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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.

Inland Freshwater Ecosystems

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Chapter Findings

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

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

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

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

5.1 Opportunities for Enhancing Carbon Sequestration in Freshwater Systems

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

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

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

Box 5.1 Carbon Storage and Sequestration in Lakes and Rivers

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

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

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

Table 5.1 Freshwater System NBCSs

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

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

5.2 Indigenous Freshwater System Management

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

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

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

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

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

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

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

5.3 Magnitude of Sequestration and Emissions Reduction Potential

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

5.3.1 GHG Fluxes in Wetlands

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

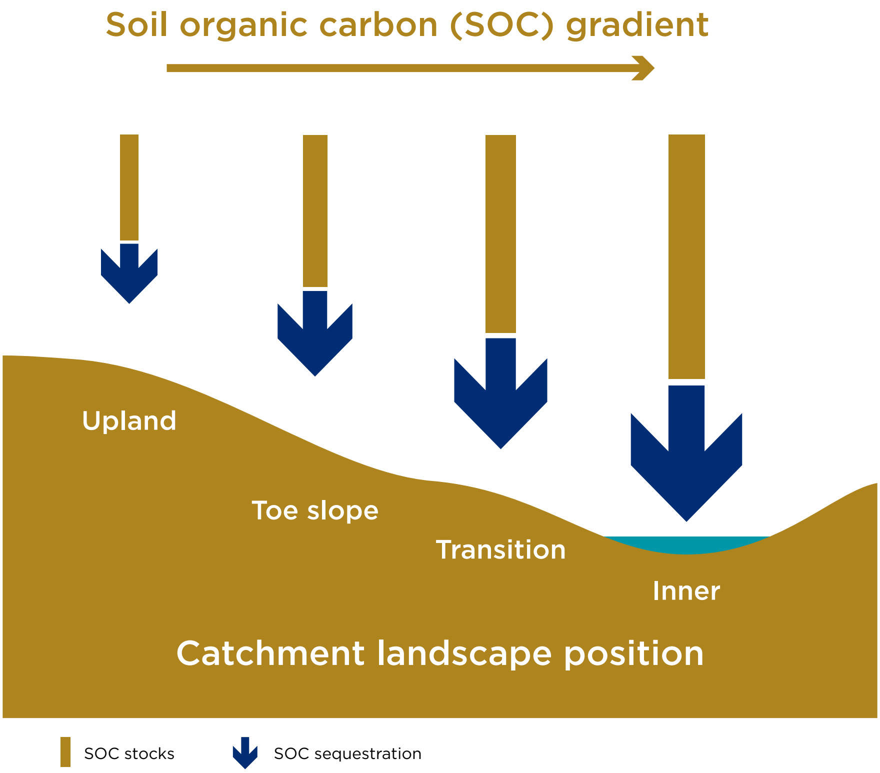
An accurate estimation of GHG fluxes is critical for calculating the sequestration potential of wetland NBCSs. In addition to CO_2 fluxes, it is also important to consider CH_4 and N_2O emissions from wetlands in order to understand the GHG balance. Around agricultural lands, runoff can lead to increased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

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

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

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

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



Adapted with permission: Tangen and Bansal (2020)

Figure 5.1 Gradient of Soil Organic Carbon Storage by Landscape Position

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

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

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

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

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

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

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

5.3.2 GHG Fluxes in Reservoirs

There is significant uncertainty around measuring carbon fluxes in reservoirs

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

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

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

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

5.3.3 Areal Extent and Area of Opportunity for Wetlands

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

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

5.3.4 Areal Extent and Area of Opportunity for Reservoirs

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

5.3.5 Estimating National Sequestration Potential for Wetlands

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

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

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

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

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

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

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

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

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

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

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

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

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

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

5.3.6 National GHG Mitigation Potential for Lakes and Reservoirs

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

5.4 Stability and Permanence

5.4.1 Sustained Sequestration in Wetlands

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

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

5.4.2 Sustained Emissions Reduction in Reservoirs

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

5.4.3 Permanence of Carbon in Wetlands

Carbon sequestered in freshwater wetlands is vulnerable to climatic change

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

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

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

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

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

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

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

5.4.4 Permanence of Carbon in Lakes and Reservoirs

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

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

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

5.5 Feasibility

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

5.5.1 Inland Freshwater Ecosystem NBCS Costs

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

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

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

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

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

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

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

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

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

5.5.2 Policy and Regulatory Challenges

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

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

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

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

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

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

Weak policy enforcement harms wetland protection and restoration

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

5.5.3 Monitoring and Accounting

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

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

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

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

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

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

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

5.5.4 Other Barriers to NBCS Implementation

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

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

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

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

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

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

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

5.6 Co-Benefits and Trade-Offs

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

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

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

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

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

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

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

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

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

5.7 Conclusion

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

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

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