbon stocks and avoiding emissions bring a multitude of co-benefits for biodiversity, water resources, and traditional land use. Once lost, carbon stocks held within peatlands are irrecoverable on the timescales required to keep warming below 2°C, highlighting the critical nature of policies and practices that deter peatland conversion.

The restoration of wetlands in agricultural regions (e.g., the PPR) offers important and valuable co-benefits. Carbon sequestration in restored marshes will likely be a secondary benefit to wetlands' well-documented positive influences on water quality, flood protection, groundwater recharge, cultural benefits, and biodiversity. A major hurdle for wetland restoration in agricultural regions is the identification of suitable sites and the cooperation of private landowners. The restoration of peatlands also has important co-benefits, and peatland restoration following peat extraction has been proven to restore the land's ability to sequester soil carbon (although regaining the soil carbon lost due to extraction will take centuries to millennia). Recreating peatlands (e.g., following open-pit mining) is expensive, and trials have tended to result in the creation of ecosystems that are very different from the original disturbed peatlands. As such, the long-term degree of carbon sequestration of these created wetlands is still uncertain.

Although lakes, rivers, and reservoirs are important aspects of the Canadian carbon cycle, their largely unmanaged nature and the lack of information about implementation of NBCSs together contribute to uncertainties around wider implementation.

6

The Marine Coastal Zone and Blue Carbon

Chapter Findings

- Canada's Atlantic, Arctic, and Pacific coasts require regionally specific approaches to NBCS application due, in part, to variations in climate that affect coastal freezing and thawing. Modern geological conditions and history make some coastlines less vulnerable to climate change impacts, such as sea-level rise.
- Additional mapping of areal extent and measurements of specific carbon budgets along Canada's coasts are required to produce more robust estimates of blue carbon sequestration potential.
- The restoration or avoided conversion of tidal wetlands provides numerous co-benefits, but the economic feasibility of these interventions and the need to determine the impact it has on development may limit their potential. Regulatory controls of coastal zones can vary substantially among jurisdictions, and local social acceptability is likewise variable.
- Although limited, research on restoration of Canadian salt marshes indicates that, immediately after the return of tides, rates of carbon storage may be even higher than those in undisturbed marshes.
- There are considerable knowledge gaps in the understanding of coastal carbon sink potential, including the impacts of NBCSs on cultural land uses — most notably, Indigenous land-use and coastal-water practices.

NBCSs relating to marine coastal ecosystems sequester what is widely known as *blue carbon*[25] and traditionally focus on carbon sequestration in mangroves,[26] salt marshes, and seagrass meadows (Nellemann *et al.*, 2009). Salt marshes are defined as coastal ecosystems "mainly occupied by halophytic[27] vegetation and exposed to low hydrodynamic conditions and tidal flooding" (Simas *et al.*, 2001). A seagrass meadow is "a coastal wetland vegetated by seagrass species (rooted, flowering plants), permanently or tidally covered by brackish/saline water" (IPCC, 2013). Carbon stored by macroalgae, such as kelp, may be a form of blue carbon (Krause-Jensen *et al.*, 2018), but the long-term storage potential and manageability is uncertain (Troell *et al.*, 2022). In the Panel's view, limited data on Canadian kelp forests make assessing NBCSs related to these zones unfeasible at this time (Box 6.1), and recent research suggests that some of

25 Blue carbon is defined by IPCC (2022) as "biologically-driven carbon fluxes and storage in marine systems that are amenable to management."

26 Mangrove ecosystems are excluded from discussion in this chapter, as they are not found in Canada (Nellemann *et al.*, 2009).

27 Plants which survive in high salinity soil or water.

these ecosystems may be a source of CO_2 when the entire system is considered (Krause-Jensen & Duarte, 2016; Gallagher *et al.*, 2022).

Most data on carbon stocks and fluxes in North American salt marshes and seagrass meadows come from the contiguous United States, underrepresenting ecosystems in higher latitudes where carbon stocks and rates of carbon sequestration are, in some places, substantially lower than global averages (Ouyang & Lee, 2014; Postlethwaite *et al.*, 2018; Windham-Myers *et al.*, 2018; Prentice *et al.*, 2020; Gailis *et al.*, 2021). Canada has more than 240,000 km of marine coastline (longer than any other country) (StatCan, 2016), which contains coastal ecosystems that sequester carbon while providing other co-benefits (Section 6.6.1). However, there is much uncertainty about the amount of carbon sequestered and its vulnerability to release in response to anthropogenic impacts and changing environmental conditions.

6.1 Opportunities for Enhancing Carbon Sequestration in Marine Coastal Areas

Tidal salt marshes and seagrass meadows store and release carbon through several processes. Organic matter from roots, rhizomes,[28] and aboveground growth is buried in coastal sediments. The decomposition processes that release CO_2 back to the atmosphere are relatively slow. As in other wetlands, the decomposition of organic matter is inhibited by a lack of oxygen due to water saturation, facilitating carbon accumulation and storage (Reddy & Patrick, 1975; Brinson *et al.*, 1981). Per unit area, both tidal salt marsh and seagrass meadow carbon stocks can be substantial, and rates of sequestration are greater than terrestrial forest or peatland soils (Mcleod *et al.*, 2011).

> "Per unit area, both tidal salt marsh and seagrass meadow carbon stocks can be substantial, and rates of sequestration are greater than terrestrial forest or peatland soils."

The accumulation of organic-rich soil tracks the rate of sea-level rise (Rogers *et al.*, 2022); where sea level has been continuously rising, such as on Canada's Atlantic coast, some marshes have been accumulating soil for thousands of years (e.g. Shaw & Ceman, 1999; Kemp *et al.*, 2018). In contrast, much of Canada's northern coastline is experiencing a declining sea level, as lands are still regaining the elevation lost by glacial depression in the last ice age (Pendea & Chmura, 2012). Although these tidal marshes accumulate organic matter, their lifespan is limited, as land uplift brings them out of the tidal frame (Pendea *et al.*, 2010; Pendea & Chmura, 2012). Where tidal marshes

28 Plant stems which grow below the surface of the soil.

transition into freshwater wetlands (i.e., fens and bogs), carbon is preserved (Pendea & Chmura, 2012), but there are currently no studies available that examine the fate of the blue carbon in other situations. On Canada's west coast, neotectonic processes (i.e., motions in the Earth's crust) cause rates of relative sea-level rise to be lower; thus, carbon accumulation rates on the British Columbia coast are lesser than on the coast of Eastern Canada (Chmura *et al.*, 2003; Mazzotti *et al.*, 2008; Montillet *et al.*, 2018; Gailis *et al.*, 2021).

As with tidal salt marshes, seagrass meadows have the potential to accrete vertically for long periods of time and accumulate carbon via their high rates of primary productivity, low rates of decomposition, and ability to trap carbon that originates from non-seagrass sources (Fourqurean *et al.*, 2012; Duarte *et al.*, 2013; Prentice *et al.*, 2020). Although seasonal ice can scour and remove aboveground biomass from eelgrass meadows, plants often dedicate more of their production to their underground structures in these conditions, likely maintaining or even increasing their belowground carbon stock (Robertson & Mann, 1984; Murphy *et al.*, 2021).

Box 6.1 Kelp Forests in Canada

Kelp is common on all three of Canada's coastlines, and global studies of blue carbon suggest it can play a significant role in carbon sequestration. Worldwide, kelp and other macroalgae are estimated to cover approximately 3.5 million km^2 (Krause-Jensen & Duarte, 2016), yet this figure is derived without comprehensive estimates of the overall distribution of kelp forests in Canadian waters. Studies have assessed distribution and trends over time for specific species and regions (Filbee-Dexter *et al.*, 2019) using methods such as aerial surveys (Rogers-Bennett & Catton, 2019), satellite imagery (McPherson *et al.*, 2021), and comparisons with historical benchmarks based on early navigational charts (Costa *et al.*, 2020). A lack of comprehensive data on the extent of these coastal ecosystems makes estimating their aggregate carbon sequestration potential problematic. Documenting long-term carbon sinks associated with kelp forests is challenging; much of the carbon collects in either coastal sediments distant from its point of origin or in the deep ocean, outside Canadian jurisdiction. Additional information on kelp forests would also be helpful to communities managing them for multiple purposes. For example, carbon storage is one of the many traditional, cultural, and ecosystem co-benefits of kelp restoration and cultivation in Gwaii Haanas (Parks Canada, 2021b).

(Continues)

(Continued)

Kelp forests and the carbon they contain are vulnerable to a range of anthropogenic, ecological, and climatic stresses, including storms and wave events that result in large losses of kelp density, biomass, and cover — these can impact between 40% and 100% of an area (Reed *et al.*, 2008; Krumhansl & Scheibling, 2012). Local management actions for conserving kelp forests, reducing eutrophication, increasing underwater light penetration, managing harvests, limiting bottom trawling, and reintroducing apex predators such as sea otters could help avert kelp loss and enhance carbon sequestration (Wilmers *et al.*, 2012; Filbee-Dexter & Wernberg, 2018; Gregr *et al.*, 2020).

Climate change is expected to reduce the resilience of kelp forests and beds, leading to large losses in kelp biomass due to warmer ocean temperatures, changes in nutrient dynamics, and increased storm frequency and intensity (Gerard, 1997; Steneck *et al.*, 2002; Springer *et al.*, 2010; Wernberg *et al.*, 2010). However, it may also facilitate the northward expansion of kelp ecosystems in the rocky substrates of the Arctic due to reduced ice cover, increased availability of light, permafrost thaw, and warmer temperatures (Krause-Jensen & Duarte, 2014; Filbee-Dexter *et al.*, 2019). Krause-Jensen and Duarte (2014) suggest that vegetated marine ecosystems possibly expanding in the Arctic could contribute to carbon sequestration. However, relatively little is known about the extent and diversity of Arctic kelp communities (Filbee-Dexter *et al.*, 2019), and more research is needed to better estimate this potential expansion, and its implications for carbon sequestration, in response to rapidly changing conditions.

Coastal ecosystems and their ability to sequester carbon are often impacted by anthropogenic stresses, including impacts from waterborne pollution such as agricultural runoff, aquaculture, or hydrologic alterations (Short & Wyllie-Echeverria, 1996; CEC, 2016a). Carbon storage rates in tidal marshes depend on a balance of factors such as plant growth, belowground carbon accumulation, and decomposition. When plant growth is affected by stress, there is decreased carbon storage as well as a loss of soil volume, ultimately reducing soil elevation to a level below what is needed for marsh vegetation to survive extended periods of tidal flooding (CEC, 2016a). Preserving or enhancing carbon storage, consequently, often relies on expanding protection for these ecosystems, or restoring them to ensure ongoing sedimentation and burial of organic material (Macreadie *et al.*, 2021).

> "Coastal ecosystems and their ability to sequester carbon are often impacted by anthropogenic stresses, including impacts from waterborne pollution such as agricultural runoff, aquaculture, or hydrologic alterations."

As such, NBCSs for tidal saltwater wetlands are similar to those for freshwater wetlands in that they involve managing, protecting, or restoring these ecosystems and their capacity to sequester carbon, while minimizing other GHG emissions, including CH_4 and N_2O. Relevant interventions include tidal wetland restoration, tidal wetland conservation, and avoided seagrass conversion (Table 6.1). The avoided conversion of tidal wetlands to other land uses can also prevent or reduce GHG emissions, though such interventions may not satisfy the criterion of additionality in regions with no-net-loss policies, such as eastern Canadian provinces, where protection is legislated (Section 6.5.2).

NBCSs for seagrass meadows include the avoided conversion or restoration of these ecosystems. Seagrass habitats have been destroyed as a result of coastal development and are sensitive to anthropogenic impacts such as high nutrient loading, which contributes to eutrophication, and water quality changes associated with sediment discharge, which can block seagrasses with soil or sand and lead to insufficient light conditions for photosynthesis (Orth *et al.*, 2006).

Table 6.1 NBCSs for Tidal Wetlands and Seagrass Meadows

Definition of NBCS	Mechanism
The **conservation of tidal wetlands** through regulation, policy, or economic incentives protects tidal wetlands from potential anthropogenic disturbances or development.	The primary source of carbon stored in tidal marshes is from plant growth, although marshes also trap particulate organic matter transported in tidal floodwaters. Wetland drainage rapidly releases this carbon to the atmosphere; conservation can avoid these emissions (Macreadie *et al.*, 2021).
In situations where tidal wetlands have already been affected, whether through conversion to agricultural lands or development, **the restoration of hydrological and biological regimes** through reflooding and the removal of dikes can eventually re-establish carbon sequestration.	The removal of hydrological restrictions enables the restoration of salt marshes and allows natural processes to restore native vegetation, aiding carbon sequestration (Bowron *et al.*, 2012; Wollenberg *et al.*, 2018; Drexler *et al.*, 2019).

Definition of NBCS	Mechanism
Tidal wetlands can be created or reinforced where they previously did not exist. Not all "living shorelines" are blue carbon-focused, but instead involve stabilization of upland embankments.	Living shorelines use the planting of vegetation to control coastal erosion and create tidal wetlands. Designs can include changing coastal rock structure to reduce wave energy (Bilkovic & Mitchell, 2013; Davis *et al.*, 2015). Additional research is required to determine the carbon sequestration of living shorelines and the potential decline in carbon stored with the age of the wetland (Davis *et al.*, 2015).
Conservation of seagrass meadows can avoid carbon release into the coastal ocean and emissions associated with the erosion of these meadows.	Seagrass ecosystems are vulnerable to waterborne stressors and other impacts (CEC, 2016a). The avoided conversion of seagrass meadows through the creation of protected areas or programs can potentially reduce anthropogenic disturbances of seagrass.
Where seagrass vegetation has been disturbed or removed, **restoration** and replanting may be possible.	Restoration efforts for seagrasses require targeted seeding or planting of seagrass shoots that consider habitat and planting strategies to increase successful restoration of vegetation (Marion & Orth, 2010).

6.2 Indigenous Coastal Land Management

Marine coastal areas have provided critical resources for Indigenous communities for millennia. Indigenous communities have applied Traditional Knowledge and practices to maintain or increase the area of tidal marshes, and as a result, the amount of carbon stored. Several treaties extend into waters, and many Indigenous Peoples do not assign different value to land and water, which could advance protected areas and legislation (e.g., Saugeen Ojibway Nation, 2022). Landscape modifications to create or enhance resource-rich areas have been undertaken by Indigenous communities along coasts across the country, affirming their longstanding occupancy and stewardship of the land (Sayles & Mulrennan, 2019).

One land management practice is the building of dikes to maintain quality hunting sites. Seasonal goose hunts are important to the James Bay Cree, not just as a means to obtain food, but also as an activity with considerable social and cultural significance (Sayles, 2015). The bay's tidal marshes, which are important feeding sites for geese, can rapidly change. Glacial rebound on the coast of James Bay lifts existing tidal marshes above the reach of tidal flooding, where they drain or become nutrient-poor freshwater wetlands (Pendea & Chmura, 2012). In efforts to maintain the existing marsh and hunting locations, Wemindji Cree on the east coast of James Bay build dikes to delay wetland succession

(Sayles & Mulrennan, 2010). Although these marsh areas and soil carbon stocks have yet to be documented, the Panel considers that this likely enhances the blue carbon sink. The proposed creation of an IPCA in James Bay (Box 6.2) could provide opportunities to measure and assess the impact of management actions on carbon stocks; however, IPCAs are not the only way Indigenous Peoples enact their authority (Section 2.4).

Indigenous people have also actively domesticated landscapes in the tidal salt marshes and applied a range of methods to manage the quality and quantity of plant resources (Turner *et al.*, 2013). The Nuu-chah-nulth, Kwakwaka'wakw, and other First Nations along the Pacific coast have a long-held tradition of creating *estuarine gardens* by mounding soils above the low elevation tidal marsh, which allows the seaward expansion of the high salt marsh (Turner *et al.*, 2013). Although plants are harvested from this marsh, increased soil carbon storage may also result; Gailis *et al.* (2021) found that carbon stocks in the high marsh were more than twice that measured in the low marsh. Similarly, sediment in the coastal zone was altered with rock to create intertidal clam habitats known as *clam gardens* (Groesbeck *et al.*, 2014). Indigenous Nations interested in renewing marsh garden cultivation could contribute to research on how marsh cultivation may have a co-benefit related to carbon storage.

Management of coastal ecosystems involves local adaptations to fluctuations in the environment (Sayles & Mulrennan, 2019). Nature-based approaches have been considered by the Squamish, Semiahmoo, and Tsawwassen Nations as ways to adapt to sea-level rise (PICS, 2020a). In these instances, it seems that marsh restoration or expansion would be the primary objective, and carbon storage would be a co-benefit. Further examination is needed to determine to what extent Indigenous management and knowledge of ecological dynamics can enhance tidal marsh soil carbon stocks.

6.3 Magnitude of Sequestration and Emissions Reduction Potential

Most carbon in salt marshes and seagrass beds is stored in soils rather than in aboveground biomass (Chmura *et al.*, 2003; Fourqurean *et al.*, 2012; Moomaw *et al.*, 2018). When these ecosystems and their sediments are disturbed through anthropogenic impacts or changes in environmental conditions, a portion of the carbon they contain (ranging from 25–100%) can be released back to the atmosphere as organic material decomposes (Pendleton *et al.*, 2012). Actions that reduce or avoid disturbances can thus reduce or prevent these emissions. Ensuring that emissions reductions linked to deliberate management actions truly result in additional sequestration requires analysis using a projected baseline (Section 2.3.2), one that factors in current (or expected) rates of wetland conversion and other relevant trends. Alternatively, actions that increase the area(s) of these ecosystems or their rates of carbon accumulation, through restoration or improved management techniques, can increase total carbon sequestered. In either case, estimating sequestration benefits requires knowledge of the carbon fluxes and soil carbon accumulation rates in these ecosystems, as well as fluxes of N_2O and CH_4 — two GHGs more potent than CO_2 — that can be emitted from salt marsh soils (Magenheimer *et al.*, 1996; Moseman-Valtierra *et al.*, 2011; Poffenbarger *et al.*, 2011; Chmura *et al.*, 2016; Roughan *et al.*, 2018).

Estimates of carbon in salt marshes and seagrass meadows should ensure it is not double counted by including carbon transported from other ecosystems (i.e., allochthonous carbon). For example, data from the Pacific coast of North America suggest that the majority of carbon that accumulates in seagrass meadow sediments originates from non-seagrass sources (Prentice *et al.*, 2020). Methodological approaches on the Pacific coast attempt to account for this, in part, by considering large woody debris (Gailis *et al.*, 2021). Policy frameworks can limit the allocation of offset credits for allochthonous carbon due to the risk of double counting (Emmer *et al.*, 2015; Macreadie *et al.*, 2019). However, detailed information on the source of the stored carbon in many of these ecosystems remains unknown.

6.3.1 Carbon Flux Estimates for the Coastal Zone

Salt marshes and seagrass ecosystems are highly productive

Globally, tidal salt marshes and seagrass ecosystems are estimated to sequester CO_2 at rates of 7.98 t CO_2/ha/yr and 1.58 t CO_2/ha/yr, respectively (IPCC, 2014b; EPA, 2017).[29] Seagrass beds have lower carbon accumulation rates than tidal marshes; however, some regions cover larger areas, and these can have higher carbon sequestration capacity in aggregate (Pacala *et al.*, 2001). Carbon fluxes from seagrass meadows in British Columbia are estimated as an average of (± SE) 0.65 ± 0.12 t CO_2/ha/yr and range between 4.6–33.1 g OC/m^2/y (0.17 and 1.21 t CO_2e/ha/yr)[30] (Postlethwaite *et al.*, 2018; Prentice *et al.*, 2020); this is somewhat lower than global estimates, which include species not found on Canada's coastlines.

Restoration of tidal wetlands has also been shown to result in the resumption of active carbon sequestration at rates similar to, or higher than, those of undisturbed wetlands (e.g., Wollenberg *et al.*, 2018; Drexler *et al.*, 2019; Arias-Ortiz

29 These flux rates were used to estimate the national carbon mitigation potential associated with blue carbon NBCSs in the United States in NASEM (2019).

30 Organic carbon (OC) is used here as reported in the primary research.

et al., 2021). Tidal marsh restoration sites have shown higher rates of carbon accumulation than neighbouring natural marsh sites of the Stillaguamish (Poppe & Rybczyk, 2021) and Snohomish (Crooks *et al*., 2014) estuaries in Washington state in the northwestern United States — although the brackish marshes in the Snohomish estuary are expected to have substantial CH_4 emissions, which may offset their carbon storage benefits. In the Stillaguamish estuary, annual carbon accumulation rates averaged 0.123 ± 0.03 t C/ha/yr (0.45 ± 0.11 t CO_2e/ha/yr) for natural and 0.23 ± 0.046 t C/ha/yr (0.84 ± 0.17 t CO_2e/ha/yr) for a restored marsh four years after flooding with salt water (Poppe & Rybczyk, 2021).

6.3.2 Variability and Uncertainty in Carbon Flux and Stock Measurements

Any estimate of carbon stocks and fluxes in these ecosystems is subject to multiple sources of uncertainty, including measurement challenges, variability in processes within ecosystems, spatial heterogeneity, and challenges in assessing areal extent. Methods of measuring soil carbon density and accumulation rates in marine coastal wetlands vary widely and can influence overall assessments of stocks and fluxes (Kennedy *et al*., 2014). Additional uncertainties include challenges with determining carbon sources and accurate quantification of the contributions of GHG fluxes to the total carbon budgets.

Soil carbon densities and depth of tidal wetland deposits are highly variable by region, complicating efforts to estimate carbon stocks

Soil carbon density (SCD), a component needed to calculate carbon stocks, can be variable. Averaging soil carbon stocks over large areas can consequently be misleading, as there is substantial variation across different regions, depending on local ecological and environmental characteristics. In Atlantic Canada, tidal marsh SCD varies from 0.008 grams of carbon per cubic centimetre (g C/cm^3) to 0.067 g C/cm^3 and averages 0.027 ± 0.002 g C/cm^3 for all sites (Chmura *et al*., 2003). The SCD in salt marshes in Pacific Canada averaged 0.026 g C/cm^3 (Chastain *et al*., 2021; Gailis *et al*., 2021). Gailis *et al.* (2021) noted significant differences between high-marsh (0.042 ± 0.013 g C/cm^3) and low-marsh (0.018 ± 0.008 g C/cm^3) SCD. On Canada's eastern coastline, most SCD measurements have been limited to the marsh zones dominated by *Spartina patens* and *Spartina alterniflora* (Chmura *et al*., 2003). In addition, less information is available on zones at higher elevations and more data are needed to understand regional differences, including dynamics related to density and types of vegetation on different coasts.

Carbon stocks depend on the depth of salt marsh soil. Chmura *et al.* (2003) estimated the global carbon stock of 250 t C/ha assuming a 50 cm depth. Canada's Pacific marshes, however, are shallow, with basal depths ranging from 17–29 cm. Thus, in Boundary Bay on the Pacific coast, carbon stocks in tidal wetlands have been measured as 67 ± 9 t C/ha for Clayoquot Sound (Chastain *et al.*, 2021), and 83 ± 30 and 39 ± 24 t C/ha for high and low marsh, respectively (Gailis *et al.*, 2021). On the east coast of Canada, tidal salt marsh soil depths may range from less than 1 m to 7 m (Shaw & Ceman, 1999; Chmura *et al.*, 2001; van Ardenne *et al.*, 2018). These differences emphasize the importance of considering local contexts when estimating carbon. Stocks could vary with ecosystem characteristics such as vegetation type, soil elevation, and soil flooding status.

Other geographic and environmental factors also contribute to regional variation (Gailis *et al.*, 2021). A relationship between SCD and average annual air temperatures has been noted in eastern North American salt marshes, with warmer surface air temperatures correlating to higher SCD (Chmura *et al.*, 2003). Carbon content in seagrass meadows varies in relation to factors such as water depth, wave height, water motion, and exposure, which impact the carbon content of their sediments as well as accumulation rates (Samper-Villarreal *et al.*, 2016; Dahl *et al.*, 2018; Prentice *et al.*, 2020). These differences make the application of global averages problematic and can lead to an overestimation of blue carbon stocks in regions where specific characteristics of the blue carbon ecosystem have not been measured (Ricart *et al.*, 2015; Postlethwaite *et al.*, 2018).

Rates of soil carbon accumulation also vary widely. Around the Bay of Fundy, rates of carbon accumulation range from 0.72 to 9.28 g $C/m^2/yr$ (2.64 to 34.1 t $CO_2e/ha/yr$) (Chmura *et al.*, 2003). Carbon accumulation rates in Pacific Canada show similarly high variability, ranging from 0.20 to 4.54 g $C/m^2/yr$ (0.72 to 16.7 t $CO_2e/ha/yr$) in Boundary Bay and averaging (± SE) of 6.75 ± 1.83 t $CO_2e/ha/yr$ in Clayoquot Sound (Chastain *et al.*, 2021). Canadian measurements tend to be consistent with the IPCC 2013 global estimates of carbon accumulation rates but show high variability within marshes (Chastain *et al.*, 2021). Studies in Clayoquot Sound and Boundary Bay both show that high-marsh locations have higher rates of sediment carbon sequestration than low-marsh ones; it was surmised these high rates of accumulation were due to deeper-rooting plants as well as increased production of belowground biomass in high-marsh relative to low-marsh zones (Connor *et al.*, 2001; Gailis *et al.*, 2021). Moreover, low-marsh deposits are less stable and less likely to hold large amounts of carbon (Gailis *et al.*, 2021); the variability apparent in these marsh systems suggests that accurate determination of carbon stocks and rates requires a sampling design that accounts for spatial variability.

Soil depth measurements are key to estimating coastal carbon stocks

Measurements of SCD are often reported to a depth of 0.5 m (e.g., Chmura *et al.*, 2003) and rarely below 1 m. Estimates of salt marsh carbon storage by the IPCC assume soil depths of 1 m (Kennedy *et al.*, 2014). As mentioned above, while average soil depths in Atlantic Canada are likely to be close to 1 m, many Pacific coast marsh and seagrass sediments are substantially shallower than 50 cm due to the specific nature of the depositional environments in the region (Postlethwaite *et al.*, 2018; Chastain *et al.*, 2021; Gailis *et al.*, 2021). National calculations of carbon sequestration potential (such as those in Drever *et al.* (2021)) may overestimate carbon stored in west coast tidal salt marshes, given their shallower sediments.

Information on carbon stocks in Canadian seagrass meadows is limited

Limited information about the area of Canadian seagrass ecosystems (McKenzie *et al.*, 2020) has resulted in few measurements of bulk carbon density of sediments in seagrass meadows in Canada relative to the length of coastline. All of the sites are vegetated by eelgrass (*Zostera marina*). At sites with the same species in North America and Europe, meadows have an average organic carbon stock of 88.2 (50.2 to 380.07) t C/ha (Prentice *et al.*, 2020). Measurements on the Pacific coast of Canada, however, find average carbon stocks of 13.43 ± 4.82 t C/ha (Postlethwaite *et al.*, 2018) to 20.5 ± 12.85 t C/ha (Prentice *et al.*, 2020), which are substantially lower than global estimates.

6.3.3 CH_4 and N_2O Fluxes

Quantification of the CH_4 and N_2O fluxes of tidal wetlands is needed to determine a wetland's overall contribution to mitigation of climate change. Salt marshes have been reported to be a sink of N_2O (Moseman-Valtierra *et al.*, 2011; Chmura *et al.*, 2016) and, where salinities are >18 part per trillion (ppt), also a sink of CH_4 (Poffenbarger *et al.*, 2011). There have been no GHG studies reported for seagrass meadows in temperate or higher latitude regions in Canada.

When tidal marshes serve as sinks for CH_4 and N_2O, they have even greater value as NBCSs. However, anthropogenic activities in watersheds can change marshes from sinks to sources. Roughan *et al.* (2018) found N_2O emissions from Prince Edward Island tidal salt marshes in watersheds that had intensive agriculture, where fertilizer runoff causes eutrophication of the coastal waters (Section 4.6.1). The control area used in this study had no N_2O emissions. Agricultural soils are also recognized as sources of N_2O emissions. A study examining the impact of reflooding of agricultural lands created by draining salt marshes showed that N_2O

emissions reduced to near zero (Wollenberg *et al.*, 2018). This demonstrates that the return of tidal flooding to drained marshes does not just reinitiate the marsh CO_2 sequestration, but further mitigates climate change by reducing emissions of the more potent GHG, N_2O, in formerly agricultural soils.

Measurements of GHG fluxes in salt marshes have been restricted to Canada's Atlantic coast. Most measurements have been taken in the *Spartina patens* high marsh, as this comprises the greatest area of the majority marshes on the eastern coast of Canada (Comer-Warner *et al.*, 2022). Studies that included sampling in other vegetation zones, however, showed a significant difference in CH_4 emissions (Alongi, 2018; Roughan *et al.*, 2018; Comer-Warner *et al.*, 2022), suggesting the need for more extensive sampling within marshes. Due to substantial differences in vegetation, results from the east coast cannot be extrapolated to tidal marshes on Canada's west or northern coasts. Thus, considerable research is still needed.

6.3.4 Estimating National NBCS Mitigation Potential in the Coastal Zone

There are challenges in estimating areal extent

In Canada, the areal extent of tidal wetlands and seagrass meadows has been mapped as 54,600 ha and 64,500 ha respectively, but this area does not include wetlands in certain locations, including James Bay and southern Hudson Bay (CEC, 2016a). Drever *et al.* (2021) estimated that the area of seagrass meadows is larger at 190,000 ha, and the authors also suggested this number is an underestimate. The Panel has limited confidence in the current evidence for estimating seagrass meadows in Canada. Due to lack of comprehensive mapping, there are no estimations of tidal salt marsh area on the coasts of the Hudson and James Bays, Newfoundland, and parts of Quebec (particularly the northern shore of the St. Lawrence) (CEC, 2016a). Research on the Pacific coast suggests that the extent of marshes has been overestimated. For example, original provincial maps of Boundary Bay, the largest salt marsh in southwestern Canada, indicated its area was 1,207 ha (CEC, 2016a), but recent research reveals the extent of the marsh is closer to 275 ha (Gailis *et al.*, 2021). In the view of the Panel, further mapping to explore and rectify these kinds of discrepancies could be augmented with LIDAR.

Estimating the carbon sequestration potential of NBCSs on a regional or national scale requires calculating the area over which blue carbon NBCSs are found. However, this is also subject to methodological challenges. Limited mapping of salt marsh area may sometimes result in poor modelling of the magnitude of carbon stocks that could be lost because of wetland drainage and erosion (Chmura, 2013). Remote-sensing techniques may be imprecise in measuring small-scale changes and therefore underestimate wetland losses through drainage or erosion (Schepers *et al.*, 2017; Windham-Myers *et al.*, 2018).

There may be considerable potential for restoring the active CO_2 sink of tidal wetlands by reflooding historically drained and diked salt marshes. Using data from CEC (2016a) and van Proosdij *et al.* (2018), Drever *et al.* (2021) estimated that "the area of undeveloped [dikeland] that could be reflooded without damaging buildings or infrastructure [is] approximately 15,000 ha in New Brunswick [...]; 16,139 ha in Nova Scotia [...]; and 12,990 ha in Quebec [...]." There has been extensive diking of wetlands along the coast of British Columbia, but the area has yet to be estimated.

Canadian seagrass ecosystems are also inadequately mapped (McKenzie *et al.*, 2020). Seagrass mapping is lacking in many parts of Atlantic Canada, but modelled estimates have been made for the Pacific coast (Murphy *et al.*, 2021). The modelling approach in British Columbia uses mapping data to identify seagrass presence and then converts these line data into polygons that are overlain on bathymetric maps (topographic maps of the sea floor) (Howes *et al.*, 2001; Short *et al.*, 2016). All area within the polygon between the coastline and a water depth of 3 or 5 m (depending on location) is estimated as seagrass area, regardless of patchiness, substrate type, or environmental condition (Howes *et al.*, 2001; Gregr *et al.*, 2013; Short *et al.*, 2016). Mapping challenges for these zones include the need to account for variation in seagrass patchiness, shape, composition, abundance, biomass, and complexity; the growth of seagrass in deep and turbid water; and challenges assessing the difference in low to moderate seagrass density from the substrate (McKenzie *et al.*, 2020). Remote, inaccessible locations, as well as the variability of turbidity and water depth in space and time, make observations challenging (McKenzie *et al.*, 2020).

Blue carbon sequestration potential associated with restoration may be overestimated

The most recent estimates for the magnitude of carbon sequestration potential associated with coastal ecosystem conservation and restoration in Canada come from Drever *et al.* (2021). Table 6.2 provides a summary of their findings for tidal wetlands and seagrass meadows, as well as the Panel's assessment of the quality and applicability of the evidence, and of the assumptions underlying the estimated values. In Drever *et al.* (2021), restoration only addressed the drained marshes of the Bay of Fundy, as data on carbon-storage potential with restoration elsewhere in Canada were not measured. Drever *et al.* (2021) did not report potential carbon sequestration from tidal wetland conservation, as tidal wetlands have high protection status in most coastal provinces (Section 6.4.2).

Table 6.2 Marine Coastal Zone and Blue Carbon NBCS Sequestration Potential, as Estimated by Drever *et al*. (2021), and Panel Confidence

Type of NBCS	Present to 2030	2030 to 2050	Panel Confidence	Panel Notes
	Annual (Mt CO_2e/yr)	**Annual** (Mt CO_2e/yr)		
Tidal wetland restoration in NB and NS around the Bay of Fundy	1.5 (1.2 to 1.8)	1.2 (0.9 to 1.5)	High	The tidal wetland restoration estimate is based on restoring 4,413 ha/yr in dikelands in NB and NS.
Avoided seagrass conversion	<0.1*	<0.1*	Low	The areal extent of seagrass used for these calculations was 813,835 ha, greater than the confirmed 190,000 ha of seagrass area estimated by Drever *et al.* (2021). Seagrass carbon stocks used by Drever *et al.* (2021) were five times higher than published evidence from BC (Prentice *et al.*, 2020).
Seagrass meadow restoration	<0.1 (0.0 to 0.8)	0.1 (0.0 to 0.3)	Low	The uncertainty, of both the area of opportunity and the estimated sequestration rate per hectare, is high.

Data source: Drever *et al.* (2021)

The Panel has indicated its level of confidence in these estimates by providing ratings for both the GHG flux and area of opportunity used by Drever *et al.* (2021) to calculate the mitigation potential. See the Appendix for Panel Confidence scale. Numbers marked with an asterisk (*) are estimates modified from Drever *et al.* (2021) with a high uncertainty. Estimates were originally reported as Tg CO_2e/yr.

> "The proposed measurement of seagrass meadow carbon stocks could be two to four times too high."

The estimates of the carbon sequestration potential of seagrass meadow restoration and avoided conversion made by Drever *et al.* (2021) relied on several assumptions, which the Panel believes contribute to an overestimation of the area of annual loss as well as carbon stocks. The total area of seagrass was derived by averaging the total area of seagrass in the United States with the area estimated for Canada, thereby basing calculations on ecosystems that are six times larger than the confirmed area of seagrass for Canada.

The estimates of carbon stocks used by Drever *et al.* (2021) (88.2 t OC/ha) do not include recent evidence from British Columbia, where carbon stocks are more than five times smaller (15.2 t OC/ha) (Prentice *et al.*, 2020). Furthermore, these measurements of carbon stocks are extrapolated to 1 m when no cores from Canada's Pacific coast extend to that depth. In the view of the Panel, the proposed measurement of seagrass meadow carbon stocks could be two to four times too high.

6.4 Stability and Permanence

Tidal wetlands and seagrass meadows can sequester carbon through soil accumulation. However, biophysical limitations on the sustainability of sequestration rates and associated carbon stocks include the scale of and resiliency to ecosystem disturbances, sea-level change, and other altered environmental conditions, including remineralization and sediment redistribution (Chastain *et al.*, 2021). Carbon stocks are vulnerable to release back to the atmosphere upon ecosystem disturbance and changed environmental conditions.

6.4.1 Permanence of Carbon Storage in Tidal Wetlands

Potential threats to tidal salt marshes include land development, lack of suspended sediment, excess nutrients, and coastal squeeze, where wetland area is constricted by vegetation succumbing to excessive flooding at the seaward side, and inland migration is prevented by infrastructure built at the upper edge (Torio & Chmura, 2013). The nature of restoration processes can influence the types of sediments deposited, thereby affecting the amount of stored carbon (Drexler *et al.*, 2020). The rate of carbon accumulation in a restored wetland may vary over time (Poppe & Rybczyk, 2021).

The rate of sea-level rise influences salt marsh carbon burial rates and potential

Climate change and increased rates of sea-level rise pose threats to the long-term stability of coastal wetlands and their carbon stocks. If the rate of sea-level rise stays below a threshold level, then marsh vegetation can persist, and soil will accumulate carbon and maintain elevation (CEC, 2016a). Rates of sediment accretion are spatially variable, and the upper range of accretion is estimated to be 5–6.7 mm/yr in marshes on the northwest Atlantic coast (Gonneea *et al.*, 2019; Holmquist *et al.*, 2021). If sea-level rise reaches predicted rates (e.g., Vermeer *et al.*, 2009), then plant production in marshes as well as carbon accumulation and marsh elevation — which depend on carbon accumulation and sediment deposition — could fail to keep pace, resulting in unvegetated deposits vulnerable to erosion (CEC, 2016a). The fate of carbon in submerged tidal wetlands is uncertain. Marsh peat found submerged on the continental shelf off the east coast of North America suggests that at least some portion of submerged carbon stocks can persist, but no research has directly investigated the fate of submerged marsh carbon stocks in Canadian waters (CEC, 2016a).

While the future stability of marshes could be threatened by increased rates of sea-level rise, macro-tidal marshes — such as those on the Bay of Fundy and St. Lawrence Estuary — appear to be resilient (Kirwan *et al.*, 2016). Moreover, predicted rates of sea-level rise in Canada are not as high as elsewhere due to the isostatic rebound in parts of eastern North America, which is 11 cm per century (James *et al.*, 2014; Daigle, 2020). Equally important may be the extent to which wetlands have been modified through land-use change, which mitigates or amplifies the impacts of climate change (e.g., through wetland restoration or drainage) (Zona *et al.*, 2009; Petrescu *et al.*, 2015). Alterations to surrounding hydrology, such as culverts or berms, can impede the drainage of tidal floodwaters, adding to stresses on vegetation.

Understanding other climate change impacts on tidal salt marshes, such as changes in temperature, requires consideration of site-specific conditions and effect interactions

Increasing temperatures will increase decomposition rates in Canadian marsh soils, but will also increase primary production, possibly boosting carbon stocks (Chmura *et al.*, 2003). Other environmental factors that could be affected include soil water-table level and air and soil temperature, all of which have an impact on CH_4 emissions; the greatest impact is soil salinity (Bridgham *et al.*, 2021). However, there is insufficient evidence on the effects of changing temperature and precipitation regimes on tidal saltwater wetlands to make generalized predictions about multiple ecosystem properties and regions (Feher *et al.*, 2017; Moomaw *et al.*, 2018).

Boreal and Arctic tidal wetlands are also impacted by coastal erosion and carbon transported from thawing permafrost (Windham-Myers *et al.*, 2018). Along the Arctic coast and Gulf of St. Lawrence, climate impacts such as changing sea-ice cover affect the terrestrial processes impacting coastal erosion and the transport of carbon, water, and nutrients (Pickart *et al.*, 2013; Windham-Myers *et al.*, 2018). Rapid shifts in salinity and seasonality in boreal and Arctic estuaries make assessing the relationships among climatic drivers, wetland extent, and carbon accumulation rates difficult (Windham-Myers *et al.*, 2018).

6.4.2 Permanence in Seagrass Ecosystems

Climate change is expected to add new stresses to eelgrass ecosystems, which could impair carbon sequestration or cause carbon releases

The seagrass species found in Canada's coastal waters is *Zostera marina* (eelgrass). It has been designated an Ecologically Significant Species (ESS) by Fisheries and Oceans Canada (DFO, 2009). Climate changes and human impacts can impact seagrass health. Climatic changes affecting light availability are expected to impact eelgrass ecosystems along with human impacts (e.g., nutrient-loading, coastal development), increasing storm frequency and suspended sediments, which in turn increase water turbidity and smother plants (Curry *et al.*, 2019; Murphy *et al.*, 2021). Increased CO_2 may enhance eelgrass photosynthetic rate and productivity, but these ecosystems are still vulnerable to the ocean acidification caused as ocean waters take up CO_2 from the atmosphere; seagrass can help reduce CO_2 concentrations in the water (Koch *et al.*, 2013; Waldbusser & Salisbury, 2014; Murphy *et al.*, 2021). Climate change is also expected to have a strong impact on the input of freshwater and the timing of snow and ice melt in northern Canada (Bonsal *et al.*, 2019), affecting seagrass meadows in James Bay and other areas of the Canadian Arctic. The protection and monitoring of seagrass in these coastal ecosystems is important due to its ecological significance (Box 6.2).

Box 6.2 James Bay Seagrass Meadows: An Indigenous-Led National Marine Conservation Area

The eelgrass meadows of James Bay were once estimated to be the most extensive in Canada (Lalumière *et al*., 1994). Although comprehensive mapping is lacking, these meadows are assumed to have degraded to a fraction of their historical extent (Murphy *et al*., 2021). While the primary factor responsible for this decline appears to be a change in local hydrology due to increased demands for hydropower and hydroelectric development (Murphy *et al*., 2021), additional environmental factors can contribute to eelgrass degradation, including rising temperatures in recent decades.

In 2021, the Mushkegowuk Council and Parks Canada signed a memorandum of understanding to begin the designation of an area of more than 91,000 km^2 in western James Bay as an Indigenous-led National Marine Conservation Area (Parks Canada, 2021a). Parks Canada is setting up research study areas around James Bay; mapping will be a potential, valuable output of this research effort, one that could confirm the current extent of the eelgrass meadows. The creation of an Indigenous-led protected area can advance reconciliation and will be designed to maintain Mushkegowuk harvesting rights and practices, consistent with Treaty rights (Mushkegowuk Council, 2020) (Section 2.4).

6.5 Feasibility

Practices for conserving and restoring tidal wetlands and seagrass meadows are subject to a range of challenges and constraints, including cost, technical feasibility, and research gaps. Existing Canadian policies demonstrate, however, that governments have tools to overcome these barriers.

6.5.1 Coastal Zone NBCS Costs

Calculation of the net costs of salt marsh restoration must account for the cost of land acquisition, surveying, construction, adjustment, repair, and maintenance of dikes (Sherren *et al.*, 2019; Drever *et al.*, 2021). These costs vary depending on land characteristics and the interventions required (Haasnoot *et al.*, 2019). Experience from Atlantic Canada provides an indication of the potential range of these costs. Current annual maintenance and repair costs for dikes on the Bay of Fundy are \$2 million/yr in Nova Scotia and \$650,000/yr in New Brunswick, as cited in Drever *et al.* (2021). A study of all wetland types in Nova Scotia estimated the cost of recent wetland restoration projects to be between \$30,000 and \$100,000/ha (Gov. of NS, 2014). The net expense of tidal wetland restoration may not be this high, however, when considering the costs of dike management will increase in the face of rising sea levels (CEC, 2016a).

> "Restoration costs may be offset by avoided costs for existing infrastructure due to mitigated disaster risk, particularly flooding."

Such costs should be considered in relation to the value of carbon sequestered and other co-benefits. Restoration costs may be offset by avoided costs for existing infrastructure due to mitigated disaster risk, particularly flooding. Drever *et al.* (2021) estimated the difference between avoided maintenance costs (when dikes are removed) and wetland restoration costs to be \$4,972/ha in Nova Scotia and New Brunswick. Wetland restoration still has a net cost, but that cost is considerably reduced after avoided expenditures on dikes are factored in.

Seagrass restoration potential is regionally variable, but costs have not been estimated

Seagrass restoration costs are likely to be high, although evidence is limited (Drever *et al.*, 2021). Seagrass restoration is possible on the Atlantic coast of Nova Scotia and in southern British Columbia, where land management can reduce threats to water quality (CEC, 2016a). However, regulatory jurisdiction over the coastal zone is complicated, potentially involving federal, provincial, municipal, and Indigenous governments. Additionally, costs will be impacted by regional variation in environmental conditions (e.g., water clarity, sediment, temperature, salinity) (CEC, 2016a) and human activities, which can all affect eelgrass survival and its restoration potential (Murphy *et al.*, 2021).

6.5.2 Policy and Regulatory Challenges

No-net-loss policies offset wetland development with restoration or creation, which influences their potential as an NBCS (both positively and negatively)

Existing policies and regulatory approaches provide examples of how wetland conservation and restoration actions can be implemented. For example, the *Nova Scotia Wetland Conservation Policy* focuses on no-net-loss in wetlands (Gov. of NS, 2011). It should be noted, however, that the loss and restoration of wetlands are not completely equal; the loss releases more CO_2 to the atmosphere than restoration can sequester. Therefore, the preservation of existing wetlands in the province tends to be more economically viable than the high costs of mitigation through restoration (Gallant *et al.*, 2020). The policy requires that construction on wetlands be offset through restoration or the creation of additional wetland area (Austen & Hanson, 2007).

Other provinces have similar policies. New Brunswick's *Wetlands Conservation Policy* (2002) considers salt marshes to be provincially significant, affording them the highest degree of protection (Gov. of NB, 2002). Prince Edward Island recognizes that wetlands serve multiple economic, social, and environmental functions; its policies aim to manage development to achieve no-net-loss of wetlands or wetland function (Gov. of PE, 2007). On the Pacific coast, British Columbia's *2015 Water Sustainability Act* protects wetlands from some human activities, but carbon is not mentioned (Gov. of BC, 2015). Complementary policy instruments are often used across the country to protect marsh habitat, such as the *1991 Federal Policy on Wetland Conservation*, the *1994 Migratory Birds Convention Act*, and the *1985 Fisheries Act* (GC, 1985, 1991, 1994).

In Atlantic Canada, no-net-loss policies mean that tidal wetland conservation has limited potential as an NBCS, because they effectively ensure that wetland conservation already occurs and nothing additional can be done. However, supplementary watershed management protections can be implemented, since no-net-loss policies do not always provide effective protection due to a lack of historical enforcement, appropriate land area, and limited capacity to recreate the qualities of pristine sites (Macreadie *et al.*, 2019). In places where legislation already exists, policy may be modified to incorporate carbon rather than creating new policy.

Conversely, the potential impact of the conservation of seagrass meadows is far greater. The designation of eelgrass as an ESS (Section 6.4.2) provides a strong basis for management actions (DFO, 2009, 2011; Murphy *et al.*, 2021). Moreover, seagrass habitat has been prioritized for conservation and inclusion in future marine protected areas in Canada; the Government of Canada aims to protect 30% of coastal and marine areas by 2030 (PMO, 2019).

Monitoring policies and enforcement for restoration and conservation are limited

Monitoring provides a baseline of conditions that can be compared with future conditions following the implementation of an NBCS, such as restoration of a wetland (Bowron *et al.*, 2014). Without a national research framework, monitoring and evaluation that account for the carbon in restored tidal salt marshes and seagrass meadows are limited to specific research sites (ECCC, 2020d). While Canada does not have an equivalent to the Long-Term Environmental Research sites in the United States, Parks Canada has permitted long-term research on salt marsh and seagrass beds in the Kouchibouguac, Pacific Rim, Gulf Islands, and Wapusk National Parks (CEC, 2016b). NBCS carbon accounting in these habitats would ideally consider environmental factors, such as double-counting carbon entering the ecosystem from other locations, as well as economic and policy concerns, such as ensuring sufficient funds to maintain a monitoring system. Even with a national framework, monitoring and evaluation would still depend on research from specific sites.

One monitoring challenge is jurisdiction, notably in cities or communities where municipal, county, and provincial/territorial interests potentially overlap, making policy development and implementation difficult (Seddon *et al.*, 2020a). For example, a living dike project in Boundary Bay required the collaboration of three jurisdictions — the City of Surrey, the City of Delta, and the Semiahmoo First Nation — to raise the elevation of a salt marsh along a 250-km stretch of coastline (Wood, 2020). Conflicting policy objectives and incentives among jurisdictions can be addressed through adaptive governance, which considers the complexities of the social-ecological system by incorporating a range of knowledges (Raadgever *et al.*, 2008; Morris & de Loë, 2016). In coastal zones, adaptive governance can provide an approach to managing jurisdictional complexities while considering the variable social awareness and acceptability of policy approaches (Schultz *et al.*, 2015).

Funding and enforcement of monitoring restoration projects over multiple years are key issues. The design and creation of NBCSs should consider the timeframe for funding and expectations for monitoring targets and maintenance (Kabisch *et al.*, 2016). The cost of carbon monitoring and accounting is a common barrier to participation in carbon-offset markets (Monahan *et al.*, 2020). Challenges to effective and consistent assessment of carbon within ecosystems should be considered in advance by the stakeholders who are planning the NBCS, along with the allocation of jurisdictional responsibilities and required funding.

6.6 Co-Benefits and Trade-Offs

6.6.1 Co-Benefits

The restoration and avoided conversion of tidal wetlands and seagrass meadows provide a wide range of ecosystem services, including protecting shorelines from erosion, stabilizing sediments by attenuating wave action, and protecting habitat for a variety of fauna and flora. Canadian salt marshes provide habitat for rare and endangered species (e.g. Mazerolle & Blaney, 2010); those habitats support artisanal harvests of waterfowl and vegetation important to Indigenous and recreational hunters and foragers (Chmura *et al.*, 2012; Dick *et al.*, 2022). Salt marshes help maintain commercial fisheries by providing nurseries for young fish and protection from larger predators (Barbier *et al.*, 2011). The uptake of nutrients and pollutants by salt marshes purifies water (Hung & Chmura, 2007), which benefits human health as well as adjacent ecosystems, such as seagrass meadows that would otherwise be vulnerable to pollutants (Barbier *et al.*, 2011). Coastal wetlands also provide social benefits associated with recreation and education (Gov. of NS, 2011; Chmura *et al.*, 2012). In general, the conservation and restoration of coastal ecosystems can increase the adaptive capacity of communities to cope with natural hazards and climate change, while also enhancing coastal livelihoods (Barbier *et al.*, 2011). Seagrass meadows also provide co-benefits in terms of shoreline protection and nutrient cycling (Murphy *et al.*, 2021); they can survive increased ocean acidification for long time periods, providing localized protection against this threat (Koweek *et al.*, 2018).

6.6.2 Trade-Offs

Competing interests and land-use values are potential barriers to wetland restoration or conservation in Canada's marine coastal areas. Demands stemming from development or the agricultural industry can make coastal areas valuable, increasing the costs of conservation. In Atlantic Canada, the maintenance of community status quo and limited local government budgets have been identified as two of the largest impediments to wetland conservation and restoration (Sherren *et al.*, 2019). The higher population density on the southern coast of British Columbia relative to the Atlantic coast impacts demands on land use and land value. There may also be concerns about the extent to which wetlands offer an equivalent level of protection from flooding compared to dikes or other infrastructure (Zhu *et al.*, 2020).

Salt marshes in Atlantic Canada historically drained and diked for agricultural use may be restorable if communities feel that residential, commercial, and transportation infrastructure can be adequately protected from disturbances (Sherren *et al.*, 2019). While tidal salt marshes can provide a similar level of coastal protection from disturbances, they may require a comparatively greater amount of land compared to infrastructure (Sutton-Grier *et al.*, 2015; Haasnoot *et al.*, 2019), but provide many more ecosystem services. The degree of coastal protection from disturbances provided by restored marshes will vary depending on geography, biomass productivity, and storm type and severity (Sutton-Grier *et al.*, 2015).

6.7 Conclusion

Tidal saltwater marshes and seagrass meadows are productive ecosystems that have the potential to maintain or improve carbon sequestration. Tidal salt marsh restoration, especially in sites on the Atlantic and Pacific coasts, has a high potential of mitigating climate change impacts. Assessing the value of NBCSs will require regionally specific approaches for each of the Atlantic, Arctic, and Pacific coasts due to variations in vegetation, climate, and sea-level change. Atlantic Canada currently has the highest feasibility for NBCS development, while Hudson Bay and the Pacific coast could permit regionally beneficial actions with additional understanding of local conditions. Further research is required to assess areas of opportunity to implement the restoration or avoided conversion of coastal ecosystems, while potential land use (including cultural uses) in jurisdictions needs to be considered, as well — most notably Indigenous land-use practices.

7

The Panel's Summary Assessment of NBCSs

NBCSs are increasingly recognized as practices that can help Canada and other countries achieve potentially significant reductions in atmospheric GHGs through the intentional enhancement of carbon sequestration. This growing awareness has led to a desire among researchers, policymakers, stakeholders, and communities to better understand how the protection, restoration, and management of ecosystems may aid in the enhancement of GHG sequestration (or reduced release of GHGs to the atmosphere). This chapter synthesizes the Panel's analysis and findings on NBCSs across different Canadian ecosystems and land-use types, summarizing key findings in relation to the Panel's charge. This synthesis provides a comparative analysis of all the NBCSs considered by the Panel according to the four main criteria used in its assessment: (i) GHG mitigation potential (in terms of either carbon sequestration or avoided emissions); (ii) constraints on continued sequestration and the permanence of carbon stocks; (iii) the costs and feasibility of implementation; and (iv) co-benefits and trade-offs. The Panel also outlines its findings on the need for meaningful and ongoing engagement with, and leadership by, Indigenous communities in relation to the potential success of NBCSs. Key sources of uncertainty, data gaps, and research priorities are identified and discussed. Moreover, the Panel's assessment takes into consideration various Indigenous perspectives on NBCSs so as to reflect a more comprehensive understanding of the potential benefits (or harms) associated with these activities.

7.1 Assessing the GHG Mitigation Potential of Canada's Carbon Sinks

Main Question

What is the potential for nature-based solutions to help meet Canada's GHG emission reduction goals by enhancing carbon sequestration and storage, and reducing emissions, in managed and unmanaged areas (e.g., wetlands, agricultural and forest systems, harvested wood, and as blue (marine) carbon), and taking into account the major non-CO_2 climate impacts that can be reliably estimated (e.g., non-CO_2 GHG emissions, albedo, and aerosols)?

NBCSs are affected by ecosystem responses to a changing climate, can produce additional climate effects, and have mitigation potentials that operate on different timescales

The GHG mitigation potential of NBCSs cannot be assessed in isolation from their impacts on other factors affecting the Earth's climate. As suggested in the Panel's charge, changes in land-use and land management practices may not only alter the rates of uptake or release of GHGs but can also alter the surface temperature of the Earth. In cases such as the expansion of forest area over land covered by snow seasonally, decreases in reflectivity (i.e., albedo) can offset a portion of carbon sequestration benefits (NASEM, 2019), thus reducing the overall mitigation potential. The release of volatile organic carbon compounds from forests and plants can also affect climate through the creation of aerosols and associated effects on cloud formation and radiative forcing, potentially enhancing mitigation benefits from NBCSs (Laothawornkitkul *et al*., 2009; Després *et al*., 2012).

Conversely, a changing climate also stands to impact the ability of ecosystems to sequester carbon or alter their GHG emissions rates. Increasing temperatures and changes in precipitation can lead to shifts in environmental conditions and associated ecosystem changes. Across much of Canada, higher temperatures and a lengthening fire season are expected to increase the likelihood and intensity of wildfires (Canadell *et al*., 2021; Jain *et al*., 2022), leading to larger releases of GHGs from Canada's extensive forests over time. In some areas of Canada, however, warming has led to increased productivity and maintenance of existing carbon stocks (if not increased carbon sequestration) (D'Orangeville *et al*., 2016; Ziegler *et al*., 2017).

Soils across the country will also be affected, as higher temperatures coupled with extreme precipitation events lead to the destabilization of carbon stocks. This is a result of increased soil redox fluctuations, alterations in microbial metabolism, and hydrology (including the form and timing of water input), all of which are key drivers of carbon fluxes, in turn regulating soil carbon stocks in forests (Section 3.3.1). More frequent and longer anoxic conditions increase CH_4 emissions in freshwater wetlands and aquatic systems affected by changes in land use, while heat and drought can encourage higher rates of decomposition of soil organic matter as freshwater wetlands grow drier, resulting in increased emissions of CO_2 and N_2O (Sections 5.4.3 and 5.4.4).

Furthermore, sea-level rise threatens to inundate some coastal areas, resulting in the loss of ongoing carbon sequestration in tidal wetlands and uncertain impacts on existing carbon stocks in submerged sediments (Section 6.4.1). In other areas of Canada, the threat of rising sea levels is lower due to continued post-glacial rebound (i.e., land uplift) and neotectonic activity (i.e., earthquakes). In general, these impacts may lessen the mitigation potential of NBCSs.

The timing of the mitigation potential of NBCSs varies. Some interventions result in immediate but short-term benefits such as the reduction of N_2O emissions with improved nutrient management of croplands (Chapter 4), while NBCSs involving land-use and ecosystem changes have impacts associated with gradual increases in carbon sequestration over longer timeframes (e.g., restoration of wetlands; Chapters 5 and 6). The sequestration and avoided emissions potential of forest management NBCSs varies, as some have limited initial impact (e.g., restoration of forest cover) while others yield immediate results (e.g., use of harvest residues in bioenergy) yet could result in net emissions over a longer timeframe (Section 3.3.2). NBCSs such as restoration of forest cover can even have net negative impacts on climate change mitigation in the years immediately following implementation due to albedo effects (Section 3.3.3), as could restoration of certain freshwater wetlands with increased CH_4 emissions immediately post-restoration (Section 5.3.1).

There are also temporal limits to some systems' abilities to uptake carbon. Some NBCSs involve ecosystems with no well-defined biophysical limits on carbon sequestration and can continue to sequester and store carbon indefinitely under favourable environmental conditions (e.g., avoided conversion of peatlands; Section 5.4.1). In others, sequestration can continue only up to a threshold, after which the net carbon flux reaches equilibrium (e.g., no-till agriculture; Section 4.4). All of these factors were considered by the Panel in its evaluation of the overall mitigation potential of NBCSs in Canada.

Table 7.1 provides a synthesis of the Panel's assessment of the overall potential associated with a range of NBCSs in forests, agricultural lands, grasslands, freshwater ecosystems, tidal wetlands, and seagrass meadows. The table indicates the extent of limits on sequestration and the vulnerability of stored carbon to atmospheric release (see the Appendix for additional details about the Panel's ratings and the scales for this assessment). Table 7.1 does not include consideration of all climate effects, but adjustments were made to account for albedo and CH_4 and N_2O emissions, where relevant to certain NBCSs. However, the Panel notes there may be uncertainty surrounding these climate effects, which are further explored in Chapters 3–6. Changes to land surface albedo, in particular, may alter the climate change mitigation benefits of increased carbon sequestration in terrestrial ecosystems. For example, the restoration of forest cover reduces the surface albedo of a given geographical area, thereby increasing the absorption of incoming solar radiation and in turn surface temperature (Section 3.3.3). The uncertainties related to the influence of climate effects should be considered when assessing the magnitude of sequestration potential of NBCSs.

Table 7.1 Summary Assessment of NBCS Mitigation Potential, Permanence, and Feasibility

	GHG Mitigation Potential[31]		Permanence		Feasibility	
NBCS	**Annual reduction** Mt CO_2e /yr in 2030	**Annual reduction** Mt CO_2e /yr in 2050	**Biophysical vulnerability to atmospheric release**	**Socioeconomic vulnerability to atmospheric release**	**Cost** mean MAC in 2030[32] (\$/t CO_2e)	**Barriers to implementation and enhanced use of NBCSs**
Forest						
Improved forest management	5 – 15††	>25††	Moderate**	High**	\$57†††	Major*
Restoration of forest cover	0 – 1††	15 – 25††	Moderate**	Moderate*	\$1,203††† (\$96 in 2050)	Major***
Avoided forest conversion	1 – 5†	1 – 5†	Moderate**	Low*	\$90†††	Moderate***
Urban canopy cover	0 – 1†††	1 – 5†††	Low*	Moderate*	\$150††	Moderate*
Agriculture & Grasslands						
Crop management	5 – 15††	5 – 15††	Moderate**	Low**	\$63 – 103††	Minor**
Soil management	5 – 15 ††	5 – 15 ††	Moderate**	Low**	\$74 – 150††	Moderate**
Nitrogen management	5 – 15†††	5 – 15†††	–	–	\$56††	Moderate***
Agroforestry	5 – 15†	5 – 15†	Low**	High***	\$11 – 3,874††	Moderate**
Avoided grassland conversion	5 – 15†	1 – 5†	Moderate*	High**	\$144††	Moderate*
Grassland restoration	0 – 1†	0 – 1†	Moderate*	Low*	\$102††	Moderate*
Improved grassland management	0 – 1†	0 – 1†	Moderate*	Low*	\$40††	Minor**

(Continues)

31 Mitigation potential is cumulative across all areas of opportunity determined by Drever *et al.* (2021). Assumptions about area of opportunity are discussed in Sections 3.3, 4.3, 5.3, and 6.3.

32 Costs are only available to 2030; NBCSs with long-term sequestration potential, including restoration of forest cover, have a lower cost per tonne in 2050.

	GHG Mitigation Potential		Permanence		Feasibility	
NBCS	**Annual reduction** Mt CO_2e /yr in 2030	**Annual reduction** Mt CO_2e /yr in 2050	**Biophysical vulnerability to atmospheric release**	**Socioeconomic vulnerability to atmospheric release**	**Cost** mean MAC in 2030 (\$/t CO_2e)	**Barriers to implementation and enhanced use of NBCSs**
Inland Freshwater Aquatic Systems						
Wetland restoration (peatlands)	0 – 1††	0 – 1††	Moderate**	Low*	$403†	Moderate***
Avoided conversion (peatlands)	5 – 15†	1 – 5†	Moderate**	High*	$363†	Moderate***
Wetland restoration (freshwater mineral)	0 – 1††	0 – 1††	High***	Moderate*	$497††	Moderate***
Avoided conversion (freshwater mineral)	1 – 5††	0 – 1††	Moderate***	Low*	$29††	Minor**
Coastal Zone						
Tidal wetland restoration	0 – 1††	0 – 1††	Moderate**	Low**	$89†	Moderate**
Tidal wetland conservation	–	–	Moderate**	Low***	–	–
Seagrass restoration	0 – 1†	0 – 1†	Moderate***	Moderate*	$150†	Moderate*
Seagrass conservation	0 – 1†	0 – 1†	Moderate*	Moderate*	$150†	Minor*

Evidence Scale rating: *Limited **Moderate ***Robust
Panel Confidence Scale rating: †Limited ††Moderate †††High

Estimates of mitigation potential are organized into five categories (0–1, 1–5, 5–15, 15–25, and >25 Mt CO_2e /yr) to characterize the likely range of annual GHG mitigation (sequestration or avoided emissions), based on Drever *et al.* (2021) at both 2030 and 2050, as detailed in Tables 3.2, 4.4, 5.2, and 6.2. Costs are the mean marginal abatement costs (MAC) for 2030, as reported in Cook-Patton *et al.* (2021), with the exception of restoration of forest cover, which also includes an estimate of the 2050 mean MAC in parentheses. The remaining columns are based on the Panel's assessment framework outlined in Section 1.2.3, which includes consideration of factors impacting permanence and feasibility (here indicated as barriers to implementation and enhanced use of NBCSs). Each column was assessed in terms of either quality of evidence (represented with *) or the Panel's confidence in the estimate provided (represented with †). Full details and definitions for rating scales are presented in the Appendix.

Successful implementation of NBCSs can meaningfully contribute to climate change mitigation, however, they will not achieve Canada's GHG reduction targets on their own

The NBCSs considered by Drever *et al.* (2021) were estimated to have the technical potential of approximately 78 Mt CO_2e/yr in 2030, ranging between 41 and 115 Mt CO_2e at a 95% confidence interval. In contrast, data for Canada extracted from Roe *et al.* (2021) provide an estimated total technical mitigation potential for a similar set of interventions as ~1,286 Mt of CO_2e/yr between 2020 and 2050. The disparity between Roe *et al.* (2021) and Drever *et al.* (2021) is primarily driven by differences in constraints on where wetland and forest NBCSs can be implemented and/or harnessed. In the Panel's view, this results in significant overestimation in many cases of mitigation potential by Roe *et al.* (2021). As such, the Panel notes that estimates by Drever *et al.* (2021) generally provide a more credible and useful baseline for Canadian policymakers, although the assumptions or evidence underlying some estimates may similarly result in over- or underestimation, or may be influenced by short-term time constraints (i.e., to 2030).

> "Even achieving the approximate 6% reduction via NBCSs will require aggressive policy support."

According to these estimates, it is unlikely that NBCS emissions mitigation in Canada could exceed 115 Mt CO_2e/yr by 2030, even with aggressive support and deployment. A credible estimate of the overall cost-effective mitigation potential (e.g., carbon sequestration or emissions reductions achievable at $100 per tonne or less) is approximately 40 Mt CO_2e/yr in 2030 (Cook-Patton *et al.*, 2021). This value translates to approximately 6% of Canada's current annual emissions — estimated at 672 Mt CO_2e in 2020 (ECCC, 2022b) — or the equivalent of removing approximately 25.4 million cars from Canadian roads,[33] suggesting that NBCSs would play a supporting and meaningful role in achieving national emissions reduction goals. They would need to complement other stringent policies aimed at reducing emissions from fossil fuel combustion and other sectors to achieve Canada's targets. Even achieving the approximate 6% reduction via NBCSs will require aggressive policy support.

33 The average emissions for passenger cars in Canada between 2010 and 2020 was 36.45 Mt CO_2e/yr (ECCC, 2022c). The number of motor vehicles (not including farm, off-road, or construction vehicles) is 23.421 million (averaged between 2009 and 2019) (StatCan, 2020, 2022). NBCSs, which were estimated to have a mitigation potential of 39.6 Mt CO_2e, would then be equivalent to the emissions reduction of removing 25.4 million passenger cars from Canada's roads.

Forest, agricultural land, grassland, and peatland NBCSs have the highest GHG mitigation potentials nationally between now and 2050

Practices in forest, agricultural land, grassland, and peatland NBCSs have the greatest potential to sequester additional carbon or reduce GHG emissions in the next three decades, though the dynamics and temporal aspects of these NBCSs differ significantly. In the short term, actions that avoid emissions in demonstrably at-risk areas tend to lead to immediate mitigation benefits; these include avoided conversion of forests, grasslands, and peatlands. Yet the Panel notes that, in many instances, demonstrating the additional nature of avoided conversion can be problematic, especially when projecting into the future of mid- to long-term timescales. For example, despite having a relatively high mitigation potential, avoided conversion of peatlands is largely uncertain due to assumptions around the future demand for oil, gas, and minerals (Section 5.3.3). Issues surrounding additionality and leakage may arise as certain areas become protected, and industry moves to use unprotected but still vulnerable areas elsewhere.

Over decades, however, the impacts of improved management and restoration actions become more significant. Restoration of forest cover on managed and unmanaged land has the theoretical potential to sequester more than 25 Mt CO_2e/yr by 2050 in Canada (Table 3.2), though the adoption of these NBCSs at larger scales is subject to many implementation challenges (e.g., access to remote areas for planting, environmental and anthropogenic pressures on land available). The expansion of forest cover may also have slight negative implications as decreased albedo from expanding canopy — and thus surface warming — occurs early, while biomass accumulation from growth accrues slowly over decades as forests mature (Section 3.3.3). In contrast, in agricultural areas, interventions in crop and soil management practices can lead to benefits in soil organic carbon concentrations or emissions reductions on shorter timescales; however, the rate of soil carbon accumulation gradually diminishes over time, eventually reaching a saturation point, and atmospheric fluxes eventually become net neutral (Section 4.4).

Wetland restoration pays off in the long term and at the regional scale

When evaluated at the national scale, the opportunity for increased carbon sequestration in restored coastal and freshwater wetlands is comparatively low with most NBCSs, likely leading to less than 1 Mt CO_2e/yr in additional sequestration. For freshwater wetlands, this largely reflects increased CH_4 emissions in the initial years post-restoration, though once the radiative forcing from CH_4 diminishes (due to its shorter atmospheric lifetime compared with CO_2), these systems will convey greater carbon sequestration in future decades

(Section 5.3.1). Moreover, both peatland and freshwater restoration can yield large CO_2e sequestration on a per-hectare basis, but the area of opportunity in Canada is relatively small compared to other NBCSs, resulting in a smaller national potential.

For marine coastal wetlands, the area of opportunity for restoration may be smaller than other national-scale NBCSs, but the local impacts of restoration may be substantial. For avoided conversion of marine coastal wetlands, existing no-net-loss policies in Nova Scotia, New Brunswick, and Prince Edward Island mean that wetland conservation fails to satisfy the additionality criterion (Section 6.5.2). However, regional differences in the opportunities for these NBCSs are significant (i.e., differences in climate, local hydrology, vegetation, and policy); such NBCSs could still play an important role in regional GHG mitigation actions, while simultaneously enhancing the ecosystem services and other co-benefits that flow from these systems.

7.2 Assessing NBCS Uncertainties, Including Considerations of Permanence and Feasibility

What are key uncertainties, and to what extent may achievement of enhanced sequestration be affected by impacts of climate change, carbon leakage (e.g., displaced elsewhere), non-additionality (e.g., sequestration would have happened anyway), impermanence (e.g., due to wildfires, drought, or land conversion) and other implementation issues?

National-level estimates of NBCS mitigation potential in Canada are based on limited evidence and many remain subject to high levels of uncertainty

Evidence of changes in GHG fluxes specific to Canadian NBCSs and carbon sinks is often limited, and studies based on similar ecosystems in other regions are not always applicable. Impacts on ecosystem processes associated with the higher latitude of Canadian terrestrial and coastal ecosystems can make studies from elsewhere in North America (or other temperate areas) less relevant (e.g., seagrass meadows; Chapter 6). Uncertainties are magnified when attempting to estimate the national GHG mitigation potential of these practices across Canada. These estimates rely on the ability to calculate the area over which such practices can be deployed and often depend on underlying assumptions that are open to debate (Sections 3.3, 4.3, 5.3, and 6.3). These include considerations and constraints related to jurisdictions and regulatory controls, the feasibility of access, the acceptability of impacts on other sectors or economic activity, the ecological and environmental suitability of regions or areas for a given intervention, social and behavioural barriers to adoption, and the need for intergovernmental coordination.

Even excluding considerations related to socioeconomic feasibility, existing geographical and environmental data are insufficient, in some cases, to identify areas over which NBCSs can be implemented or expanded. For example, the absence of adequate knowledge regarding the extent of seagrass meadows (such as a clear baseline or historical data) results in high uncertainty when estimating the scope of seagrass restoration (Section 6.3.4). While the availability of geographic and environmental data significantly enhances the certainty of an NBCS's potential, the Panel notes that complete datasets are unlikely to be acquired. Thus, the full extent of the area of opportunity for an NBCS is not necessarily required for successful implementation — rather, what is needed is improved monitoring of GHG mitigation and ecosystem processes associated with NBCSs to better understand the potential for implementation.

The vulnerability of Canada's carbon stocks represents a significant climate change liability that could easily counteract any identified mitigation potential

The Panel assessed all carbon stocks associated with NBCSs as potentially vulnerable to being emitted to the atmosphere due to biophysical and socioeconomic factors. Biophysical threats to natural carbon stocks stem from changing temperature and precipitation patterns, as well as sea-level rise. Aboveground forest biomass is vulnerable to release due to increasing risks of wildfire and insect disturbance; wildfires also pose a risk to soil carbon sequestered in forests and peatlands (Sections 3.4 and 5.4). In some cases, coastal wetlands are likely to be "squeezed" between ongoing coastal development and rising sea levels (Section 6.4.1). These impacts vary regionally and are offset by neotectonics and post-glacial rebound on Canada's west and northern coasts, respectively, reducing the rate of sea-level rise and accumulation of tidal wetland soil.

Carbon losses from peatlands due to wildfire and drought may be offset by longer growing seasons and CO_2 fertilization; however, there is significant uncertainty about the implications of permafrost thaw in peatlands, in particular, as it may increase carbon sequestration or enhance carbon losses from the current soil stocks (Section 5.4.3). Similarly, the longer thermal stratification periods in lakes and reservoirs may lead to prolonged anoxic conditions and increased CH_4

emissions from aquatic systems (Section 5.4.4). In the agricultural sector, the primary biophysical threat is drought (as dry conditions result in soil erosion and degradation), but these systems (much like peatlands in areas of high potential resource extraction) are also at higher risk of losing stored carbon due to socioeconomic factors such as changes in market conditions, policy regimes and incentives, or landowner preferences, which can lead to losses of previously stored carbon (Section 4.4).

NBCSs are also not uniform in the way they affect the vulnerability of carbon stored in these systems. For example, some forest management NBCSs (fire management activities, including Indigenous cultural burning; Box 3.3) may decrease the risk of large losses of stored carbon (Section 3.6.1). Alternatively, some management practices (e.g., restoration of forest cover with single species) may reduce resilience to future disturbances (e.g., insect-related disease outbreak) and are less likely to effectively store carbon over longer time periods (Section 3.3.2). The Panel notes that increased release of carbon from natural sources may reduce the efficacy of NBCSs, and thus, the protection and/or conservation of these systems is imperative to achieve successful climate mitigation.

> "Increased release of carbon from natural sources may reduce the efficacy of NBCSs, and thus, the protection and/or conservation of these systems is imperative to achieve successful climate mitigation."

A comprehensive assessment of carbon sink potential requires factoring in political and socioeconomic aspects related to feasibility and cost of implementation

Estimates of mitigation potential can be misleading given costs, jurisdictional challenges, and socioeconomic barriers to the implementation of NBCSs in some sectors (Section 2.3). Understanding the practicalities of implementation requires consideration of both the direct costs of these interventions, as well as related factors such as opportunity costs associated with other potential land-uses, social and cultural barriers to adoption, the risks of emissions leakage, and the availability of suitable policy and regulatory tools for supporting deployment (e.g., markets, payments for ecosystem services) (Sections 3.5, 4.5, 5.5, and 6.5). Drever *et al.* (2021) estimated that the cost-effective potential GHG mitigation of NBCSs in Canada is roughly half (51%) of their estimated total technical potential. Roe *et al.* (2021) estimated that ~30% of their estimated technical GHG mitigation potential in Canada is below the cost-effective threshold of \$100/t CO_2e.[34] Cost estimates underlying these calculations are based on limited evidence, often extrapolated from a few studies focusing on specific regions or contexts. Limited consideration of factors such as leakage, commodity market effects, efficacy of policy instruments, additionality, transaction costs, and behavioural or social resistance to the adoption of new practices means that they are more likely to be underestimated than overestimated. In the Panel's view, more research assessing these factors is needed.

In the Canadian context, lower-cost abatement opportunities averaging less than \$50/t CO_2e include most agroforestry NBCSs, as well as avoided conversion of mineral wetlands and adding legumes to pastures (Table 7.1). The Panel notes that, although agroforestry practices are estimated to be relatively cost-effective, these costs are likely to be underestimated and will be affected by uncertainties, such as issues of reversibility and unaccounted-for nuisance costs. NBCSs achievable at slightly higher costs — between \$50 and \$100/t CO_2e — with relatively short-term mitigation effects include improved forest management, avoided forest conversion, cover crops, reduced or no-till practices, and nutrient management; most of these NBCSs are included in the Highest Overall Promise category of Figure 7.1.

For some of these NBCSs, implementation may even be associated with lower cost or even no-cost opportunities, depending on local soil and environmental characteristics (e.g., nitrogen management). Other NBCSs in this cost bracket have either a low mitigation potential on a national scale, or their effects are only realized at long timescales. For example, tidal wetland restoration (with an average marginal abatement cost (MAC) of \$89/t CO_2e) has a regionally limited mitigation potential and low Panel confidence in the MAC itself. In the short term, restoration of forest cover has a very high MAC (\$1,203/t CO_2e in 2030); however, when considered over the long term, the costs are reduced to \$96/t CO_2e and the mitigation potential increases as trees gradually sequester carbon, offsetting initial capital expenditures associated with their implementation over a longer timeframe (Section 3.5.1). The high costs associated with the remainder of NBCSs most commonly stem from opportunity costs associated with forgone revenues (e.g., avoided peatland conversion).

34 In this case, the largest difference between the cost-effective and technical potential comes from the restoration of forest cover, of which only 12% of the total technical potential was estimated as cost-effective.

Highest Overall Promise

Scientifically well understood to provide moderate to high CO_2e sequestration or emissions reduction, with low to moderate socioeconomic barriers to implementation and biophysical risks to permanence

Crop management

Soil management

- Biochar has a high cost

Nitrogen management

Improved forest management

- High socioeconomic vulnerability to release

Restoration of forest cover

- Low potential and high cost in 2030
- Major barriers to implementation

Improved forest management

- High socioeconomic vulnerability to release

Avoided freshwater mineral wetland conversion

Improved grassland management

Grassland restoration

Tidal wetland restoration

+ Moderate scientific understanding of magnitude and low socioeconomic vulnerability to release
- Some socioeconomic barriers to implementation

Seagrass restoration

+ Moderate scientific understanding of magnitude
+ Limited scientific understanding of area of opportunity
- Moderate costs

Lower Risk, Lower Reward

Low sequestration or emissions reduction potential, and low to moderate scientific understanding, but with low to moderate socioeconomic barriers to implementation and biophysical risks to permanence

Comes at a Cost

Moderate sequestration or emissions reduction potential, with moderate to high socioeconomic barriers to implementation and biophysical risks to permanence, and low-moderate scientific understanding

Agroforestry
- ⊕ Lower costs for silvopasture, alley cropping, and shelterbelts

Avoided grassland conversion
- ⊕ Good scientific understanding of carbon fluxes

Avoided peatland conversion
- ⊕ Good scientific understanding of carbon fluxes

Urban canopy cover
- ⊕ Good scientific understanding of magnitude
- ⊕ Low biophysical vulnerability

Seagrass conservation
- ⊕ Minor socioeconomic barriers
- ⊕ Limited understanding of area of opportunity

Peatland restoration
- ⊕ Low socioeconomic vulnerability
- ⊕ Good scientific understanding of magnitude and socioeconomic barriers

Freshwater mineral wetland restoration
- ⊕ Good scientific understanding of magnitude, biophysical risk, and socioeconomic barriers

Lowest Potential

Low CO_2e sequestration potential with high socioeconomic barriers to implementation and biophysical risks to permanence, and low-moderate scientific understanding

Positive ⊕ or Negative ⊖ Deviation from the Grouping

Figure 7.1 Categorization of NBCSs to 2050 at a National Scale

The Panel's groupings of NBCSs (to 2050) based on four criteria: (i) magnitude of sequestration/emissions reduction potential at the national scale, (ii) socioeconomic barriers to implementation, (iii) biophysical risks to permanence, and (iv) scientific understanding of categories (i)–(iii). Categorization of NBCSs is based on the evidence presented in Chapters 3–6 and the Panel's corresponding assessment, using the same criteria as Table 7.1. The positive (+) or negative (-) sign represents instances in which one of the identified criteria deviates from the overall category the NBCS has been placed within.

The Panel notes, however, that these MACs represent only the mean value of the economic cost for each NBCS, and real costs may vary significantly depending on local and regional factors. Further, the costs presented below, calculated by Cook-Patton *et al.* (2021), do not include values associated with transaction or monitoring costs. Grafton *et al.* (2021) estimated that transaction and monitoring costs could add an additional 9–47% to the overall cost of an NBCS. In addition, Cook-Patton *et al.* (2021) assumed that land is permanently allocated for NBCS use in the opportunity cost analyses, while, in reality, some land could be switched out of NBCS use if lower-cost mitigation options become available, or if decarbonization of the economy sufficiently advances.

Outside of costs, the Panel evaluated feasibility based on a categorical scale measuring the severity of barriers to adoption and deployment. Of the NBCSs assessed, four were found by the Panel to have relatively minor barriers to adoption: crop management, improved grassland management, avoided conversion of freshwater mineral wetlands, and avoided conversion of seagrass meadows. The feasibility challenges in other NBCS categories are more significant for various reasons, including behavioural and sociocultural factors that may slow adoption rates on private land (e.g., agroforestry NBCSs). Among forest NBCSs, feasibility challenges stem from a variety of factors, including access, consistency with current timber harvesting and forest management practices, and potential conflicts with other public land management objectives (Section 3.5). Restoration of forest cover was deemed by the Panel to have high initial costs, and implementation may be regionally constrained due to a variety of factors, including agricultural demand, infrastructure development, and extractive industries (Section 3.5.1).

However, as the price of carbon increases, economic investment in the restoration of forest cover may become increasingly viable in Canada, so long as mechanisms are available for forest managers to realize these benefits and there is agreement among the complex assessments of land-use changes and decisions at the agriculture-forestry interface (Section 3.5). Current biophysical barriers associated with expanding restoration of forest cover in remote and northern areas may be impacted due to warming conditions and extending growing seasons, though ultimately these climate changes will alter boreal forest species composition and result in a lagged increase in tree canopy (Section 3.4). However, some forest management practices (e.g., changing use of harvest residue and harvested wood products) and avoided peatland conversion also face notable barriers to deployment based on costs and other implementation challenges within existing forest management and harvesting systems (Sections 3.5 and 5.5).

Indigenous self-determination is a precondition and catalyst for the implementation, adoption, long-term deployment, and success of NBCSs

All carbon stocks across Canada are on the traditional territory of Indigenous Peoples and these communities are critical to the long-term success of many NBCSs. As such, the Panel notes that the story of carbon sequestration in Canada is intrinsically interconnected with ongoing Indigenous-led land and resource management (and by extension, reconciliation). This is seen most explicitly in the concept of *all my relations* (Section 2.4), which acts as a reminder that everything is connected, including the air we breathe, the water we drink, and the land we walk on (Nandogikendan, n.d.). The ecosystems within which communities exist are conserved and cared for — a natural extension of the respect one gives to any relation. As a result of this care, the carbon stored within these ecosystems has also been conserved. Thus, in the Panel's view, the benefit of enhanced carbon sequestration in many of these ecosystems is the direct result of Indigenous stewardship over land and water.

Advancing the self-determination of Indigenous Peoples has the potential to enhance carbon sequestration and emissions reductions and, in turn, contribute to Canada's environmental targets, such as GHG emissions reduction goals. When communities themselves engage in ecosystem management efforts, in accordance with their traditions and values, decision-making processes for sustained NBCS use may be enhanced (Sections 3.2, 4.2, 5.2, and 6.2). The Panel believes that Indigenous governments and communities are best placed to effectively manage the natural environment in ways that both strengthen the conservation of current carbons stocks as well as enhance the ongoing sequestration of atmospheric carbon and reduction of emissions.

As agreements extending beyond local ecosystems to the broader issues of self-determination and land sovereignty, existing and future IPCAs may be effective in respecting Indigenous communities, their relationships to the land, and the environment more generally. While the Panel notes that IPCAs may not always be established in areas facing an imminent threat of land-use conversion (resulting in their inability to be considered additional), the main purpose of IPCAs is not to enhance NBCSs but rather to codify self-determination for Indigenous communities (Sections 5.2 and 6.2). Although this acknowledgement and respect for self-determination may result in increased carbon sequestration, as discussed above, it ought not to be considered a requirement in the application and approval processes. At their most fundamental, IPCAs represent land and water management agreements that function within the boundaries of a community's goals; only when a community chooses to enter into partnerships with federal, provincial, or territorial governments for the purpose of enhanced carbon sequestration or emissions reductions do these practices become potential NBCSs (Section 2.4). As such, it is important for the federal government to be aware of the multifaceted nature of these Indigenous-led relationships, to ensure that IPCAs remain a tool of self-determination rather than colonization.

Another example of collaborative and respectful relationships between Indigenous and non-Indigenous communities are Indigenous Guardians programs (Section 3.2). As Indigenous-led bodies that collaborate and engage with land-users, industry representatives, researchers, and governments directly, Indigenous Guardians ensure communities have the capacity to make well-informed decisions based on the values and priorities they choose. By fostering self-determination and ensuring that free, prior, and informed consent is achieved in all land management decisions, Indigenous Guardians can serve to ensure that self-determination and Indigenous governance structures are respected and upheld when discussing potential NBCSs (Section 2.4). Other initiatives, such as the Buffalo Treaty in the prairie provinces (Section 4.6.2) and Indigenous-led carbon credit programs in British Columbia (Box 3.2), further reinforce the idea that, when traditional ways of being and knowing are centred in land management decision-making processes, carbon sequestration and emissions reductions may result from the increased economic autonomy and enhanced livelihoods of community members. In the Panel's view, these are all attributes that will increase the likelihood of sustained management and monitoring of NBCSs.

"While many NBCSs may have high technical and economic potential, there is no guarantee of high adoption rates due to the context-dependent nature of individual decision-making."

Behavioural barriers are a significant but uncertain element in determining the feasibility of NBCSs

Behaviours in the form of cognitive, emotional, and social characteristics of a given individual, community, organization, or institution can negatively impact the feasibility of an NBCS. Behavioural barriers are therefore also uncertain. While many NBCSs may have high technical and economic potential, there is no guarantee of high adoption rates due to the context-dependent nature of individual decision-making (Section 4.5.2). Certain behaviours can impede acceptance of NBCSs despite high mitigation potential and cost-effectiveness. Land-use change for restoration of forest cover, for example, may be resisted due to the perceived value and prioritization of land for agricultural production over forested area, as well as potential difficulties associated with negotiating contracts for such practices on public land (Section 3.5). In the agricultural sector, farmers may be particularly risk-averse, viewing the potential of reduced crop yields as outweighing the environmental and economic benefits of improved nitrogen management (Section 4.5.2).

Additionally, the Panel notes there is a potential for optimism bias — the tendency for individuals to believe they are less likely to experience negative outcomes than others. This bias could impede the acceptance of NBCSs; though individuals may view practices to mitigate potential harm as beneficial, they may not view them as necessary for the success of their particular project. Overall, behavioural barriers represent a critical element in feasibility considerations despite their considerable uncertainty.

Increased monitoring of NBCSs is needed to realize their full potential

The Panel identified accurate and sustained monitoring of NBCSs as critical and necessary across all ecosystems and action types, although approaches will vary. Many of the NBCSs discussed in this report rely on sparse or coarse datasets, some of which may not represent the complexities and variances associated with carbon stocks and fluxes (Novick *et al.*, 2022). This lack of data results in uncertainties at the policy level, where issues of additionality or permanence may be overlooked and the benefits and impacts of NBCSs may not fully be understood (Novick *et al.*, 2022). In the agricultural sector, for example, the need for comprehensive, centralized, and accessible data for understanding soil organic matter and soil organic carbon trends, in relation to land-use practices and climate change, has been identified as a priority for providing a benchmark for assessing human impacts on soils (Harden *et al.*, 2018). While the International Soil Carbon Network has been promoted as an avenue for achieving this goal (Harden *et al.*, 2018), the Panel believes that Canada could develop a better-resolved monitoring network and platform to help track the relationship between Canadian NBCSs and soil carbon. This would establish the necessary baselines with which to track progress of NBCSs and their responses to climate change (e.g., connecting the National Forest Inventory to the study of climate responses and NBCSs; Section 3.5.3).

Monitoring would ideally also extend to the implementation and practice of policy mechanisms in place, which are meant to support and ensure the success of NBCSs. No-net-loss policies associated with wetlands along the Atlantic coast offer a good example of this issue. Policies requiring that loss of wetlands be offset through the creation or restoration of other wetland areas have the potential to incentivize the conservation of existing coastal wetlands and the associated carbon stocks (Section 6.5.2). However, under this policy approach, a long-term carbon stock could be lost while a new wetland is created that cannot replace the carbon that was lost. Furthermore, policies of this sort have not been uniformly enforced, resulting in ineffective protection and a reduction in the practice's overall magnitude of sequestration potential (Section 6.5.2).

In the Panel's view, comprehensive monitoring and enforcement of policies (provincial/territorial and federal) related to the conditions of an NBCS's operation are critical in ensuring the benefits of each practice are truly realized. Moreover, in ensuring that monitoring is comprehensive, the Panel believes additional benefits may be gained from NBCSs, such as increased knowledge of the ecosystems in which these actions are being carried out. This increase in knowledge may further benefit decision-makers by increasing overall confidence in how well-informed decisions may be.

Increased monitoring of NBCSs will also improve knowledge about the cost-effectiveness of these activities. In many instances, cost estimates are based on synthetic calculations of amounts landowners are paid for the delivery of NBCSs (Section 2.3.1). More information about the successes (or shortcomings) of NBCSs would allow decision-makers to better assess the true costs of these actions, which may be different than the simulated costs. This is critical if carbon-related markets are to be established. However, the Panel notes that increased NBCS monitoring does not come without added costs, which must also be considered in assessing the feasibility of any given project or activity.

7.3 Assessing NBCS Co-Benefits and Trade-Offs

> *What are the implications, benefits, or risks of implementing nature-based solutions focused on enhancing carbon sequestration, including for biodiversity, ecosystem services, economic factors, and Canada's GHG emissions?*

Many NBCS co-benefits have been described in this report: positive impacts on biodiversity, promotion of soil health, protection from hazards such as flooding, and space for social and cultural activities. Similarly, trade-offs to the implementation of certain NBCSs have been discussed, including risks to livelihoods, climate impacts and feedbacks (excluding impacts on CH_4 and N_2O fluxes and changes in albedo of land cover), though competing land-use priorities are unavoidable in many contexts. When considering all NBCSs, several common themes emerge that can inform decision-making about which NBCSs are most appropriate for implementation in specific places.

Wider implementation of many NBCSs in Canada may be desirable due to their co-benefits, even in the absence of the additional carbon sequestration they provide

Many NBCSs are associated with well-documented positive co-benefits in terms of ecosystem services, biodiversity protection, cultural value, and climate change adaptation. They can provide tangible social and economic co-benefits, including those associated with property values (e.g., scenic/aesthetic amenities, water quality improvements), avoided flood damages, improvements in recreation experiences, and improvements in threatened species' conditions (Sections 3.6, 4.6, 5.6, and 6.6). Even where GHG mitigation benefits are low, these co-benefits alone may justify wider adoption of such practices. For example, despite a relatively low potential for carbon sequestration, the restoration and preservation of marshes in the Prairie Pothole Region have a multitude of positive effects, including habitat for endangered species, flood protection, maintenance of water quality, and recreational services (Section 5.6). Similarly, the climate mitigation effects of urban forests are relatively minor, and the costs far outweigh the benefits if carbon sequestration is the only consideration. Yet, urban forests contribute to reducing temperatures in cities, with the potential to save lives by reducing the urban heat-island effect (Section 3.3.2). Protection and restoration of coastal wetlands contribute to climate change adaptation by protecting coasts and communities from storm surges and erosion; proper management of these ecosystems can translate to significant savings from disaster impacts (Section 6.5.1). These examples illustrate the importance of considering opportunities to co-fund or implement NBCSs in conjunction with actors or decision-makers with responsibilities outside of carbon sequestration, although the Panel notes that, in such circumstances, carbon sequestration (or reduced emissions) should be considered a co-benefit itself rather than the motivation for conservation or restoration.

However, these co-benefits will vary depending on the location of the NBCS activity and the surrounding natural and human environments. They will also depend on other factors that affect land use, such as human population growth, urbanization, and economic conditions of the energy, agricultural, and forestry sectors. This variation is reflected in the economic valuation ranges for ecosystem services. Relatively little is known about the economic value of ecosystem services in Canada (Olewiler, 2017); though many exist, the overall number of studies per year has not increased since 1975, and there are many research gaps in terms of certain resources (such as air quality) and location (with very few studies in the territories) (Macaskill & Lloyd-Smith, 2022). Despite this, the demand for environmental valuation research remains. To properly estimate the value of NBCS co-benefits, further study is warranted in: up-to-date and regionally distributed studies, promising practices in non-market valuation methods, changes to peoples' behaviours and preferences, as well as to the state of the environment itself (Macaskill & Lloyd-Smith, 2022).

Several of the benefits discussed in previous chapters are more intangible than the perceived trade-offs. For example, a study of the behavioural aspects required for the conversion of shelterbelts found that the costs for planting and upkeep of trees were weighed much more heavily by landowners than the potential long-term benefits of shelterbelts (Section 4.5.2). These long-term benefits include carbon sequestration, improved aesthetics, and enhanced biodiversity, and are all more difficult to quantify than start-up and maintenance costs. Certain forest management practices (i.e., restoration of forest cover) have similar challenges, where the carbon benefits may only be seen decades in the future, while implementation may require upfront costs (Section 3.5.1). Conservation and restoration of wetlands is also subject to this tension. High upfront costs to restore or protect a wetland are juxtaposed with benefits such as flood protection (which may not be apparent in the short term) or benefits to biodiversity (which may take years to manifest and whose value is subjective). Additionally, restoration of mineral-soil freshwater wetlands may result in upfront increases in CH_4 emissions — a notable trade-off in terms of climate mitigation, with the contribution to atmospheric cooling felt only decades after implementation (Section 5.3.2). As such, the Panel believes it is important to ensure consideration is given to both relevant co-benefits and costs when assessing the value of NBCSs — costs and/or related trade-offs for practices must take into account the various additional benefits that may be accrued with successful implementation; however, any co-benefit itself must similarly be evaluated against the costs of the action, as well.

A better understanding of the value of co-benefits, supported by policy, can help reduce perceived market-related trade-offs

Negative market-related effects, and the uncertainties associated with them, are primary trade-offs when implementing NBCSs. Loss of yield in crops or wood products, reduction in profits, and risks to employment are all cited as significant concerns to those considering NBCSs. For example, reducing fertilizer use can have direct impacts on the growth of crops, thereby affecting yield and profits among agricultural producers who are increasingly pressured by markets and demand for food (Section 4.5.1). Reducing horticultural peat extraction or preventing the expansion of oil, gas, and mineral exploration or mining activities in peatlands will directly impact industries, reducing employment opportunities and significantly affecting profits (Section 5.6). Reducing the harvest of forests and avoiding forest conversion will inherently reduce yield in forestry operations and can potentially heavily impact communities that depend on logging for employment (Section 3.6.2). These trade-offs should be carefully considered when implementing NBCSs but should not act as a deterrent — while initial costs may increase, some costs may be temporary (e.g., employment adjustments). More importantly, making strides to better quantify co-benefits, and using policy mechanisms and funding programs to incentivize the adoption of NBCSs and mitigate some of these trade-offs, can help reduce the overall negative market-related effects.

Although an exhaustive review of policies, programs, and regulations for the implementation and continued use of NBCSs across Canada is outside of the scope of this report, the Panel discussed several avenues that may hold promise for achieving the goals of carbon sequestration through NBCSs. For example, the integration of forest-based resources into climate policy frameworks, clarity on policy mechanisms that incentivize sequestration or avoided conversion, the alignment of reporting requirements among different sectors, no-net-loss policies, and policies to value intact ecosystems can all work to advance NBCS uptake in Canada (Sections 3.5.2, 5.5.2, and 6.5.2). Carbon credit programs in the agricultural sector and cross-compliance within Business Risk Management programs have been suggested as ways to advance NBCSs in Canada, though not without drawbacks and trade-offs (Section 4.5.2). Other programs and agreements, such as Indigenous Guardians and IPCAs, offer the potential to conserve at-risk carbon stocks while advancing Indigenous self-determination, as discussed in Section 7.2.

When choosing appropriate policies for implementing NBCSs, the Panel emphasizes the importance of assessing both private and public costs and benefits, particularly when dealing with private landowners. Decision-making structures for choosing among policy options underscore the complexity of private vs. public benefits and employing the most effective policy designs and incentives or penalties for striking a balance between them (Section 2.3.2). Critically, policies for advancing the use of NBCSs must be designed for geographic and environmental characteristics unique to the ecosystems, regions, and political contexts in which they are deployed.

This regional variation does not preclude action on a national scale. The Panel emphasizes that, despite the regional variability of many of the solutions discussed throughout this report, there are opportunities for decision-makers to make progress on implementing NBCSs across jurisdictions. For example, the *Declaration of the Premiers of Canada* includes commitments to "promote actions that support intergovernmental and cross-sector linkages in addressing climate change and that are inclusive of all sectors of the economy; implement programs and measures to adapt to climate change and reduce GHG emissions; [and]

implement policies to reduce GHG emissions," among others (Premiers of Canada, 2015). These pledges are relevant to NBCSs and provide a potential avenue to implement, monitor, and improve them nationally while maintaining regional specificity and mitigation. Nevertheless, the design, development, and evaluation of policies for cost-effective implementation of NBCS programs remain key uncertainties associated with the future of such programs in Canada and, in the Panel's view, deserve further research.

Some NBCSs are incompatible with each other or other land management objectives, while others are complementary

Additional considerations in the implementation of NBCSs are their interactions with broader land management objectives, as well as with each other. In the forestry sector, for example, assessing the balance of co-benefits and trade-offs is complex and subject to higher levels of uncertainty due to the often-incongruent nature of NBCSs with many current land management goals. Intensively managing forests in support of the production of harvested wood products (HWPs) could jeopardize other forest management priorities (e.g., providing habitat for wildlife, or ensuring forest diversity, resilience, and climate adaptation), depending on assumptions about the GHG emissions associated with maintaining, harvesting, and using HWPs. However, there is uncertainty in accounting for carbon stored in HWPs (Section 3.3.1). Furthermore, actions that require increased harvesting, such as the use of HWPs and harvest residue for biofuels, are directly at odds with other forest NBCSs, such as extended rotations, which sequester carbon through reduced harvesting (Section 3.3.2). This demonstrates that there are many pathways to reducing emissions or sequestering carbon, but not all contribute to other policy and land management objectives.

NBCSs can also be complementary. Nitrogen management, and fertilizer management in general, will not only have direct impacts on N_2O emissions from fields and croplands where fertilizer is applied but also help reduce emissions from downstream freshwater and marine ecosystems (Section 4.6.1). The management of fertilizers is related to the wider concept of watershed management, where decisions around land uses consider all downstream effects for rivers, lakes, and wetlands (including control over harmful algal blooms). Employing nutrient management on a watershed scale conveys widespread environmental benefits, both for emissions reduction and for water quality and ecosystem health.

7.4 Contributions to Global Emissions Pathways and Warming

To what extent do Canadian carbon sinks and potential enhanced sequestration influence or contribute to future global emission pathways and warming, consistent with the Paris Agreement goal of holding global average temperature increases to well below 2°C?

NBCSs can play a modest but important role in contributing to Canada's GHG mitigation goals and targets

It has been suggested that, on national and international scales, NBCSs can provide emissions reductions of up to one-third of the total current annual global emissions, either through the intentional enhancement of carbon sequestration or reduction in GHGs released to the atmosphere (Griscom *et al.*, 2017; Roe *et al.*, 2021). Such practices, alongside fossil fuel emissions reductions, will contribute meaningfully to meeting the goal of the Paris Agreement of holding the global average temperature increase to between 1.5–2°C. In Canada, there is awareness of the opportunities for carbon sequestration and emissions reductions offered by ecosystems across the country, as evidenced by the Government of Canada's strengthened climate action plan and commitment to invest over $3 billion in NBCSs over 10 years (ECCC, 2020a).

While the opportunities presented by NBCSs are real, they should be considered in the context of the overriding need to decarbonize energy systems and reduce emissions. Based on the review and estimates of Drever *et al.* (2021), NBCSs that are cost-effective in the short term (between now and 2030) are unlikely to offset more than 6% of Canada's current GHG emissions. And while the potential of these solutions may increase (or decrease) in the long term, there is currently no available evidence to accurately determine their influence beyond 2050. Accordingly, NBCSs cannot be fully relied upon to achieve international climate commitments such as the Paris Agreement, especially as many of the solutions identified throughout this report are not currently included in Canada's national emissions accounting framework (Section 2.1.5). Instead, NBCSs offer one approach among many to effectively reduce GHG emissions, and their role in international climate policy is best considered as a supporting element. Success in meeting climate mitigation goals and targets will require a suite of other actions by foreign governments, most importantly those achieving ongoing, deep, and sustained reductions in emissions from fossil fuel combustion.

Canada can foster greater awareness and knowledge about NBCSs through their implementation, accelerating their deployment elsewhere and leading to additional emissions mitigation benefits

Although the climate impacts of NBCSs within Canada are small in a global context, more widespread adoption of these approaches can yield co-benefits related to international carbon sequestration efforts. Canada is one of the most ecologically diverse countries in the world, featuring extensive deciduous and coniferous forests, native grasslands, inland waterways and wetlands, Arctic tundra, and vast coastlines; as such, it is in a unique position for implementing and promoting NBCSs across multiple ecosystems. In their analysis of increasing support for NBCSs in the European Union, Faivre *et al.* (2017) outlined four critical components required for such promotion to be successful: "building the evidence base," creating a "repository of best practice examples," "creating [an NBCS] community," and "creating [widespread] awareness." Canada is well positioned to fulfill these goals.

In the Panel's view, increased use and monitoring of NBCSs domestically will allow for innovation, experimentation, and expansion of concepts, providing new evidence and helping to identify promising practices across different ecosystems and land-use sectors. Knowledge gained by Canadian researchers and practitioners can, in turn, be shared among governments and practitioners in other jurisdictions, enhancing Canada's readiness and resilience to climate change. It may even benefit further as this community of practice expands and NBCS knowledge-sharing across borders increases. Such learning-by-doing is critical if the higher levels of NBCS mitigation potential estimated by some studies (e.g., Griscom *et al.*, 2017; Roe *et al.*, 2021) are to be achieved. Additionally, as the practice of these NBCSs expands globally, the evidence required to support them will likewise increase, and many of the identified knowledge gaps and uncertainties may be resolved (e.g., area of opportunity).

Applying NBCSs can help lessen the risks of rising GHG emissions from Canadian ecosystems, which are of global significance and represent a liability to successful global climate change mitigation

The global climate risks associated with increasing (and accelerating) emissions from Canada's terrestrial, aquatic, and coastal ecosystems are substantial — in contrast with the more modest mitigation benefits of NBCSs. Wildfires have been responsible for hundreds of Mt of CO_2e emissions from Canadian forests and peatlands in recent years (Sections 3.3.1 and 5.4.3), and such fires are predicted to become more common and intense as the temperature rises. Wetlands across Canada are also threatened by increasing temperature, which may lead to heightened atmospheric emissions (Section 5.4.3). While subject to considerable

> "Limiting warming to 1.5–2°C will likely only occur in the face of forward-looking climate mitigation policies that move rapidly to reduce anthropogenic emissions across sectors, since Canadian NBCSs will not be able to single-handedly safeguard carbon within such ecosystems."

uncertainty in terms of magnitude, permafrost thaw

uncertainty in terms of magnitude, permafrost thaw in northern Canada has the potential to increase carbon emissions far beyond that which can be sequestered through current NBCSs (Box 2.2).

These emissions could have globally significant impacts, turning current natural carbon sinks into significant carbon sources and contributing to climate feedback loops that may amplify and accelerate warming in an irreversible manner (Collins *et al.*, 2013; IPCC, 2014a). In crossing critical climate thresholds, NBCSs may become less effective, sequestering (or reducing emissions of) negligible amounts of carbon in comparison to rising emissions from terrestrial, aquatic, and coastal stocks in response to changing environmental and climatic conditions (Cooley & Moore, 2018). Preserving and protecting Canada's current carbon stocks is of significant importance in combatting global climate change. The Panel recognizes that Canada cannot unilaterally preserve all its current carbon stocks; preservation of which requires a reduction in overall GHG emissions. Limiting warming to 1.5–2°C will likely only occur in the face of forward-looking climate mitigation policies that move rapidly to reduce anthropogenic emissions across sectors, since Canadian NBCSs will not be able to single-handedly safeguard carbon within such ecosystems. However, they can play a role in both contributing to additional carbon sequestration and preserving current stocks from release.

7.5 Panel Reflections

In response to its charge from Environment and Climate Change Canada, the Panel reviewed a wide range of literature on the various NBCSs found across Canada's numerous ecosystems. Beyond reflecting on the technical mitigation potential of the NBCSs identified, the Panel's review resulted in an overall assessment of the various elements that are critical to the design, implementation, and exercise of NBCSs as tools for climate mitigation in Canada, moving forward. These elements, which include the permanence and feasibility of the actions explored, as well as considerations of additionality and the various co-benefits and trade-offs associated with them, all influence the projected success of NBCSs and are thus critical for well-informed decision-making.

The Panel notes that, despite the technical potential of many of the practices identified, attempts to enhance carbon sequestration in ecosystems across the country will not succeed without meaningful cooperation among multiple levels of government as well as various industry and community stakeholders. This includes the incorporation of Indigenous knowledge and leadership as well as the intentional enhancement of Indigenous stewardship over land and water, especially as it relates to self-determination, self-governance, and local environmental control. Because NBCSs are inherently land- and water-based, and because many are closely related to Indigenous land management practices, their relationship with Indigenous Peoples is fundamental, and the expertise, involvement, and leadership of Indigenous Peoples in the design, planning, and execution of these actions is of the utmost importance. Without such involvement, the full potential of many NBCSs may not be realized, and the various co-benefits attached to these practices may not be attained.

Overall, the Panel believes that Canada's — and the world's — future depends on the success of a host of actions across all sectors to mitigate climate change, including, but clearly not limited to, those associated with NBCSs. In the Panel's view, the question moving forward should not be solely about the extent to which rates of natural carbon sequestration in Canada's various ecosystems can be enhanced, but rather about how carbon stocks can be protected in order to enhance the efficacy of the NBCSs identified. Ultimately, natural carbon stocks in Canada will create feedbacks that can be either beneficial or adversarial to our future; in order for NBCSs to be most effective, a pathway of strong climate mitigation must be undertaken.

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Appendix

Evidence Scale

The following scale was adapted from the IPCC's *Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on the Consistent Treatment of Uncertainties* (Mastrandrea *et al.*, 2010). It informed the judgment of the Expert Panel on Canada's Carbon Sink Potential with respect to the robustness of underlying evidence examined for this report.

Limited	**Limited or inconsistent evidence from few studies of uncertain quality or applicability** (e.g., limited availability of peer-reviewed studies and/or evidence from few study sites, questionable applicability to Canadian context, limited applicability to the regional context, limited supporting evidence and/or evidence of uncertain quality/reliability, inconsistent lines of evidence).
Moderate	**Multiple, mostly consistent lines of evidence** (e.g., independent, peer-reviewed studies with mostly consistent findings or evidence from multiple sites; direct or indirect relevance to the Canadian context; regional applicability; possibly supported by other types of evidence, including Indigenous knowledge).
Robust	**Multiple, consistent independent lines of high-quality evidence** (e.g., numerous independent, peer-reviewed studies with consistent findings or evidence from many study sites; direct relevance and applicability to the Canadian and/or regional context; accompanied by additional supporting evidence, including Indigenous knowledge).

Panel Confidence Scale

Limited	The Panel is **not confident** in the quality or applicability of the evidence and/or assumptions underlying the estimated values. Additional lines of evidence are very likely to change the estimates (e.g., Canada-specific evidence, evidence from multiple sites, Indigenous knowledge). Impacts of climate change, though difficult to fully predict in terms of net outcome, are very likely to pose great risks that will shift estimated values.
Moderate	The Panel is **moderately confident** in the quality or applicability of the evidence and/or assumptions supporting the estimated values. Additional lines of evidence could change the estimates (e.g., Canada-specific evidence, evidence from multiple sites, Indigenous knowledge). Impacts of climate change, though difficult to fully predict in terms of net outcome, could pose at least a moderate risk of shifting estimated values.
High	The Panel is **confident** in the quality or applicability of the evidence and/or assumptions supporting the estimated values; additional lines of evidence or climate change impacts are unlikely to substantially adjust the sequestration potential estimates.

Magnitude of Sequestration Potential

The following categories and ranges were used to assess NBCS potential for enhanced carbon sequestration. Sequestration potential was assessed for two separate time periods (between now and 2030, and 2030–2050). In the Panel's judgment, based on available evidence, estimates of sequestration potential represent the likely range or national GHG mitigation potential of the combined amount of carbon sequestration that could be expected with the adoption of related NBCSs in Canada, assuming all technically viable opportunities are taken advantage of at or below a price of $100/t C (this price point is arbitrary, but consistent with the cost estimates of mitigation potential used in other studies).

1	0–1 Mt CO_2e/yr
2	1–5 Mt CO_2e/yr
3	5–15 Mt CO_2e/yr
4	15–25 Mt CO_2e/yr
5	>25 Mt CO_2e/yr

*Mt CO_2e/yr used for consistency with Canada's *National Inventory Report* GHG emissions data.

Permanence

Constraints on permanence were assessed based on the following scale:

Vulnerability to Atmospheric Release	
High	Recent or predicted environmental, climatological, and socioeconomic trends suggest that carbon stored in these systems in Canada is likely (>50% chance) to be released back to the atmosphere within 20 years following NBCS deployment.
Moderate	Recent or predicted environmental, climatological, and socioeconomic trends suggest that carbon stored in these systems in Canada is moderately likely (10% – 50% chance) to be released back to the atmosphere within 20 years following NBCS deployment.
Low	Recent or predicted environmental, climatological, and socioeconomic trends suggest that carbon stored in these systems in Canada is unlikely (<10% chance) to be released back to the atmosphere within 20 years following NBCS deployment.

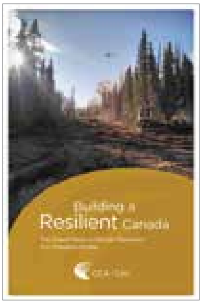
Feasibility

Feasibility was assessed in relation to the extent and severity of barriers impeding the adoption of NBCSs, based on the following scale:

Minor	There are minimal technical, socioeconomic, regulatory, and/or behavioural barriers preventing rapid and sustained adoption of these NBCSs, leaving them with widespread applicability and potential in the Canadian context.
Moderate	Moderate technical, socioeconomic, regulatory, and/or behavioural barriers are likely to impede adoption of these NBCSs, resulting in slower or constrained implementation, and somewhat limiting their applicability and potential in the Canadian context.
Major	Major or pervasive technical, socioeconomic, regulatory, and/or behavioural barriers are likely to prevent the adoption of these NBCSs, except at small scales or in isolated circumstances, strongly limiting their applicability and potential in the Canadian context.

CCA Reports of Interest

The assessment reports listed below are accessible through the CCA's website (www.cca-reports.ca):



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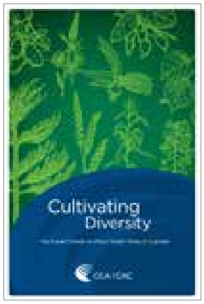

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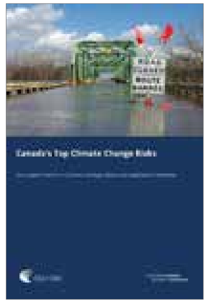

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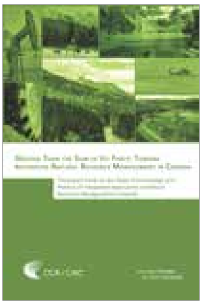
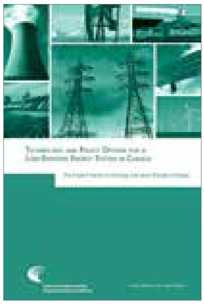


Greater Than the Sum of Its Parts: Toward Integrated Natural Resource Management in Canada (2019)



Technology and Policy Options for a Low-Emission Energy System in Canada (2015)

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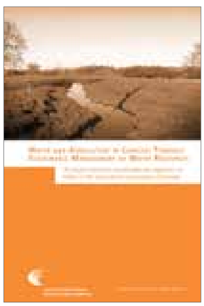
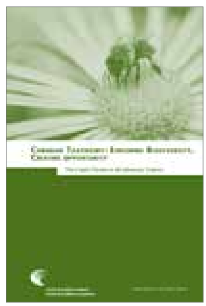


Water and Agriculture in Canada: Towards Sustainable Management of Water Resources (2013)



Canadian Taxonomy: Exploring Biodiversity, Creating Opportunity (2010)

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