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This chapter is an excerpt from the CCA report *Nature-Based Climate Solutions*. Information about the charge, the expert panel authors, the sponsor, other ecosystems, and references can be found in the full report.

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).

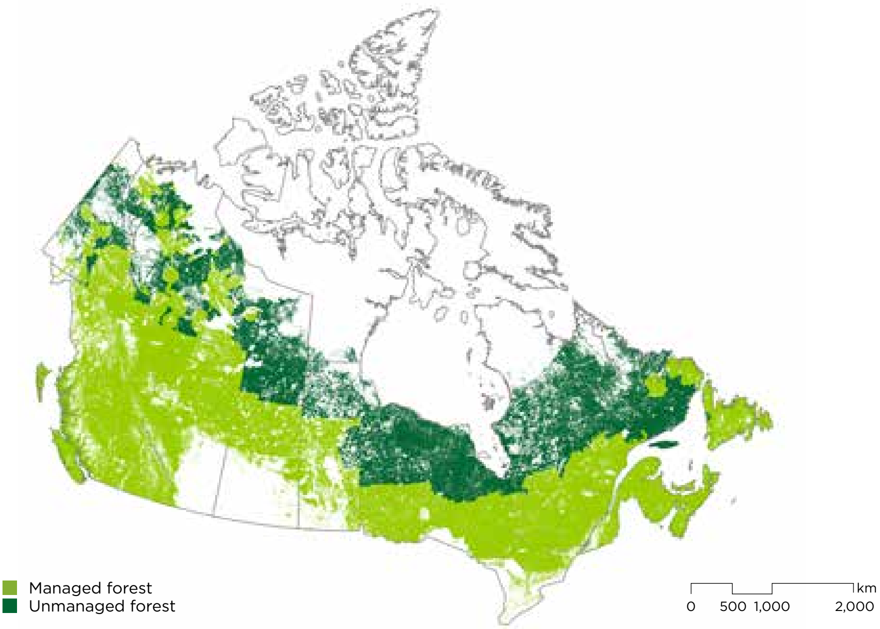

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Figure 3.1 Forest Area in Canada

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

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[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).

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[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

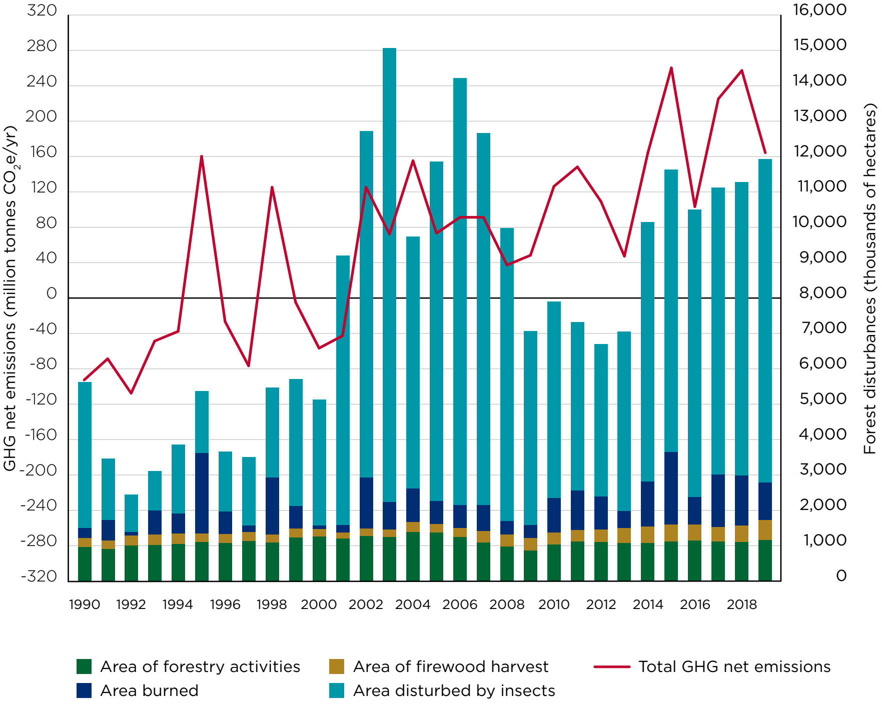
3.3.1 Estimating Forest Carbon Fluxes in Canada

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

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[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

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[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).

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[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.

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[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

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[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.