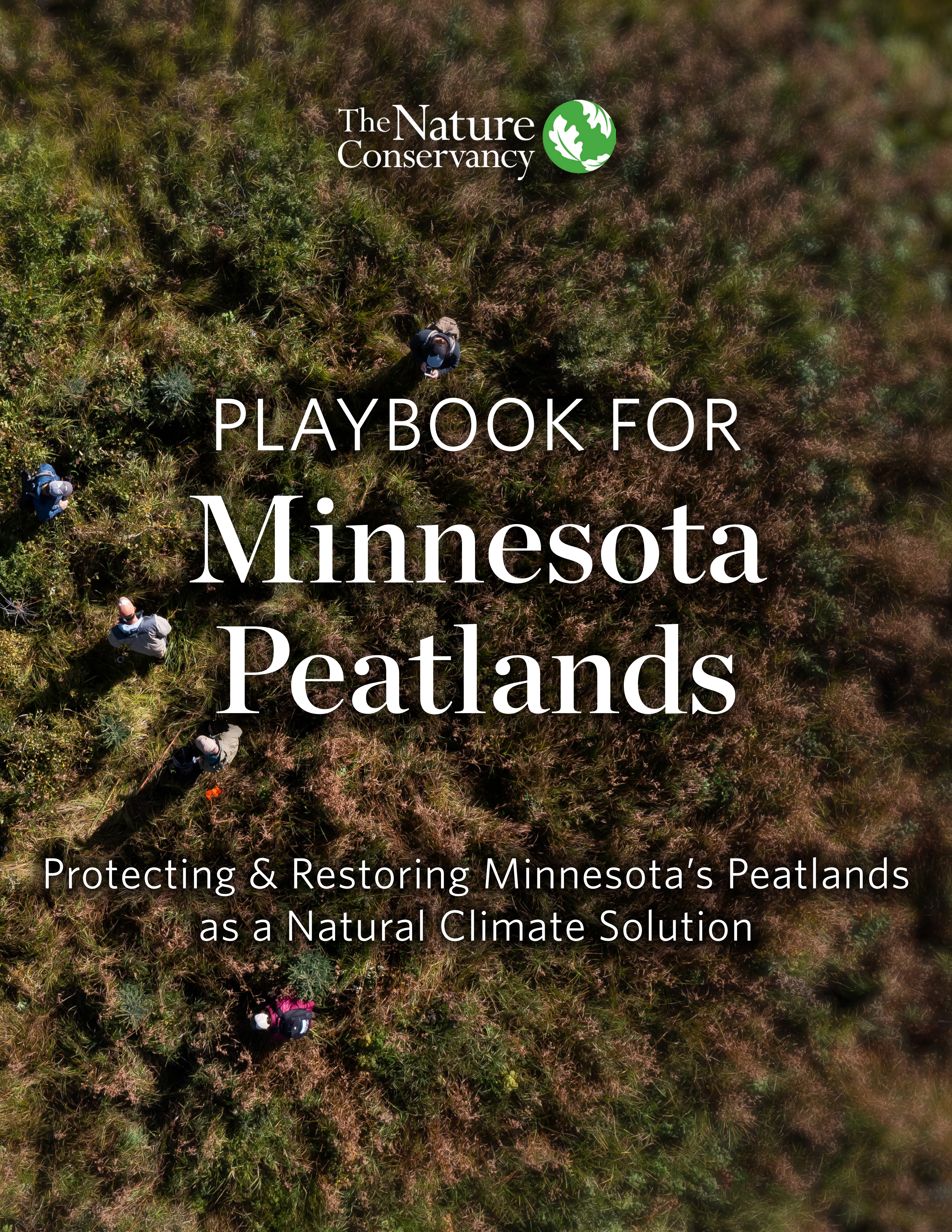

The Nature Conservancy

PLAYBOOK FOR Minnesota Peatlands

Protecting & Restoring Minnesota's Peatlands as a Natural Climate Solution

January 2026 Update/Errata

The original published version of this document cited the MPCA 2022 report Greenhouse gas reduction potential of agricultural best management practices as the source for greenhouse gas avoidance from the retirement and rewetting of cropped and pastured peat soils. Table 32, page 62 of the MPCA report, presented estimated avoided emissions from retiring and rewetting cropped and pastured histosols of 1.48M and 1.04M CO2 equivalent short tons (including accounting for direct and indirect N2O and CH4 effects) per 100,000 acres, respectively, based on an extensive literature review and analysis. In our original Peatland Playbook (January 2025), we incorrectly converted these figures to per acre emissions avoided as 1.34 and 0.95 MT per acre, estimates that were comparable to mid-range estimates from published studies reported in our chapter's NCS Solutions for Minnesota report (2021) and Carbon Calculator (2022). However, the correct conversion should have been 13.4 and 9.5 Mt per acre. In this edition we have revised our estimates in the text and Tables 6 and 8 (pages 45 and 50) using the corrected conversion factors, which substantially raises the estimated emissions reductions benefits of restoring fully drained cultivated and pastured histosols relative to potential gains from re-wetting partially drained peatlands.

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This work would not be possible without the impactful work and collaborations from our many partners across Minnesota and around the world, including but not limited to:

- Pew Charitable Trusts
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- Ecosystem Investment Partners
- SEH Inc.
- University of Minnesota

We would also like to acknowledge that all of the lands and waters discussed in this Playbook are the homelands of the Ojibwe and Dakota peoples, who are the historic and current stewards of this land. As discussed in the Playbook, tribes have been central to peatland protection in Minnesota for centuries, especially at times when white settlers were working hard to ditch and drain these landscapes.

The Nature Conservancy is committed to creating a future in which nature and people thrive, and achieving our mission must encompass inclusion, collaboration, and supporting Indigenous Peoples. We recognize that as an organization that owns and manages land, the systems and regulations of private property, protection, and lands and waters management that have been core to our work came at a dire cost to Indigenous Peoples. With these words, we acknowledge the traditional stewards, past, present, and emerging, and recognize our institutional history, responsibility, and commitment. We are committed to gaining deeper awareness of the history and enduring impacts of colonialism—including our own contributions to this history as an organization—and resulting responsibilities, including building partnerships based on respect, equity, open dialogue, integrity, and mutual accountability.

Adapted from TNC's Voice, Choice, Action Framework: tncvoicechoiceaction.org

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Protecting & Restoring Minnesota's Peatlands as a Natural Climate Solution

Keeping Minnesota's peatlands healthy is critical for achieving climate goals, but a legacy of drainage has compounded the challenge.

Summary

Globally and in Minnesota, natural ecosystems are key to the climate and carbon cycle and play a critical role in achieving climate mitigation goals. This is especially true of peatlands, a type of carbon-rich wetland ecosystem estimated to store more than 30% of the world's terrestrial soil carbon while occupying just 3% of the land surface. Most of this carbon is stored below ground in deep, organic-matter-rich peat soil layers. Peatlands begin to release carbon once they are drained or disturbed. Many peatlands have already been lost or degraded through drainage for forestry, grazing, agriculture, and other forms of land use conversion, and rising temperatures threaten to flip many remaining peatlands from carbon sinks to sources (Humpenöder et al., 2020; Loisel et al., 2021). Peatland soils represent a huge source of irrecoverable carbon that is at risk of being released due to warming and drying under land use conversion and projected high carbon emissions climate change scenarios. For this reason, both protecting and restoring peatlands have been identified as potentially critical Natural Climate Solutions (NCS). These restoration, conservation, and land management activities can increase carbon storage or reduce carbon/greenhouse gas emissions (GHG) from ecosystems to help mitigate global average temperature rise. The potential accelerated loss of carbon from peatlands due to warming is, at the same time, one reason why it is so critical to keep global warming as close as possible to 1.5° C above pre-Industrial averages (Griscom et al., 2017; Roe et al., 2019).

Minnesota contains more peatlands—at least 6 million acres—than any other of the contiguous 48 United States. Peatlands cover more than 10% of the state by area and account for at least 37% of the stored terrestrial carbon (Walker, 2011). Most of Minnesota's intact peatlands occur as large open bogs, extensive lowland conifer forested peatlands, and groundwater-fed fens. Historical drainage and conversion of peatlands to cropland and other land uses has caused persistent shifts in the carbon balance of Minnesota's peatlands. Ongoing carbon stock losses from partially drained peatlands in Minnesota—a legacy of extensive ditching and drainage efforts in the early 20th century—have been estimated at ~38,000 metric tons (MT) per year (Krause et al., 2021); however, some estimates in the literature suggest that re-wetting peat could potentially save even more than that per year. Re-wetting drained peatlands may also provide additional carbon sequestration benefits.

Given the critical role that protecting and restoring peatlands plays in the global carbon cycle, the Minnesota, North Dakota, and South Dakota Chapter (Tri-State Chapter) of The Nature Conservancy (TNC) is working with partners to develop a strategy to protect and restore peatlands in Minnesota as an important component of an overall climate change mitigation strategy. This Peatland Playbook describes those science-based efforts to estimate the potential climate benefits of peatland protection and restoration in Minnesota, identify promising targets for restoration, and propose strategies for continuing these efforts.

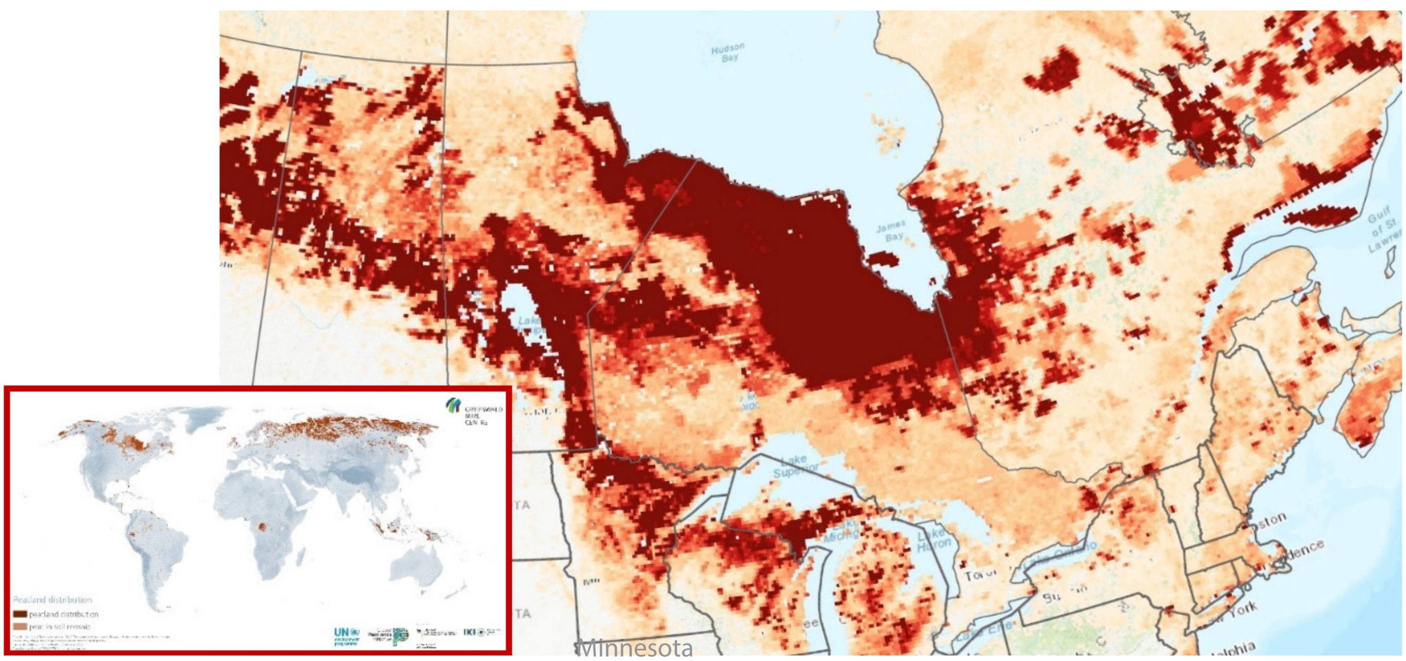


Figure 1. Minnesota peatlands in context of global and North American peatlands extent. (Data from Hugelius et al. 2020; inset from Global Peatlands Assessment, UNEP 2022)

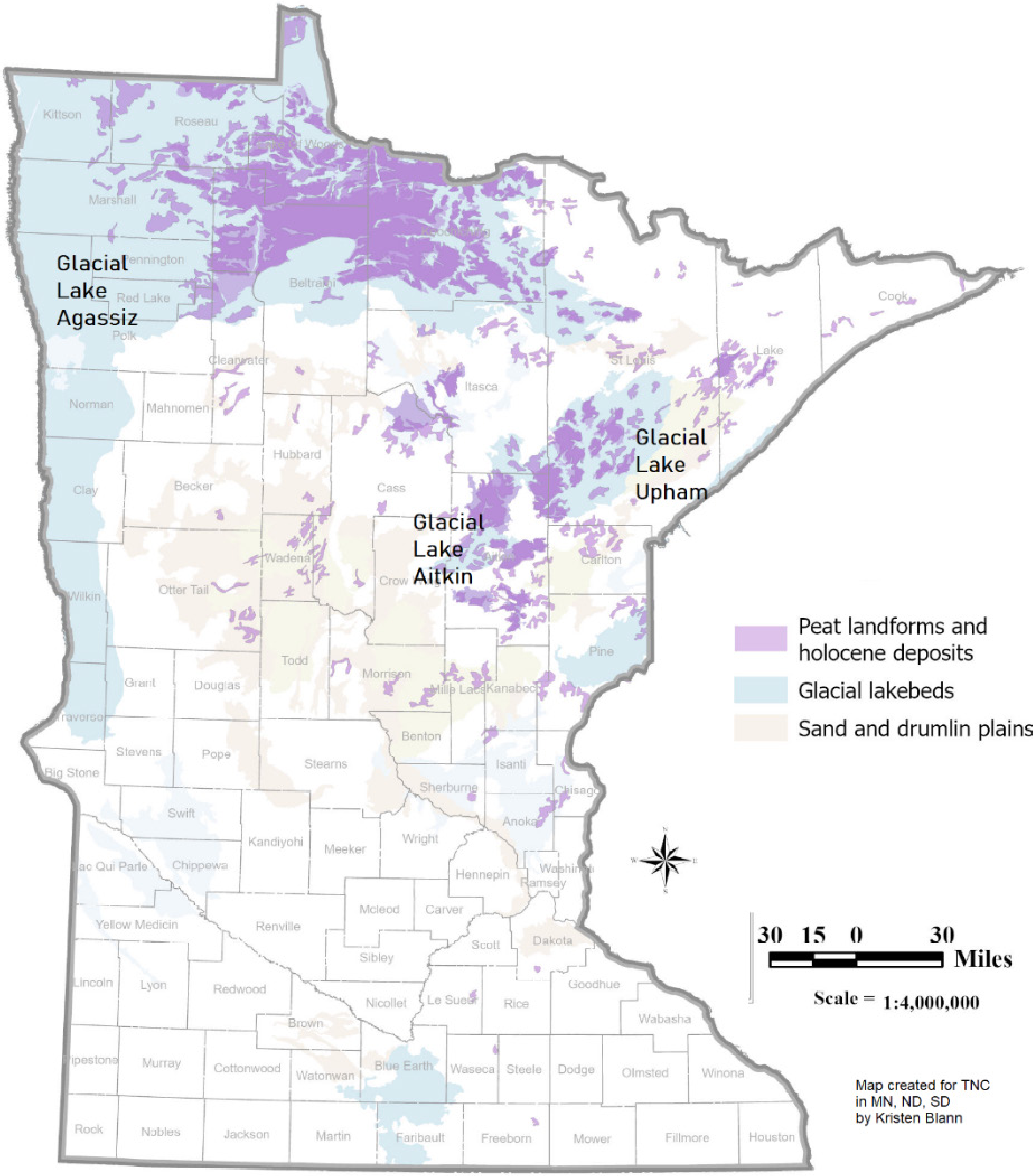


Figure 2. Peat landforms and ecological land type associations in relation to extent of glacial lake basins (map compiled from MN ECS land type association data layer and Quaternary Geology lobes from Minnesota Geological Survey (MGS, Lusardi, 1994).

Photo: TNC

Background: Minnesota's peatlands

Peat is partially decayed plant material that accumulates in soil under moist and often cool climates, where waterlogged conditions prevent microbes from breaking down dead plant material and leaves. In the process, the carbon dioxide (CO_2) that plants remove from the atmosphere becomes sequestered underground so long as waterlogged conditions are maintained. While all peatlands are wetlands, not all wetlands are peatlands. A peatland is typically defined as a wetland that accumulates peat, or partially decayed plant matter. Peatlands are also generally referred to as fens, bogs, and swamps, though peatland definitions can vary widely (Lourenco et al., 2022).(see Box 1).

Minnesota's true peatlands are largely an extension of a band of northern temperate peatlands stretching across Canada into the Great Lakes region (Figure 1). They predominantly developed during the Holocene epoch (the past 6,000–8,000 years), when favorable peat-forming conditions persisted due to cool, wet climate periods combined with poor drainage in the depressions left behind by Ice Age glaciers.

In Minnesota, most of our peatlands formed either by lake in-filling or by "paludification." In the first case, peatlands formed as lakes and ponds left behind by the retreating glaciers, and which gradually filled in around the edges with floating mats of sedges and other plants while organic matter accumulated at their bottoms. In the second process, flat or gently sloping ground developed into raised bogs formed by mosses and sedges that accumulated organic matter faster than the rate of decomposition, cutting them off from local groundwater. The most extensive peatlands in Minnesota formed in the remnant glacial lake basin Upham in Aitkin and St. Louis counties (including the Sax-Zim Bog as well as Toivola Bog and Wawina Peatlands) and Glacial Lake Agassiz (Red Lake, northern Minnesota and Ontario Peatlands).

Box 1. Peat and Peatland Types

Bog vs fen vs swamp

Bogs receive their moisture from rainwater and runoff low in dissolved minerals. Only a small number of specialized plant species can survive these acidic and nutrient-poor conditions. Bogs have undulating terrain covered by Sphagnum moss as well as low shrubs, cottongrass, and sparse stunted spruces and tamarack. Bogs tend to have a surface layer of minimally decomposed fibric peat.
Fens are influenced by groundwater with near-neutral to basic pH and carrying dissolved minerals supporting higher plant diversity than bogs. Calcareous fens are a rare and distinctive type of fen; they depend on a constant supply of upwelling groundwater rich in calcium and other minerals and support diverse and unique rare plants. Fen plant communities are dominated by low shrubs and fine-leaved sedges, with brown mossses and Sphagnum mosses common. Peat in fens tends to be more highly decomposed (hemicsapric) than in bogs. Swamps are forested wetlands often adjacent to lakes or streams. They may be fed by surface or groundwater but are saturated or flooded for many weeks or months each year. Not all swamps are peatlands: Minnesota's lowland conifer swamps, dominated by black spruce and/or tamarack, may be bogs or fens, but white cedar, black ash, shrub swamps, and bottomland hardwoods typically have lower soil carbon and therefore less often meet the definition for peat soils.

Peat vs Histosol

Peat is a general term for soils formed from partially decayed plant matter and can include the barely decomposed fabric Sphagnum peat common in northern bogs to the highly decomposed capric sedge/reed mucks of wet meadows. Histosol is an older term in the USDA's soil taxonomy classification system, and is characterized by a thick layer of organic soil. Histosols must have a layer of organic soil material at least 40-60 cm deep. In many cases, peat and histosols are synonymous, and histosols, which are extensively mapped in the United States, can be used as a proxy for peatlands.

Sphagnum vs sedge peat

Sphagnum peat is formed from partially decomposed Sphagnum moss, which is resistant to decomposition and abundant in nutrient-poor acidic bogs. It tends to be less decomposed (fibric), with very low bulk density and high hydraulic conductivity. Reed/sedge peat is formed from partially decomposed reeds, sedges, grasses, and other herbaceous vascular plants, which are less resistant to decomposition than Sphagnum and abundant in more mineral-rich, neutral pH environments, resulting in higher rates of decomposition. Reed/sedge peat is often more decomposed (hemic or sapric), with higher bulk density and lower hydraulic conductivity.

BOX 2. Peatland Systems according to the Minnesota Native Plant Community classification

The Minnesota Department of Natural Resources' Native Plant Community Classification system recognizes 3 peatland types at the system level: acid peatlands, open rich peatlands, and forested rich peatlands.

Broadly speaking, acid peatlands include the more nutrient-poor bogs and fens, which are also called "ombrotrophic" in reference to the fact that they receive their moisture and nutrients primarily from precipitation or runoff, and which are largely disconnected from local groundwater. These highly acidic and nutrient-poor conditions are only suitable for a small number of specialized plants, but those that have adapted to these harsh conditions tend to be widely distributed globally across the boreal peatlands. Ground cover is dominated by hummocks and hollows of Sphagnum moss with cottongrass and low ericaceous shrubs, such as bog laurel, bog rosemary, leatherleaf, and labrador tea.

Acid peatlands may be completely open or forested with sparse stands of stunted spruce and tamarack trees. Carnivorous plants, such as pitcher plant and sundew are common and have adapted to the nutrient-poor conditions by trapping and digesting insects. Due to the acidic conditions and recalcitrant litter from sphagnum, the soils in these systems tend to be minimally decomposed fibric peat.

BOX 2. Continued

Open rich peatlands have some influence from groundwater, which provides a source of minerals, but are still generally low in nitrogen and phosphorus. These systems host higher plant diversity, dominated by low shrubs, such as leatherleaf, bog rosemary, and bog birch, and fine-leaved sedge. Hummock-hollow topography is common, with Sphagnum on hummocks and brown mosses in hollows. High water tables prevent tree growth, leaving these systems open.

Open rich peatlands may eventually transition to acid peatlands as peat accumulation leads to separation from groundwater and Sphagnum mosses increase the system's acidity. Moderately decomposed hemic soils are common in these systems.

Similar to open rich peatlands, forested rich peatlands also receive groundwater inputs, allowing for greater plant diversity than acid peatlands. However, fluctuating water tables allow for denser canopies of coniferous trees, favoring shade-tolerant understory species with extensive cover of feathermosses and brown mosses, as well as abundant shrub and forb cover. The soils of these forested rich peatlands are often also hemic or even more decomposed sapric peats.

BOX 2. Continued

Highly disturbed, degraded, or recently rewetted peatlands may also feature vegetation more typical of wet meadow/carr wetland type.

For more information about Minnesota's peatlands, see:

Minnesota's Peatland Scientific & Natural Areas
dnr.state.mn.us/snas/peatlands.html

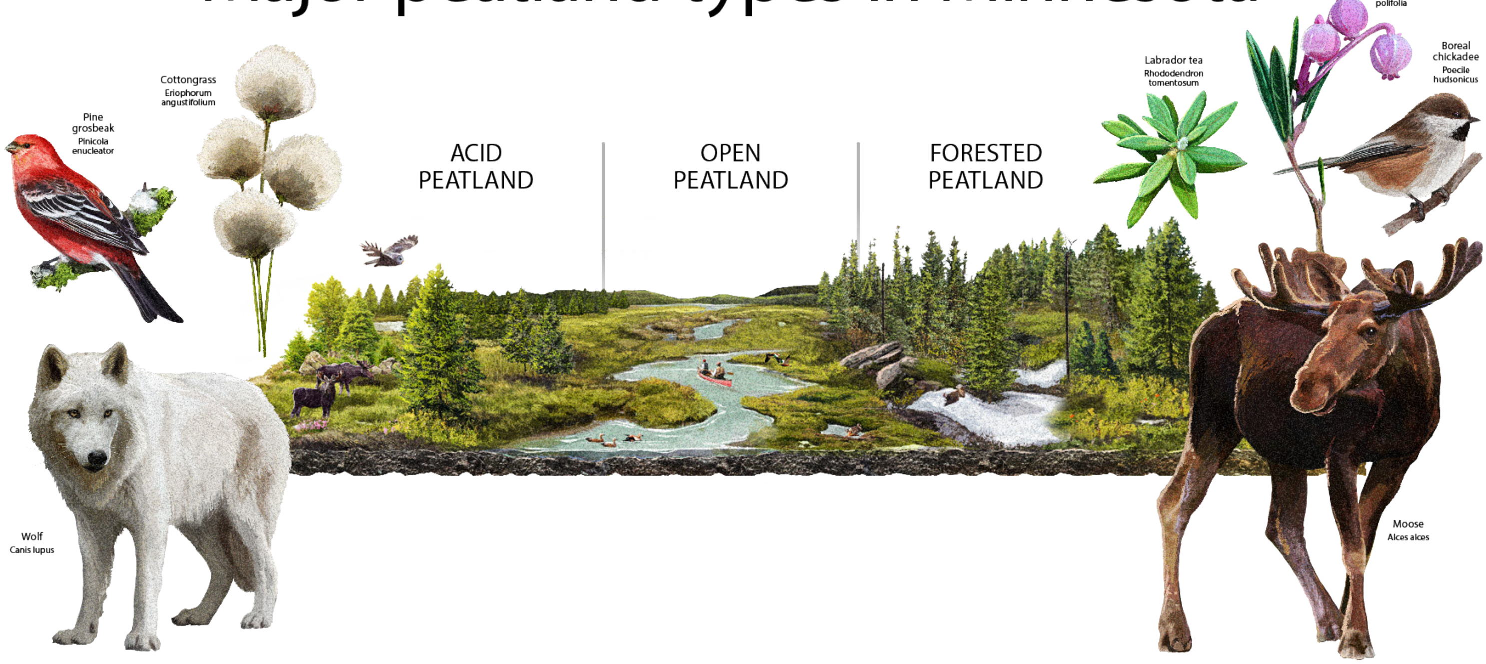
Restoring Minnesota's Peatlands for Climate & Water
nature.org/en-us/about-us/where-we-work/united-states/minnesota/stories-in-minnesota/peatland-restoration-study/

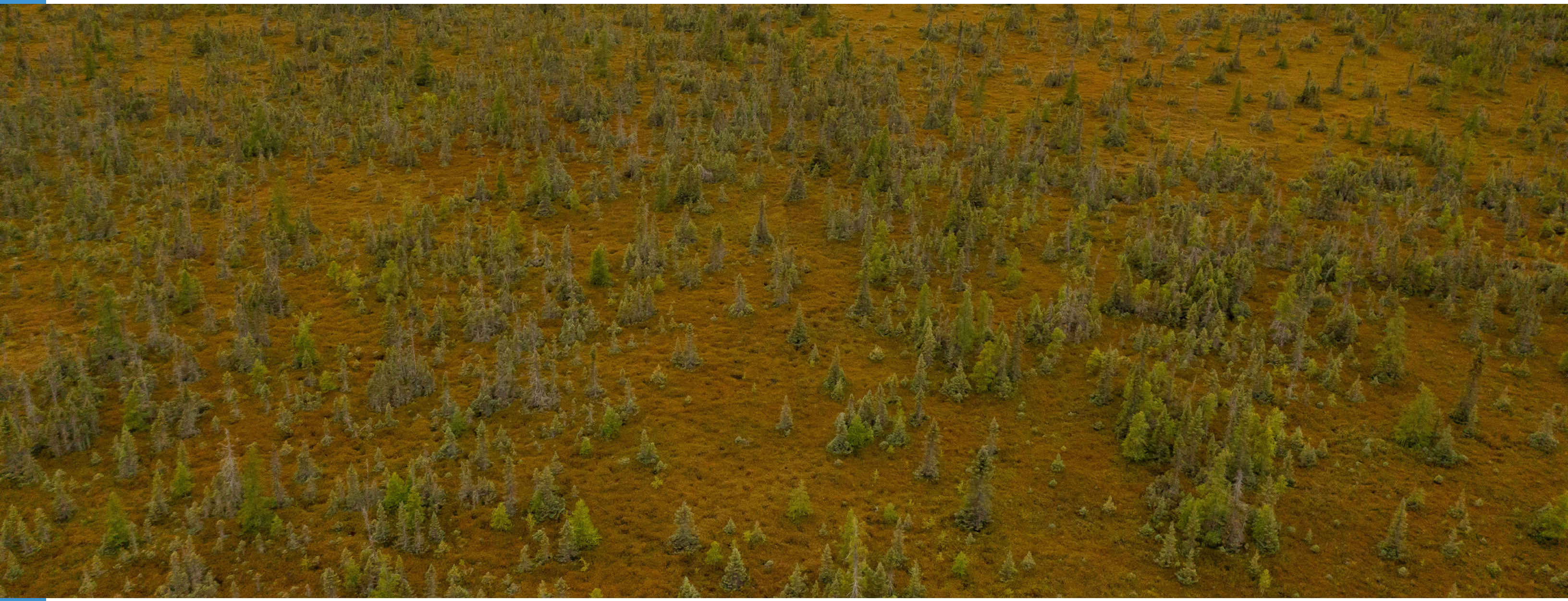
Peatland Restoration in northern Minnesota
ncsprototypingnetwork.naturebase.org/en/projects/united-states-peatlands

Key Takeaways

- Peatlands are wetlands characterized by the long-term accumulation of partially decayed plant material known as peat, which sequesters carbon underground due to waterlogged conditions.
- Minnesota's peatlands are part of a northern temperate peatland band formed in the Holocene era around 6,000–10,000 years ago because of melting glaciers and a cool, wet climate paired with poor drainage.
- The formation of Minnesota's peatlands is mainly attributed to lake in-filling, where shallow ponds and lakes gradually filled in with organic matter, or where flat grounds developed into raised bogs formed by mosses and sedges accumulating peat faster than the rate of decomposition.

Major peatland types in Minnesota





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Historic conversion and drainage: a lasting legacy

Until the late 19th century, the place now known as Minnesota was a landscape dominated by wetlands of various types including bogs, fens, marshes, swamps, and wet prairies. The Indigenous people who stewarded these landscapes valued the peatlands as intact ecosystems that furnished them with food, medicines, furs, and other necessities. However, when European settlers moved into the landscape, they viewed these poorly drained areas as wastelands, and made massive drainage investments to make land available for "productive" agriculture and forestry uses. In support of this project, the federal government passed a series of Swamp Acts starting in the 19th century to encourage draining wetlands throughout the Great Lakes States (Dahl and Allord, 1996).

State and local governments in Minnesota took up the charge in earnest throughout the early 1900s, dredging long trenches and using explosives to drain millions of acres of wetlands. While not everyone supported these large-scale drainage efforts, as much as 90% of historic wetlands in southern and western Minnesota were drained. These efforts enabled the intensive row crop agricultural production systems that dominate those parts of the state today.

Based on the updated 2018 Statewide Altered Watercourse mapping project, more than 41,000 miles of streams in Minnesota have been altered or modified in some way—representing nearly half the total, and nearly double previous estimates. Of this, at least 7,000 miles cross areas with peatlands. Restoring peat in these areas, therefore, has the potential to generate both climate benefits and restore more natural waterways.

Peatland areas that have been completely drained and converted represent a significant loss of stored carbon, in addition to ongoing losses. In 2018, the Minnesota Pollution Control Agency (MPCA) listed cultivated histosols—thick, organic-rich soils indicative of potential peat

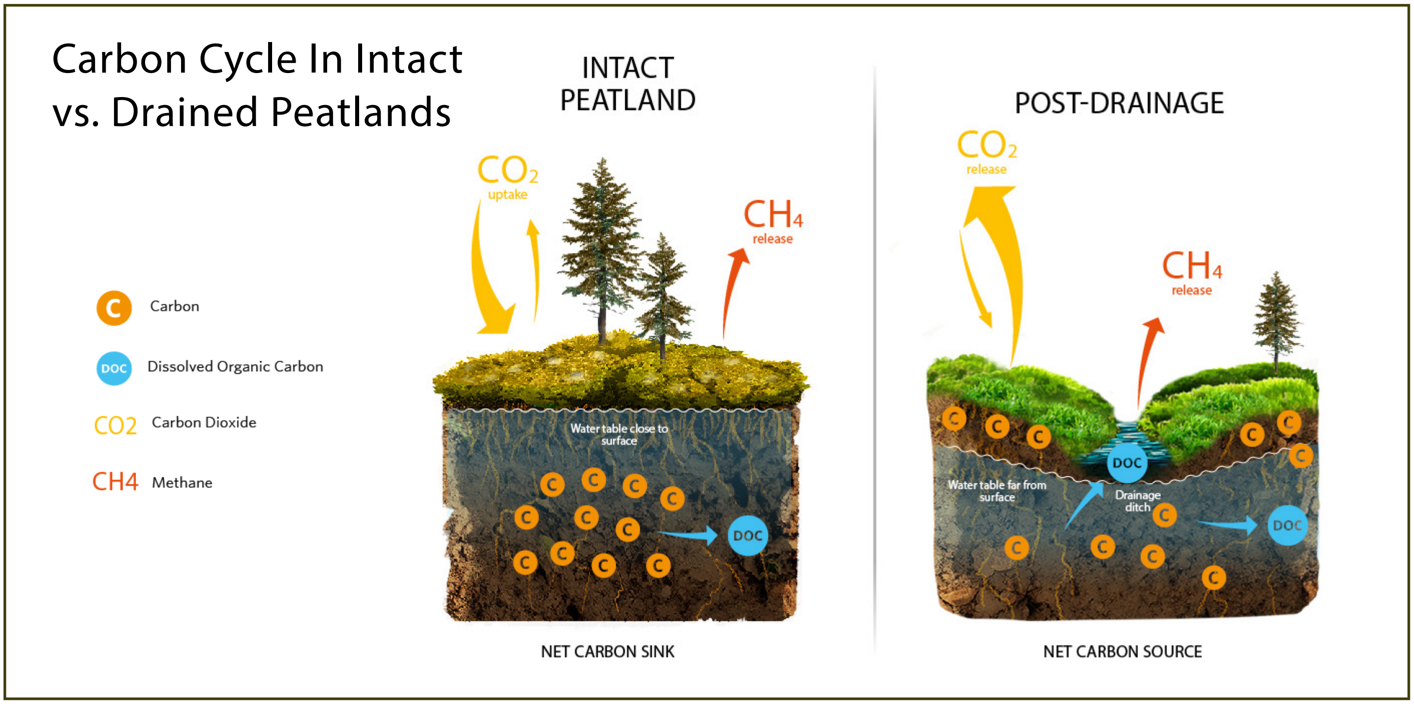


Figure 3. By definition, intact peatlands are net sinks for carbon; this is true in the long run even when accounting for the higher short-term radiative forcing of CH4. By lowering the water table, drainage exposes Carbon stored in the peat. This ultimately leads to increased CO2 emissions while having variable impacts on CH4 production, with slow-moving ditches even serving as hot spots for methane release at times.

soil forms—as the fourth largest source of GHG emissions statewide, just behind light trucks (MPCA 2023.) Historically, the state's largest areas of complete peatland loss and conversion were in central, southern, and western Minnesota. Despite being partially or fully drained, many of these areas still have peat soil characteristics, often in conjunction with landscape position and topographic modeling indicative of wetlands (Natural Resources Research Institute, 2019).

In contrast, large peatlands— both intact and partially-drained— persist in northeastern Minnesota and north of Upper and Lower Red Lakes. In these more extensive northern peatland areas, many drainage efforts were economically unsuccessful, and millions of acres reverted to state and county administration via tax forfeit, beginning largely during the Great Depression. Today these lands are managed primarily as county and state lands.

Even in these partially drained northern peatlands, the legacy of ditching still contributes to ongoing carbon stock losses and peat degradation.

Peatland ecology is largely governed by hydrology—the patterns governing water quality, water chemistry, water flow, and water table dynamics. Disrupting these dynamics has had profound impacts on the accumulation of peat, landforms, vegetation, and carbon. Ditches dug through peatlands lower the water table, leading to oxidation (decomposition) of organic matter and the release of CO2 and other greenhouse gases (Krause et al., 2021), as shown in Figure 3. Although many ditches have not been maintained in decades, they are often still part of active public ditch networks upstream and downstream and continue to provide a preferential flow path for surface waters through the peatlands. Without active intervention, many of these systems may

Lateral Drainage Effect in Peatlands

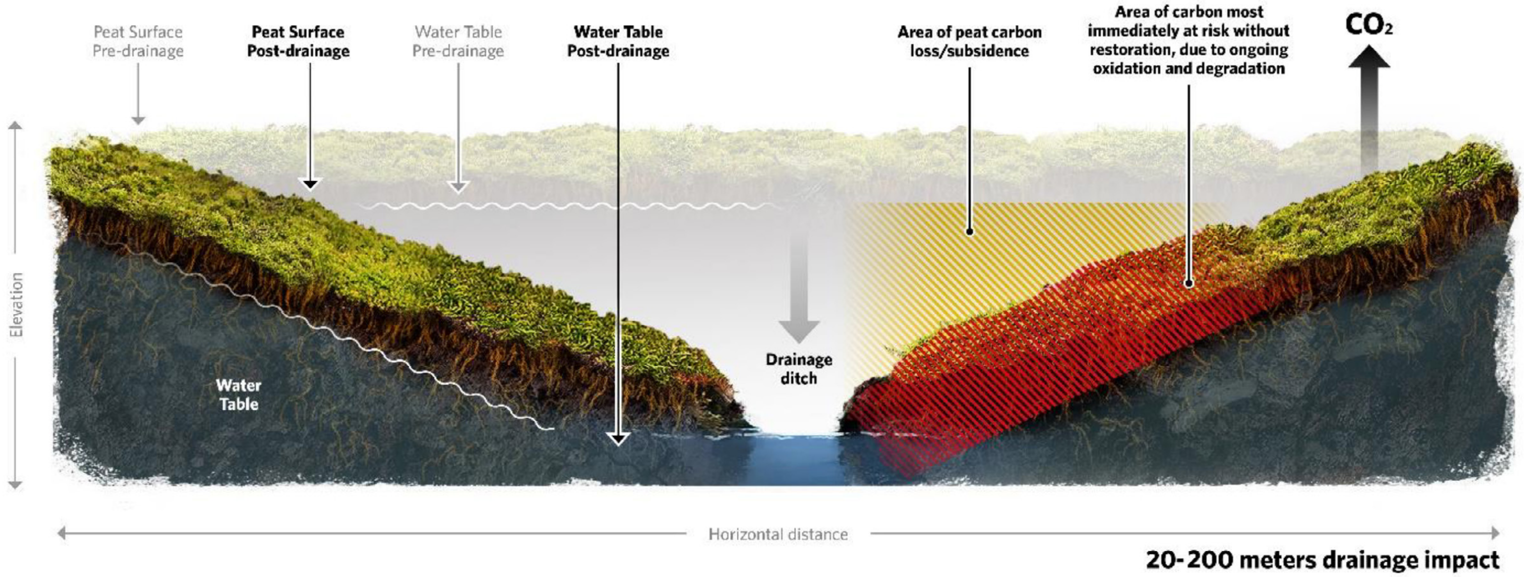


Figure 4. Lateral drainage effect in a northern Minnesota ditch. The light grey outline shows the approximate soil and water surface prior to drainage ditch construction in the early 1900s. The water table line in the left foreground shows the predicted lateral effect from the drainage ditch. Restoration of Minnesota's partially drained peatlands through ditch filling and re-wetting therefore potentially involves both peatland NCS pathways: peatland protection (avoided conversion by stopping ongoing stock loss) and peatland restoration (carbon storage and sequestration by reversing and re-starting the accumulation of peat based on re-wetting of the peat and restoring the water table elevation).

not recover hydrologically for many more decades, though some may be capable of healing on their own, given adequate time.

Recent mapping and modeling show about one-sixth of total peatlands in northern Minnesota may be experiencing ongoing carbon stock losses as legacy impacts from ditching, contributing an estimated 38,000 metric tons (MT) of carbon emissions per year.

The original intent and purpose of drainage ditches was to lower the water table in saturated or wet areas of the landscape by providing channelized outlets. Drainage ditches impact wetland hydrology by drawing down the adjacent water table, with lateral effects extending out perpendicularly. Figure 4 shows a cross-sectional conceptual diagram of the remaining potential drainage impact of a ditch, where not all the peat and muck has yet been fully oxidized and mobilized to the atmosphere, releasing greenhouse gases. These lateral effects can extend 100 meters or more to either side of the ditch depending on slope, ditch depth, soil type, and other properties (MN BWSR, 2013). Recent estimates in Minnesota indicate that this water table impact also causes ongoing carbon losses that extend laterally about 100-150 meters from the ditch, with decreasing impacts further from the ditch (Krause et al., 2021; Reagan, 2023).

In general, re-wetting drained peatlands greatly reduces loss of carbon as CO2 via decomposition by restoring anaerobic, saturated conditions favorable to peatland vegetation and long-term peat accumulation (Wille et al., 2023). However, wetter conditions may increase methane (CH4) production in the short term. (approximately 28x the global warming potential (GWP) of CO2 over 100s). However, CH4 has a short atmospheric lifetime, and emissions do not have a cumulative impact on warming like CO2. The overall weight of evidence in the literature on re-wetting peatlands strongly suggests the longer-term CO2 emission reduction benefits and reestablished organic matter accumulation far outweigh the climate impacts of increased CH4 emissions. Thus, the long-term net carbon benefits of restoring drained peatlands via re-wetting are substantial and increase the sooner peatlands are restored (Figure 5).

Drainage ditches also export large quantities of carbon to downstream ecosystems in the form of dissolved organic carbon (DOC). the DOC carried in ditches results in significant overestimation of the carbon sink strength of many wetlands (Dinsmore et al., 2010; Leach et al., 2016). DOC also plays a role in the mobilization and bioaccumulation of methylmercury in fish and other animal tissue, a major water quality issue in many Minnesota watersheds. By restoring peatlands, closing ditches, and increasing residence time, there is potential to reduce DOC export downstream and potentially methylmercury export as well (Kolka et al., 2011; Waddington et al., 2008). However, although current research is examining the effects of restoration on DOC and mercury transport in Minnesota, the processes involved are complex and we need a better understanding of them.

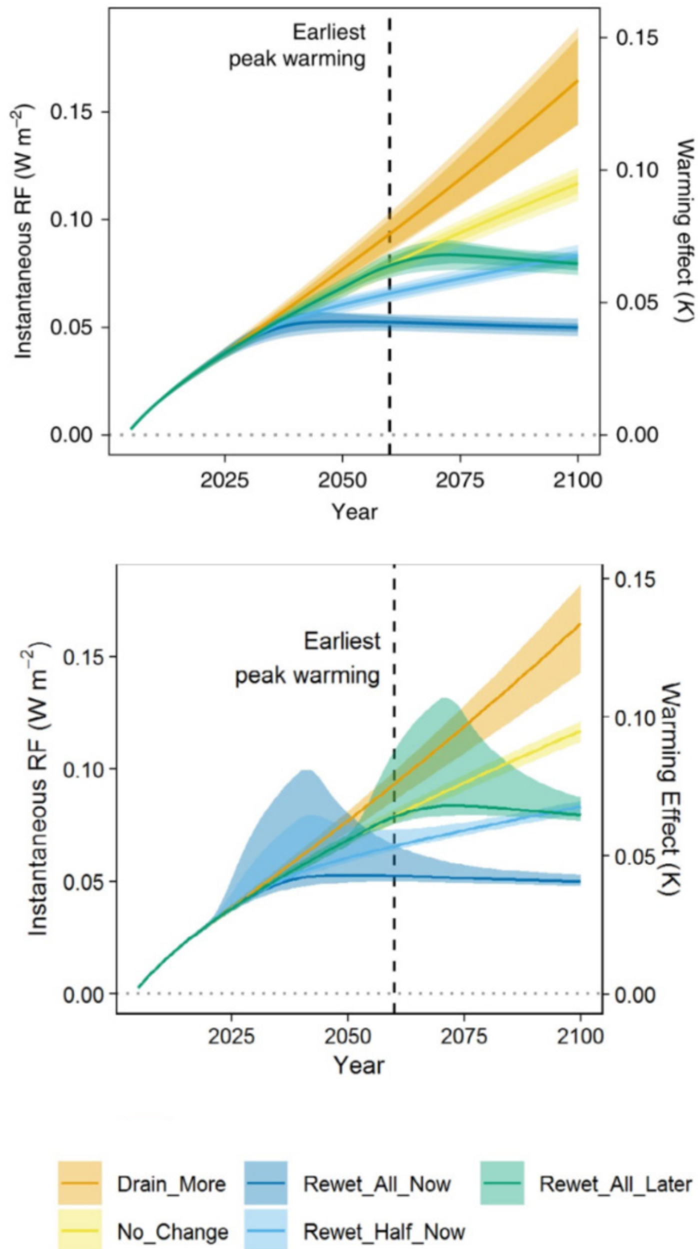


Figure 5. Restoring the sink: implications of short-term tradeoffs between CH4 and CO2. Radiative forcing (RF) is the difference between the solar energy coming into the Earth's atmosphere and the amount reflected back to space; it is a key measure of the greenhouse effect. The graphs show radiative forcing and global climatic warming effects of global peatland management without (left) and with (right) an initial 10-times-larger-CH4-peak for 5 years after re-wetting, under various scenarios. Drain_More: Assumes that the area of drained peatland continues to increase from 2020 to 2100 at the same rate as between 1990 and 2017; No_Change: The area of drained peatland remains at the 2018 level; Re-wet_All_Now: All drained peatlands are re-wetted in the period 2020–2040; Re-wet_Half_Now: Half of all drained peatlands are re-wetted in the period 2020–2040; Re-wet_All_Later: All drained peatlands are re-wetted in the period 2050–2070 (Günther et al. (2020). Nature Communications 11:1644; Figure reprinted from Figure 2 of RAMSAR Policy Brief)

Photograph © Derek Montgomery

Legal protections and Indigenous conservation efforts

After earlier eras promoting drainage, public perception of the importance of wetlands and peatlands began to shift in the late 1980s, partly in response to growing efforts from conservationists, scientists, Tribal Nations, and others to articulate the value of protecting them in their natural state. The Minnesota Wetlands Conservation Act (WCA), passed in 1991, established a goal of "no net loss" of wetland functions and services, and multiple peatland areas were designated in the 1990s under the Scientific and Natural Areas Program administered by the Minnesota Department of Natural Resources (DNR). Since these changes came into effect, Minnesota has maintained relatively strong legal protections for peatlands. Wetlands in general are subject to the WCA and several other regulatory programs, most of which are implemented and coordinated at the local level but overseen and administered by the Board of Water and Soil Resources (BWSR). Drainage or impacts due to infrastructure, development, mining, or other purposes generally require a wetland permit that requires mitigation through wetland restoration or a wetland mitigation bank. However, there are numerous de minimus exemptions under the WCA that allow some excavation of minimal size and depth without a wetland permit for uses such as horticultural peat, as well as a silvicultural exemption (relevant to drainage on state and private forested peatlands). Additionally, although mitigation wetlands are supposed to replace the same types of wetlands and wetland services in the same watersheds, this is not always possible in practice. While WCA acknowledges that carbon sequestration is a service that wetlands provide, mitigation requirements do not explicitly require carbon accounting or monitoring at this time. Furthermore, regardless of the quality of the restoration, there is still a lag time in the recovery of wetland hydrology, vegetation/biodiversity, restoration of carbon dynamics, and other benefits. In part to account for these drawbacks, credits for replacement wetlands are typically offered at mitigation ratios ranging from 2:1 to 8:1, an aspect of mitigation law that does provides some opportunity to increase peatland acreage beyond "no net loss."

Tribal Nations and Indigenous communities in Minnesota have also contributed significantly to peatland conservation and stewardship. In particular, the Red Lake Nation actively opposed county, state, and federal efforts to drain and develop northern Minnesota peatlands for decades, both on- and off-reservation, recognizing their intrinsic values as well as their provision of habitat for wildlife and cultural resources such as medicinal plants, contributions to water quality and storage, and the other services they provided (Meyer, 1992). This culminated in the 1970s with a resolution by Red Lake tribal leaders to preserve the peatlands untouched in response to a large proposed peat mine energy development in the peatlands north of Red Lake Nation that was, fortunately, ultimately abandoned. To this day, some of the larger areas of undrained, intact peatlands in Minnesota occur within the Red Lake reservation boundaries, as part of the larger expanse of the Red Lake peatlands. Other Tribal Nations with significant peatland areas on-reservation include Fond du Lac, White Earth, Bois Forte, Mille Lacs, and the Leech Lake Band of Ojibwe. However, in many cases, treaty resources such as wild rice lakes, wetlands, and flowages have been and continue to be impacted by drainage activities on adjacent public and private lands.

On state- and county-owned land, peatlands are managed according to their designation as public wildlife management areas, forestry lands, conservation or recreation areas, as well as based on mining regulations and other obligations under statute. These varied interests are not always in accordance with peatland conservation and restoration. There is growing demand for copper, nickel, and rare earth materials driven by expanded production of electric vehicles and other products deemed necessary for the clean energy transition, and many mining companies are eyeing northern Minnesota's mineral resources. Several new mining projects in this region are proposed or in the pipeline. Although the acreage of remaining peatlands at risk of complete drainage or conversion is relatively limited, these peat areas play an outsize role in terms of at-risk carbon stocks, potential implications for water quantity and quality, connected and intact wildlife habitat, and biodiversity. The challenge for Minnesota science and policy is to keep pace with emerging threats and challenges to ensure we continue to manage our peatlands in ways that benefit people, water, wildlife, biodiversity, and climate.

Research-backed strategies for restoring and protecting peatlands

For several years, The Nature Conservancy in Minnesota has identified wetland and floodplain restoration as a major element of our overall freshwater strategy under our Resilient Waters program. To that end, we have been implementing wetland restoration projects for multiple benefits in central Minnesota since 2017 or earlier, including many peatlands. However, this report details our initial efforts to identify peatland-specific restoration opportunities and to characterize the biophysical, social, institutional, and economic feasibility of peatland protection, management, and restoration across the overall landscape.

The focus of our analysis in this document is largely expanding this strategy to prioritize restoration of partially-drained peatlands in northern Minnesota, particularly on public lands, as part of our climate mitigation strategy. Expanding our ability to assess carbon benefits of restoring drained organic-soil wetlands in southern Minnesota provides additional ability to prioritize, target, and assess benefits of floodplain and wetland restoration.

Although the focus of this document is on restoration opportunities and feasibility, we emphasize that protection—i.e., avoiding irreversible carbon loss from additional conversion, drainage, or other avoidable impacts to peatlands, wherever possible—is the most critical priority for peatlands in Minnesota and globally, due to their large carbon stores that have accumulated over millennia.

In order to achieve our carbon mitigation and sequestration goals and align with stakeholder needs, we consider the following peatland protection and restoration strategies. They take into account cost, carbon mitigation effectiveness, and geographic extent of the need and opportunity:

1. Protect intact peatlands from further degradation as well as direct conversion threats such as agriculture, mining, and development.

2. Restore and re-wet partially drained peatlands.

3. Completely restore fully drained and converted peatlands.

Photograph © Derek Montgomery

Key Takeaways

Historical Wetland Loss and Drainage Efforts:

- In the late 19th century and early 20th century, federal, state, and local governments undertook efforts to drain wetlands, impacting millions of acres of wetlands and peatlands in Minnesota.

Carbon Loss and Restoration Challenges:

- Draining peatlands contributes significantly to greenhouse gas emissions. Even partially drained peatlands experience ongoing carbon stock losses due to historic ditching, contributing an estimated 38,000 MT of carbon emissions to the atmosphere annually.
- Re-wetting drained peatlands is crucial for long-term carbon benefits, despite short-term CH4 emissions, and can also reduce downstream carbon export.

Legal Protections and Indigenous Conservation Efforts:

- The Minnesota Wetlands Conservation Act in 1991 inaugurated relatively strong legal protections for peatlands in the state. In addition, Tribal Nations including Red Lake Nation have actively opposed drainage efforts, recognizing peatlands' intrinsic values, cultural resources, and importance for wildlife and biodiversity.
- Additional forms of protection, including designation of peatland SNAs and calcareous fen protections in statute, have been added more recently.
- However, challenges persist such as exemptions for horticultural peat and ongoing threats from agriculture, forestry, mining, and climate change.

Peatland Strategy:

- The Nature Conservancy proposes a three-pronged peatland strategy: protect large standing carbon stocks, re-wet partially drained peatlands in the north, and restore fully drained peat wetlands for multiple benefits.
- This document will focus on opportunities and strategies for peatland restoration on partially drained peatlands.

Photograph © Derek Montgomery

Quantifying the benefits of and exploring opportunities for peatland restoration

We began our science-based approach for quantifying the potential climate mitigation benefits of peatland protection and restoration pathways by identifying the current and historical extent of peatlands in Minnesota.

We worked to assess existing carbon stocks, determined where peatlands have been most affected by drainage ditches and other hydrologic alterations, and compiled estimates of long-term carbon accumulation rates and shorter-term emissions factors associated with different peatland types and conditions.

We also derived maps of historical peatland extent by compiling publicly available data layers for soil properties, existing wetland inventories, historical vegetation, and existing native plant communities.

We then combined peatland extent with empirical estimates of avoided carbon stock loss and carbon sequestration rates associated with different peatland protection and restoration strategies.

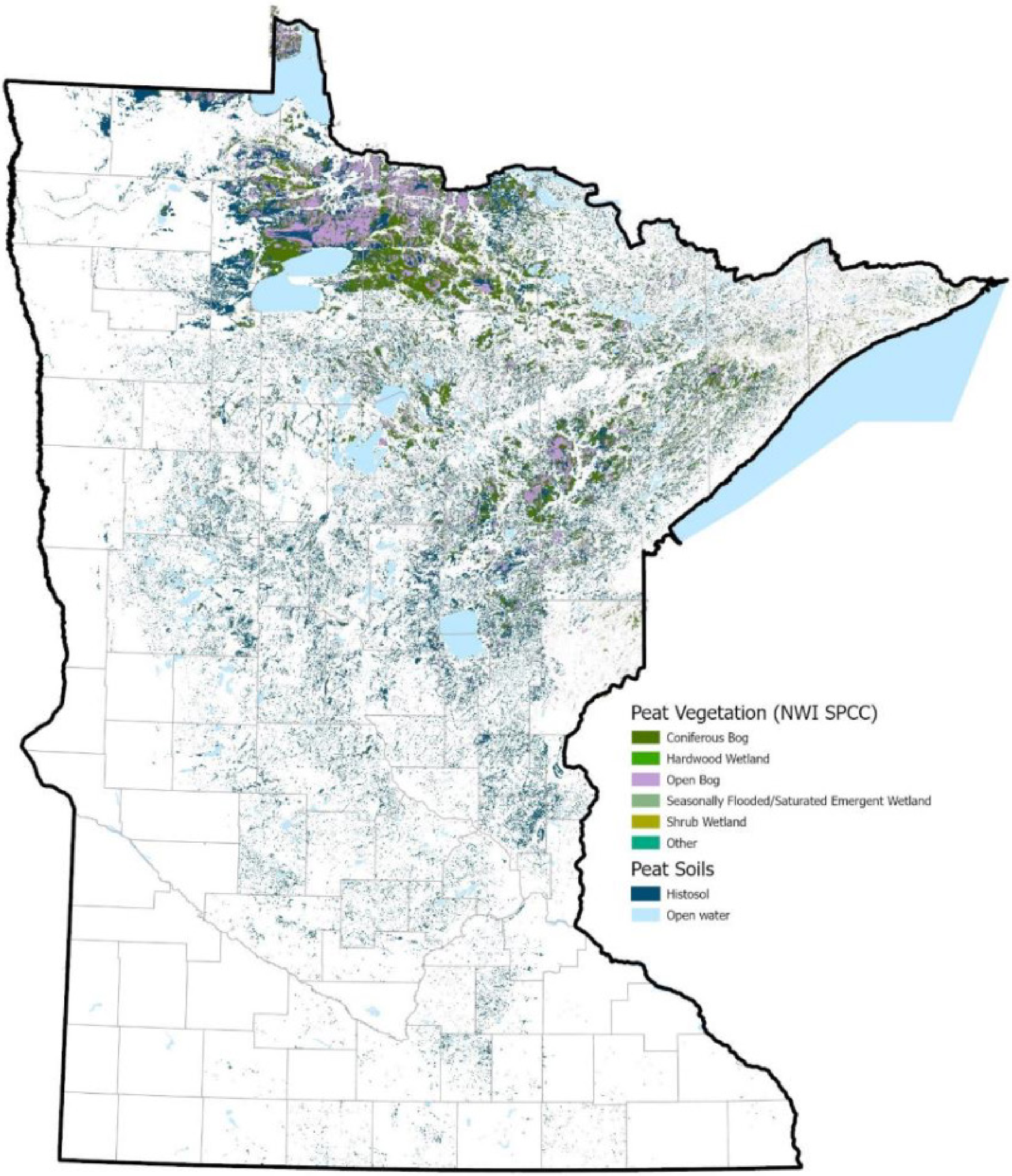


Figure 6. Minnesota peatland extent as represented by overlay of NWI simplified plant community types (MNDNR, 2019) with mapped histosols (USFS 2024).

Peatland and peat soil inventory

Globally and in Minnesota there is considerable variation in how peatlands can be defined and mapped, depending on the availability and quality of data, the scientific discipline involved, and whether the primary interest is in vegetation, soil, or economic properties of the peat, etc. Contradictions in definitions often relate to the minimum depth or percent of organic matter required for a soil to be considered as peat, and whether carbon content is based on mass or volume (Lourenco et al., 2022).

Minnesota actually has an abundance of available data on soils, vegetative communities, and existing peatland inventory work done by our state natural resource agency, the DNR, and others. This includes a statewide Peat Inventory Project conducted from 1976-1982 to assess the energy and horticultural potential for the state's peat resources as well as inform a comprehensive policy on peatland management.

Early peat inventories actually estimated the statewide extent of peat at over 7 million acres; larger than recently cited figures of 5-6 million (Minnesota Soper 1919; MNDNR 1981a, Glaser 1987). These datasets vary in their accuracy and spatial resolution, as well as how complete they are statewide. Although peatlands can be identified, mapped, and/or classified by a variety of attributes (soil types, plant communities, hydrogeomorphic wetland categories, etc.), a single complete statewide coverage of drained and remaining peatlands did not exist prior to this project, although efforts have recently begun to update the state's peat maps and data layers.

To assess both intact and potentially drainage-impacted peat wetlands in Minnesota, we used multiple geospatial data layers to assess the extent of remaining intact and partially-drained peatlands as well as fully drained and converted peat soils.

To view these data layers online, see the Potentially Restorable Peatlands Mapping Tool developed by BWSR concurrently with the development of this Playbook http://bit.ly/4hyum8Q

Peat soils are classified as histosols, based primarily on depth and organic carbon content (Kolka et al., 2016). To estimate carbon and peat volume loss from ditched peatlands in Minnesota, Krause and 16 colleagues (2020; 2021) developed a peatland layer for Minnesota based on the updated Minnesota National Wetland Inventory (NWI), a Minnesota-specific update to the NWI, completed by the Minnesota DNR in 2019 (MNDNR, 2019) The NWI was intersected with histosols as mapped at the level of taxonomic order by the National Resources Conservation Service's (NRCS) digital Soil Survey Geographic (SSURGO) database (USFS 2024). Krause et al. (2021) limited their analysis to areas of equal to or greater than 85% histosol content that intersected NWI wetlands, irrespective of whether peat was indicated in the NWI wetland classification. However, this approach resulted in the inclusion of only 86% of the area of all wetland features classified as peatlands based on hydrogeomorphic class in the updated NWI.

Building on the Krause et al. (2021) approach to ensure the broadest possible inclusion of potential peat, we compiled a comprehensive set of statewide layers of peat soils and wetland types in Minnesota by cross-walking the statewide

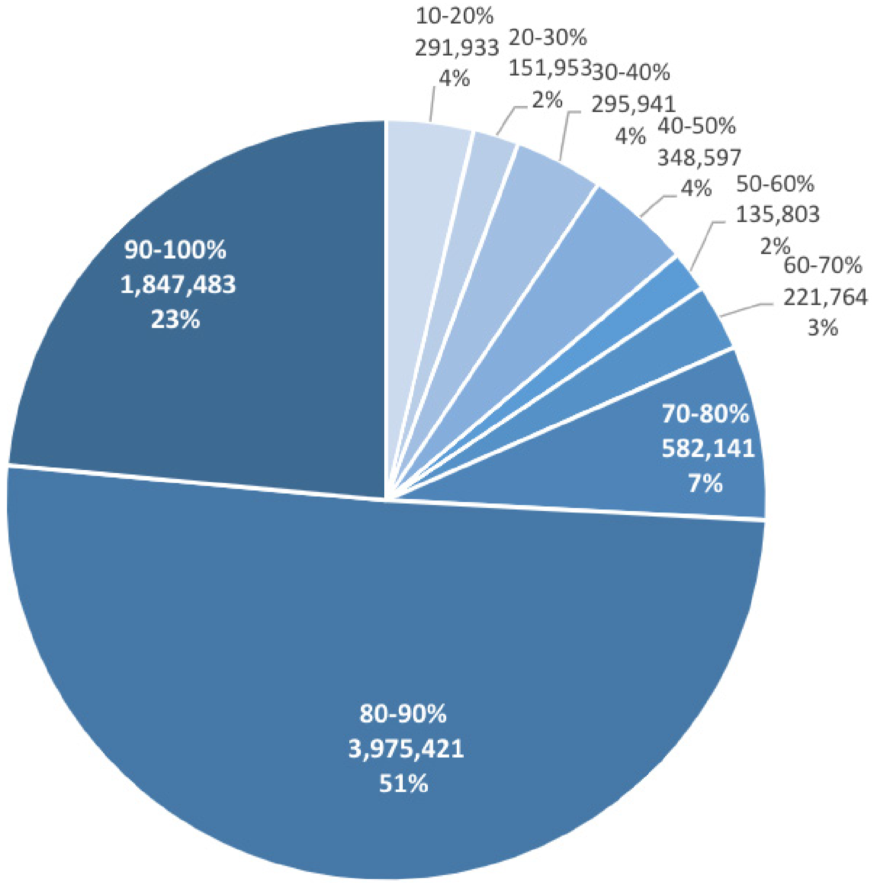


Figure 7. Statewide acres by percent histosol content. (Total 7.8 million acres)

SSURGO soils data[1]—expanded to include soils with 10% or more histosol content, as well as other relevant SSURGO variables relating to peatland types including carbon content, nutrient status, texture, and chemistry—with the NWI, the 2019 National Land Cover Dataset (NLCD), and several other vegetation models developed to characterize native wetland plant communities and potential.

Based on this newly compiled SSURGO histosol layer, 7.8 million acres statewide are mapped as having 10% or more histosol content in soils. The vast majority of these areas are characterized as in natural, native, or perennial land cover, in spite of the extensive artificial drainage networks that remain. 6.7 million acres intersect with the updated NWI (Table 1, Figure 8). An additional 490,000 acres of these histosols are not mapped in the NWI, but classified as woody or emergent wetlands in the 2019 NLCD. Excluding lakes and open water, about 60% of the total NWI wetland acreage has soils classified as histosols

[1]Histosols are defined by the NRCS as "soils that are dominantly organic . . . commonly called bogs, moors, or peats and mucks. A soil is classified as a Histosol if it does not have permafrost and is dominated by organic soil materials." SSURGO categorizes "histosols" as one of the soil taxonomic orders using the "taxorder" variable in the component attribute table. This layer is derived from a nationwide analysis compiled by the USFS based on the USDA-NRCS gSSURGO (gridded Soil Survey Geographic) database, in which the "component" additional table was joined and queried by a custom Python script, and from taxorder and taxclname (Seq 83 and 84 in the table found here) a dataset was derived showing histosols in 10% brackets based on the percentage of histosols within the components for the map unit. Analysis was conducted on all soils with 10% or more histosols.

(Table 1). Wetland types most likely to be mapped as peatlands are conifer bogs and open bogs. Wetland types less likely to be mapped as histosols are deep marsh, shallow open water, and non-vegetated aquatic communities. While these wetland types do often occur on mineral soils rather than peat, this could also indicate some potential mismatch or error in mapping.

More than half the state's northern peatlands are in state or county ownership. Since the era when most northern peatlands reverted to state or county ownership, the main economic use of peatlands by area has been for forestry, though mineral leases (including peat mined for horticulture as well as other mineral resources) provide the bulk of revenue (see discussion in next session).

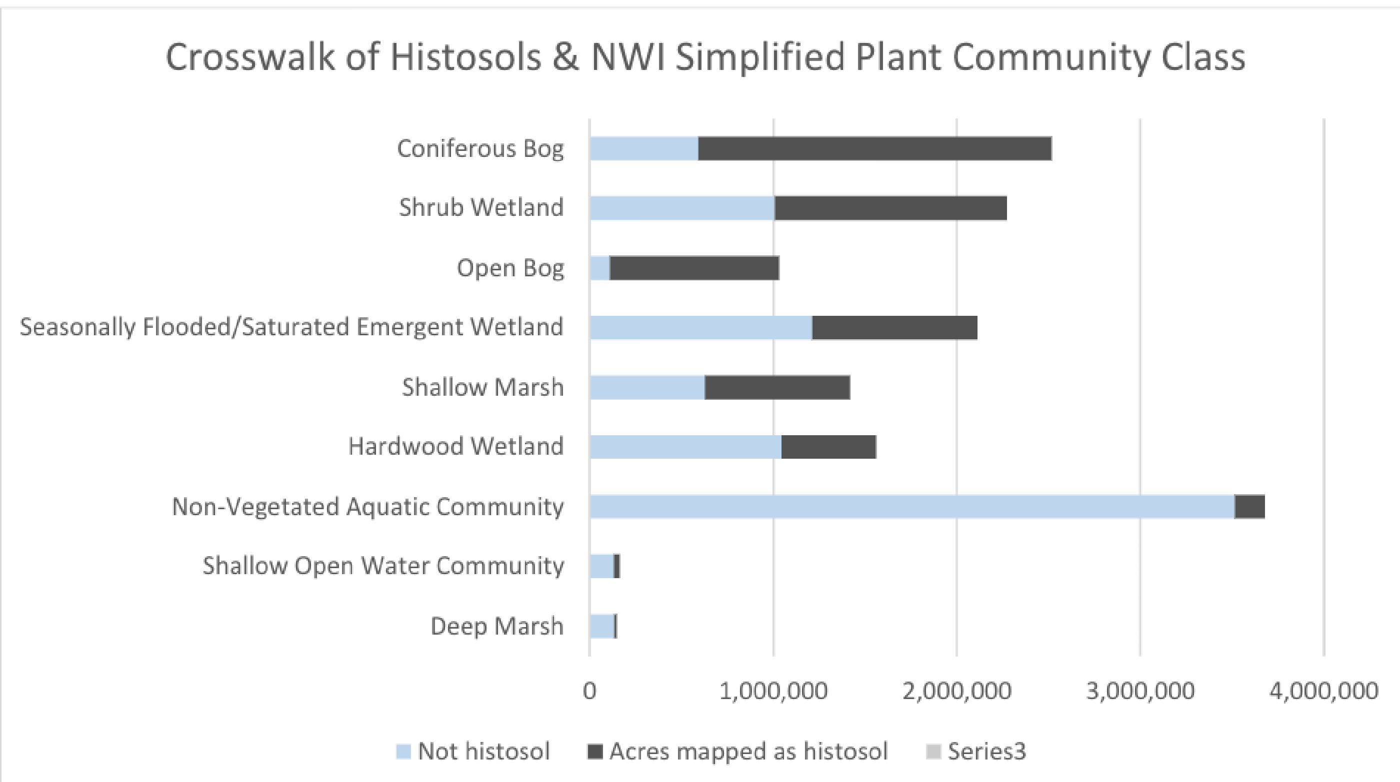


Figure 8. Crosswalk of NWI simplified Plant Community Class (SPCC) with histosols.

Photograph © Derek Montgomery

Table 1. Crosswalk of soils containing 10% or more histosols with the simplified plant community class from Minnesota updated National Wetland Inventory.

NWI SPCC Wetland type	Total acres	Acres mapped as histosol	%	% of total NWI types	Acres not mapped as histosol	SOC, 0-1 m MT/ha
Open Bog	1,029,976	920,877	89%	7%	109,099	629
Coniferous Bog	2,515,913	1,923,881	76%	17%	592,032	610
Deep Marsh	149,036	14,645	10%	1%	134,391	516
Shallow Marsh	1,419,407	790,751	56%	9%	628,656	514
Shrub Wetland	2,273,197	1,267,193	56%	15%	1,006,004	489
Shallow Open Water Community	166,184	33,274	20%	1%	132,910	486
Seasonally Flooded/Saturated Emergent Wetland	2,110,629	899,894	43%	14%	1,210,735	471
Non-Vegetated Aquatic Community	3,676,934	164,995	4%	25%	3,511,938	390
Hardwood Wetland	1,561,812	518,176	33%	10%	1,043,636	350
Total	14,903,088	6,702,845				

Box 3. Sources of Geospatial Data on Peatlands

Minnesota's peatlands range from the lowland conifer forests, swamps, bogs, and patterned peatlands of northern and northeastern Minnesota to smaller bogs and fens in the south and west. However, at the outset of this project, there was no comprehensive statewide data layer characterizing vegetation, hydrology, and soil characteristics for all of Minnesota's "peat lands." We used the following data layers and sources to describe peatland extent and characteristics:

The Soil Survey Geographic (SSURGO) Database generally has the most detailed level of soil geographic data developed by the National Cooperative Soil Survey (NCSS) in accordance with NCSS mapping standards. The tabular data represent the soil attributes and are derived from properties and characteristics stored in the National Soil Information System (NASIS). Histosols are identified as a taxonomic order using the "taxorder" variable in the component attribute table. Other variables in SSURGO tabular datasets can be used to characterize soil organic content, taxonomic reaction class (an indicator of pH), texture, etc.

Minnesota Wetland Inventory (Kloiber et al. 2019). The Minnesota Wetland Inventory is a publicly available GIS database based on the original National Wetlands Inventory (NWI) as completed for Minnesota by USFWS and updated by MNDNR, Ducks Unlimited, and St. Mary's University from 2008-2013. In addition to the principal wetland classification scheme adopted for the NWI (Cowardin et al. 1979), the MWI classifies wetlands using the Circular 39 wetland type system often referenced in Minnesota wetland statutes (Shaw and Fredine 1956) as well as a simplified hydrogeomorphic (HGM) classification based on landscape position, landform, waterbody type, and water flow path, adapted from a system developed by Brinson (1993) for the U.S. Army Corps of Engineers and adapted by Tiner (2014) for inclusion in remote-sensing-based wetland inventories. Although none of these classification systems explicitly and consistently distinguishes between peatland versus mineral wetlands, crosswalking them against the histosol soil layer provides a relatively complete picture of peatland hydrologic and vegetation types.

MNDNR Native Plant Communities is a database published on Minnesota's Geospatial Commons based on field survey data collected by MNDNR Division of Ecological and Water Resources through the Minnesota Biological Survey (MBS). It is conducted by county, extracted and attributed through a rigorous internal process based in part on the Minnesota Ecological Classification System developed for native plant community complexes used by the EWR. Data are complete only for state parks and counties that have completed surveys, and partially complete for state forests and WMAs.

Potential Native Plant Communities of northern Minnesota: a geospatial model of potential peatland systems developed at the University of MN-Duluth's Natural Resources Research Institute (NRRI) as part of an effort to map potential Native Plant Communities (NPCs) across the major forested ecological subsections of northeastern and north-central Minnesota (Brown et al. 2013). The peatland layer developed by NRRI includes three different peatland system types

Box 3. Continued

(i.e., Acid Peatlands, Forested Peatlands, and Open Peatlands) mapped across the three ecological sections that make up the Laurentian forests of Northeastern and north-central Minnesota.

Other datasets used to characterize existing and potential vegetation and land cover included the Cropland Data Layer (NLCD). Additional datasets we considered but ultimately did not make significant use of included the MNDOT Historic Vegetation Potential model and the Marschner map of pre- settlement vegetation. Additional analysis including these and more recently obtained datasets is included in an Appendix.

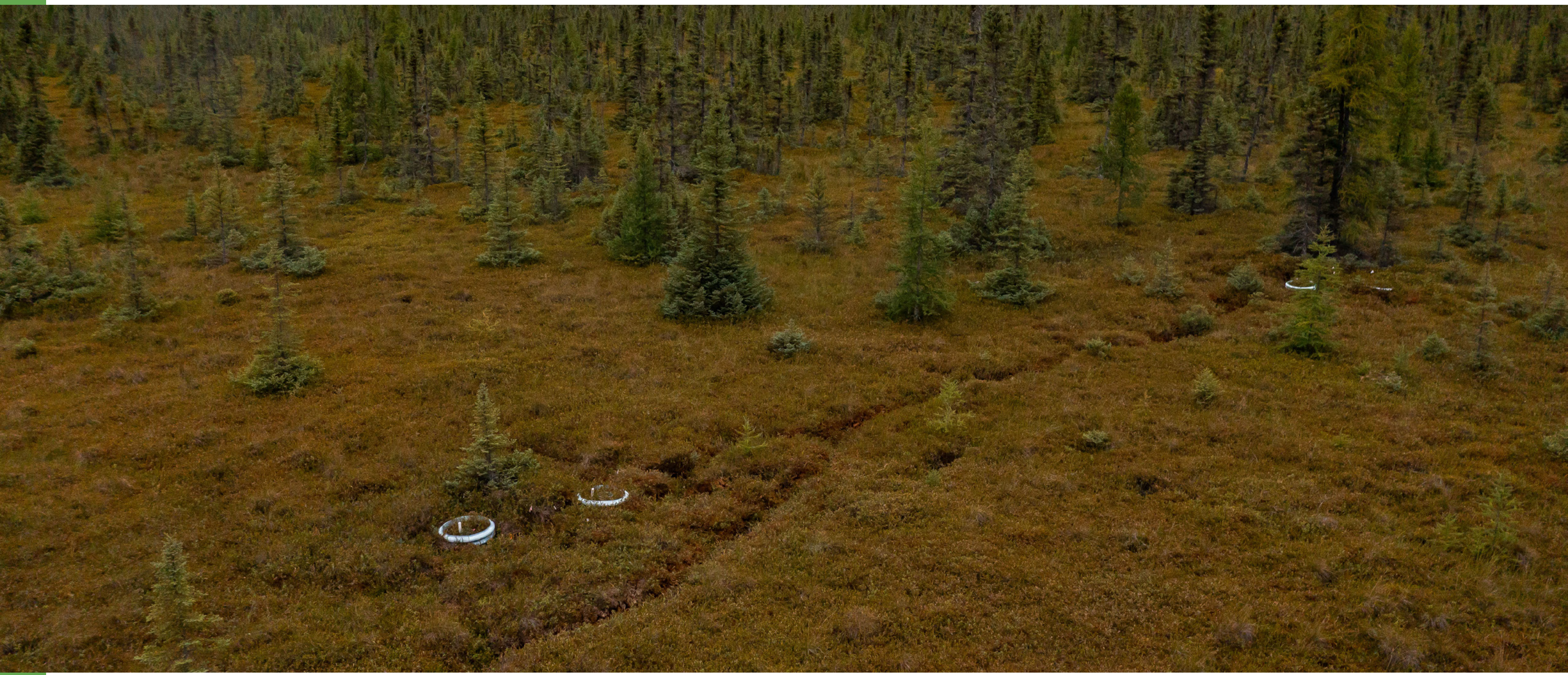
(Brinson and others, 1993; Brown et al., 2014; Cowardin, 1979; Kloiber et al., 2019; Shaw and Fredine, 1956; Tiner, 2014)

Photograph © Derek Montgomery

Key Takeaways

- We mapped peat soils based on 10% or more histosol components in order to estimate re-wetting opportunity on both drained and partially drained lands (see later section in document).
- 7.8 million acres of land in Minnesota has 10% or more histosol content. 6.7 million acres of this is accounted for as wetland area in the state.

Photograph © Derek Montgomery



Photograph © Derek Montgomery

Estimated peatland soil carbon stocks for Minnesota based on SSURGO

Minnesota peatlands are sometimes referred to as "boreal peatlands" (included as part of the southern extent of North American boreal peatlands), or as part of a band of "temperate" (non-permafrost) peatlands extending into Minnesota from Canada. Peat deposits of this region, including northern Minnesota, tend to be deeper than those of the subarctic, with higher long-term net carbon accumulation rates (Bridgham et al., 2006; Gorham, 1991; Grigal et al., 2011; Kolka et al., 2016; Ovenden, 1990).

Assessing the overall potential for terrestrial carbon sequestration in Minnesota, Anderson and colleagues (2008) estimated that 5.7 million acres of peatland in the state contain 4,250 million metric tons (MMT) of carbon, or approximately 745 metric tons of stored carbon per acre. This estimate used data from the 1980s Minnesota DNR peatland inventory, the USDA-NRCS STATSGO and NASIS database, and the 1990 LMIC land cover data. Carbon stock estimates from that analysis were generally accurate for northern Minnesota counties, as the 1980s Minnesota DNR peatland inventory was based on extensive soil sampling and soil cores that included information on peat depth, profiles, botanical origin, and Von Post decomposition. The 5.7-million-acre area estimate, however, did not include many of the organic-soil wetlands in the central and southern part of the state classified as wet meadows, shrub swamps, or forested swamps, many of which have peat or muck soils.

For the purposes of summarizing peatland carbon stocks spatially, we created a statewide raster map of soil organic carbon (SOC) in the top 100 cm of soils as derived from the NRCS digital soil database SSURGO (SOC0_100).

The amount of carbon stored in soils—particularly in the top layer most likely to be exposed or impacted by conversion, erosion, drainage, drought, or other water table impacts—also represents the amount of carbon that can be lost to the atmosphere as CO2, if wetland systems are degraded through drainage or natural disturbances such as peatland fires.

Summing that layer statewide, we estimated total carbon in the top one meter at 4.49 Petagrams (Pg), or 4.49 billion metric tons. Soil organic carbon in the soil layer mapped as 10% or more histosol component totaled 1.99 Pg, representing 44% of total soil carbon in the top one meter while making up just 15% of the state by area. Repeating this analysis for estimated SOC at 100-150 cm and 150-999 cm and summing the results from all three depth profiles, histosols account for 3.1 of a total of 6.1 Pg of carbon statewide, or more than half of all soil organic carbon.

This estimate is smaller than the 4.25 Pg estimate reported by Anderson et al (2008), and is likely an underestimate, as SSURGO estimates and accuracy vary by county and are increasingly incomplete or inaccurate at greater depths. Furthermore, our compiled digital soil maps are incomplete for three of the highest peatland-containing counties: Cook, Lake, and Pine (although very recent updates to SSURGO have filled in some of these gaps, these updates were not available at the time of this analysis).

We also note that in the decades since SSURGO and STATSGO data was originally mapped and digitized, there likely has been additional loss of peat from oxidation and decomposition.

Peatland area and carbon stocks by public ownership and administration

Of the approximate 51 million acres of total land (not including more than 3 million acres of open water) within the borders of Minnesota, approximately 12.5 million acres (around 25%) are currently owned and/or administered by federal, state, or county authorities. Another 0.7 million acres are tribally owned.[2]

Of the 7.8 million acres of land identified as having peat soils (10% or more histosol content), roughly 4.5 million (~60%) are in public ownership.

The majority of these peatland areas are state-owned, particularly in northern Minnesota. Historically, wetlands, including peatlands, were more likely to stay in or revert to state ownership. In general, the peat soils that are in private ownership occur in smaller, less extensive patches (and often include lower percent histosols), whereas the larger peat landscapes are much more likely to be in public ownership.

They are managed under a variety of different state administrative and surface interest categories, depending on how they were acquired and for what purposes they have most recently been designated, which has important implications for strategy and opportunities for carbon management, as described later in this section.

Photograph © Derek Montgomery

Federal Lands

Across Minnesota, approximately 3.8 million acres are federally owned and managed. This includes United States Forest Service (USFS) lands (primarily the Chippewa and Superior National Forests), National Parks (Voyageurs National Park), and other federal lands (including the Boundary Waters Canoe Area Wilderness, BWCAW). Of this, peat soils have been mapped on about 671,000 acres, primarily in the Superior and Chippewa National Forests. USFS is actively developing research, strategies, and guidance on peatland carbon management and restoration as well as improved forest management techniques for managing the carbon stored in these peatland soils. Major initiatives include developing improved mapping of peatlands and peat soils, especially forested wetlands that may not be adequately mapped by NRCS SSURGO. Perhaps most significantly, there are multiple research initiatives aimed at better understanding fire in peatlands. Although many peatland communities, particularly certain Sphagnum types, can be both resistant to and adapted to natural fire regimes, there is a growing need to understand forest management and other strategies that can minimize the risk of peat carbon loss due to fire, particularly the more intense fires increasingly common with climate change. Based on analysis of the SSURGO Soil Organic Carbon in the top 100 cm layer (Soc0_100), federal lands have a total carbon stock of at least 302 MMT.

State Lands

Statewide, the DNR manages a total land portfolio of at least 5.6 million acres. This includes management units designated for a variety of natural resource goals, administered by different DNR divisions, including State Forests, State Parks, Scientific and Natural Areas, and Wildlife Management Areas. Surface interests and management obligations across these lands differ according to how the land was acquired throughout the state's history. For example,

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School Trust Lands (STL) and Consolidated Conservation (Con-Con) lands (discussed below) are subject to different obligations in statute as compared with lands acquired directly to meet specific conservation or natural resource goals. These categories are not mutually exclusive: for example, the majority of School Trust Lands are also designated as State Forest, comprising more than half of the approximately 4 million acres of State Forest lands overall. In addition, the state owns nearly 3 million acres of county-managed lands acquired via tax forfeit, managed by the counties where they are located. The majority of tax forfeit lands are located in St. Louis, Koochiching, Aitkin, Itasca, Cass, and Beltrami. These are also the counties with the most county-administered peatlands.

School Trust Lands

More than half of state DNR managed lands are managed on behalf of the Office of School Trust

Land (OSTL), representing almost half of the DNR's total managed forest acres (Fernholz et al., 2021). Today this includes 2.5 million acres of surface interests and an additional 1 million acres of severed mineral rights. With the establishment of statehood in 1858, the U.S. Congress originally granted Minnesota lands equivalent to sections 16 and 36 of every township "for the use of schools." Through a series of "Swamp Acts" Congress added to these lands, eventually granting Minnesota up to 8.1 million acres. By the early 20th century, however, much of this land had been exchanged or sold, including most of the lands in the southern part of the state that were considered suitable for agriculture. The remaining lands were largely consolidated in northern Minnesota as School Trust Lands. Largely thanks to the inclusion of Swamp Act lands and the process by which less productive northern lands were exchanged for agricultural lands in southern Minnesota, more than 60% of current School Trust Lands (1.4 million acres) are mapped as having 10% or more histosols. Under the Minnesota Constitution, these are required to be managed for income to the permanent School Trust, which is primarily generated from mineral royalties, timber, and land sales.

Today, all 2.5 million acres of Minnesota School Trust lands are located within ceded territories with a small subset situated within tribal reservations boundaries. More than two million acres, or 92%, of Minnesota's School Trust Lands are located in 10 northern Minnesota counties. School Trust Lands are a substantial share of the total land base in a number of these counties. The remaining School Trust Lands are dispersed throughout other parts of the state, with less than 500 acres remaining in the southern third of the state.

Of the 2.5 million acres of School Trust Lands, the majority are designated as State Forests. The total area of overlap between Trust Lands and peat soils (1.4 million acres, or 55% of total surface interests) includes the majority of "stagnant" (low-lying, wet peatlands) generally not managed for timber. However, some forested peatlands or lowland conifer systems are considered to have "productive" stands of black spruce, tamarack, and northern white cedar. These generally occur on hemic or sapric peat, as opposed to fibric peat (St. Louis County peat inventory, 1980s.)

Approximately 600,000 acres of School Trust Lands are considered "non-productive" in terms of forestry, but may be subject to mineral leases, most of which correspond to peatland areas. Currently, active mineral leases on School Trust Lands peatlands include ~8,700 acres leased for peat harvesting and more than 30,000 acres for industrial minerals, the bulk of which (nearly 28,000 acres) is for non-ferrous minerals (i.e., the lease relating to the proposed Talon Copper-Nickel mine near Tamarack, MN). Mineral leases provide the majority of the revenue to the Trust.

Based on analysis of the SSURGO Soil Organic Carbon in the top 100 cm layer (Soc0_100), 2.44 million acres of School Trust peatlands statewide have a carbon stock of 400 MMT of carbon just in the top one meter. The top 10 counties for STL (Koochiching, St Louis, Itasca, Aitkin, Cass, Lake, Beltrami, Roseau, Cook, and Clearwater) have a total stock of 375 MMT and account for 94% of the total SOC in the top 1m. Mean SOC per acre on STL in those top 10 counties is at least 161 MT/acre.

<u>Consolidated Conservation Lands</u>
Another 1.55 million acres of state-owned land in Minnesota are known as Consolidated-Conservation (Con-Con) lands. These lands represent the bulk of non-School-Trust-Land state-owned peatlands, and stem directly from the attempts to drain the peatlands that ultimately failed. Accordingly, 64% of these lands—nearly 1 million acres—intersect the

Photograph © Mark Godfrey

histosol layer. The late 1800s and early 1900s saw a peak of drainage activities when many ditches were being built by local drainage districts in northern Minnesota in an attempt to convert wetlands to productive agricultural lands. When many of these projects failed to produce arable agricultural lands, Minnesota's Con-Con lands became state owned through tax forfeiture in 1929, 1931, and 1933. Mass tax-delinquency and abandonment caused defaults on bond payments and several counties were near bankruptcy. To prevent this, the state was given title to 1.6 million acres of land known as Con-Con lands. Today, any income generated from these lands is split evenly with the counties. While most are managed as state forest lands, a significant portion are designated as state wildlife management areas (WMAs). The majority of Con-Con lands are in counties that also have extensive peatlands: Aitkin, Beltrami, Koochiching, Lake of the Woods, Mahnomen, Marshall, and Roseau. Based on SSURGO, Con-Con lands have a total carbon stock in the top meter of soil of 339 MMT.

Acquired Lands

In recent decades, the state of Minnesota has also engaged in direct land acquisition to meet natural resource goals, such as conservation, recreation, and economic development. 1.49 million acres have been acquired by the state through purchase, county board action, gift, condemnation at the seller's request, or transfer of custodial control. DNR can only purchase land from willing sellers. Non-profit land trust organizations can also choose to purchase lands and then gift property to the state, typically for the purpose of conservation or recreation designations such as Wildlife Management Areas (WMA), Aquatic Management Areas (AMA), or Scientific and Natural Areas (SNA).

Wildlife Management Areas

Minnesota's WMA system started in 1951, when the State established its "Save the Wetlands" program to buy wetlands and other habitats from willing sellers to address the alarming loss of wildlife habitat in the state. Established to protect lands and waters that have a high potential for wildlife production, public hunting, trapping, fishing, and other compatible recreational uses, a large proportion of the state's ~1.4 million acres of WMA lands are wetlands (71% intersect the updated NWI), including peatlands (~40% with mapped histosols). The largest of these is Red Lake WMA, with approximately 80% of the 324,677-acre WMA having some mapped histosols.

<u>Scientific and Natural Areas</u>
Minnesota's SNA program was established to protect natural features of exceptional scientific or educational value including native plant communities, habitats, rare species, and geologic features. As of 2023, Minnesota has designated at least 169 public Scientific and Natural Areas across 216,000 acres, including the 18 original peatland SNAs established by the legislature, in recognition of their special significance to the state. The majority of the state's largest SNAs are peatlands, including the largest, Red Lake Peatland, at nearly 88,000 acres. Over 177,000 acres of SNAs are mapped as histosols. With a total carbon stock in the top 100 cm of at least 46 MMT, Minnesota's SNAs already protect some of the highest average carbon stock.

<u>Tax Forfeited Lands</u>
In addition to the 5.6 million acres of state-owned lands administered by DNR, an additional 2.83 million acres of "tax forfeited lands" (of which nearly one-third are located in St. Louis County) are technically state-owned but administered by the county where they are located. The DNR has oversight and approvals for some timber sales, certain leasing activities, and some sales of the land, but most management is done by the county where the land is located. The title to the lands is held by the state in trust for the respective taxing districts. As with Con-Con lands, many of these lands were abandoned because they were unsuitable for agriculture or forestry. Tax forfeit lands have an estimated total carbon stock in the top 100 cm of 313 MMT, and roughly 1/3 (1 million acres) have peat soils (i.e., mapped histosols).

Photograph © ColdSnap Photography

Estimated extent of drained (fully converted) peatlands

In their 2019 GHG inventory, the MPCA listed "cultivated histosols" as the 4th largest statewide source of GHG emissions. To develop an estimate of the extent of peatlands and peat soils that have been completely drained and converted to urban, agricultural, or other land uses, we intersected soils with 10% or greater histosol content with areas in urban or agricultural land cover (NLCD) (See Table 2, Figure 9).

Unsurprisingly, the majority of peat areas that have been fully drained and converted are concentrated south and west of a band that runs diagonally across the state from northwest to southeast, corresponding to the prairie forest border. These histosol wetlands in the southern and western half of Minnesota were almost entirely drained for agriculture in the late 19th to early 20th century.

Estimated extent of partially drained peatlands

Previous analyses estimated that up to one-sixth of Minnesota's remaining peatlands are potentially affected by legacy drainage (Ahlering et al., 2021). To refine our estimate of carbon mitigation potential from the restoration of partially drained peatlands, we focused our analysis on peatlands that are impacted by ditches but which have not been fully converted (i.e., remaining in natural or perennial cover). We then characterized these areas based on soil and other physical properties identified as important in the literature, as well as layers characterizing public land ownership and administration.

Lateral effects reported in the literature range from 20 m to more than 200 m, and depend on factors such as slope, ditch depth, and properties of the peat soil (i.e. how quickly water is able to move through the subsurface). BWSR setback guidance for peatlands therefore suggests lateral effects of 150 m or more for peatlands. To assess the carbon mitigation potential of restoring partially drained peatlands in Minnesota, we intersected the peat soil layer with the 150 m lateral effects buffer around altered watercourses based on BWSR setback guidance and lateral effects reported in the literature (Gerla, 2019; Krause et al., 2021). Using information on ditches and altered water courses from the Minnesota state Altered Watercourse Layer, intersected with the SSURGO histosol layer, and assuming a potential hydrologic impact zone of 150 m on either side of the ditch, our analysis shows a total footprint of ditched peat soils of 846,000 acres. Limiting the analysis to include only acres in wetland or other natural perennial vegetation results in a statewide opportunity area of 642,000 acres (Table 2).

The majority of partially-drained peatlands are concentrated in two areas of northern Minnesota: (1) the Red Lake peatlands and adjacent Rainy River and Lake of the Woods drainages in northern Minnesota and (2) eastern Aitkin and southwestern St. Louis County, including portions of the Mississippi River and St. Louis River drainages (Figure 9).

There are many additional smaller patches of peatlands or peat soils that are only partially impacted by drainage, where publicly or privately maintained ditches occur adjacent to relatively intact peatland vegetation located throughout the state, particularly in central Minnesota.

For the purposes of our peatlands strategy, we summarize peatland ownership categorized based on the major needs and implications for our feasible strategies: private lands, county tax forfeit lands, federal and state managed forest lands, state WMAs, as well as surface interests discussed in the previous section such as School Trust Lands and Con-Con lands. Nearly one-third of a million of the ditch-impacted histosols occur on publicly administered lands (Tables 3 and 4). This includes 133,000 acres of ditch-impacted peatlands on state forest lands, more than 84,000 on WMAs, and ~72,000 acres on School Trust Lands (Table 4).

Finally, we summarize soil organic carbon and histosols in relation to data on active mineral and peat leases (Table 5) maintained by MNDNR and available via the public Minnesota geospatial commons. Mining operations impact peatlands both through the direct impact of the mine footprint, as well as through alteration of downstream hydrology, water quality, and chemistry caused by drainage, subsurface dewatering, and downstream surcharged releases. Water that has passed through mine tailings also

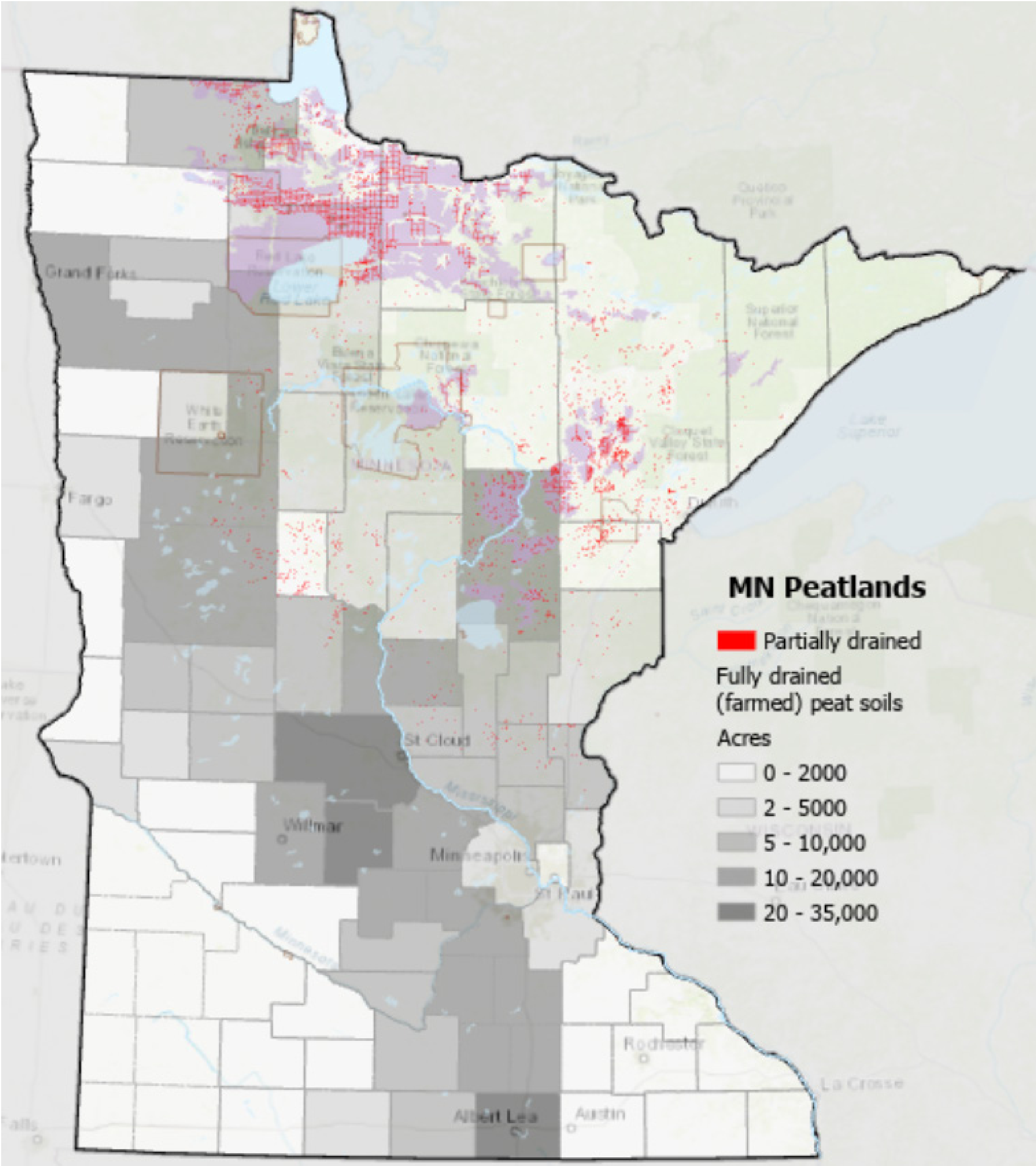


Figure 9. Fully drained (converted and/or farmed) and partially drained peatlands in northern Minnesota.

Table 2. Summarized estimates of partially drained and fully converted peatlands and peat soils in Minnesota based on land cover and intersection with peat soil.

NLCD intersection with histosols	Partially drained (within 150 m ditch buffer)	Total drained peat (converted)
Developed (roads, etc) barren land	32,300	116,00
Cropland + Pasture = "Cultivated histosols"	52,775 119,134	326,600 151,900 478,000
Perennial cover (wetland, forest, grass, etc)	642,000	na
Total (rounded)	846K	594K

Table 3. Peat soils and partially drained peat in Minnesota by major ownership/administration.

	Total acreage	Total C stock to 100cm (MMT)	Peat acreage (histosols > 10%)	Ditched (partially drained) peat
Federal	3.5 M	302	671 K	21 K
State	5.7 M	910	2.79 M	254 K
Tax forfeit (state-owned, county administered)	3.0 M	313	1.004 M	56,740
Reservation / Tribal Trust Land	2.8 M	277	679,650	30,850
Private (implied)	40+ M	>2000	>3M acres	>300 K
Total Statewide	54 M	4487	7.8 M	674 K

Table 4. State-owned and administered peat soils and partially drained peat by major designation and surface interest.

State designation type:	Total acreage	Total C stock to 100cm (MMT)	Peat acreage (histosols > 10%)	Ditched (partially drained) peat
State Forest	3.8 M	669	1.67 M	132,550
Wildlife Management Areas	1.38 M	243	615 K	84,240
Scientific & Natural Areas	216 K	46	177 K	17,040
State surface interest/ obligations				
Consolidated Conservation lands	1.55 M	339	995 K	138,500
School Trust Land	2.5 M	398	1.4 M	72,400
Acquired	2.4 M	178	413 K	1,300

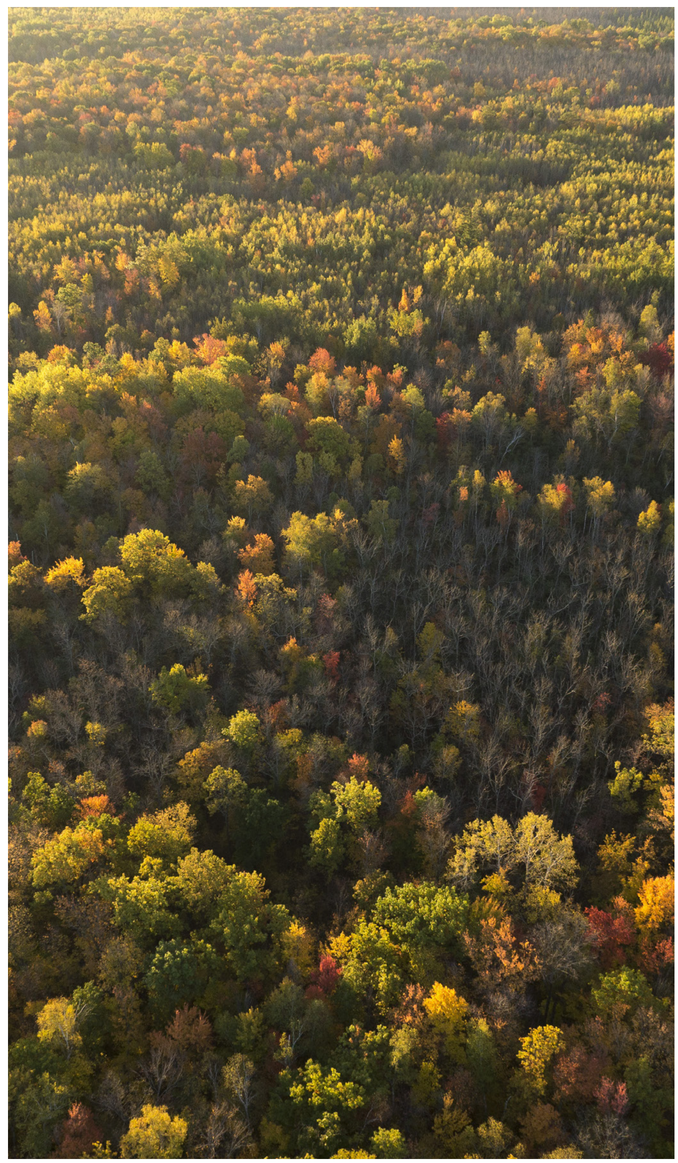
*Totals for state land categories do not match Table 2 as they include just the largest land categories, but are not mutually exclusive.

Table 5. Peat soils and carbon stocks on lands under active mineral or peat mining lease.

MINERAL & PEAT LEASES	Acres	Acres, histosol > 10%	% Histosol	Total C stock to 100 cm (MMT)
Taconite	3,375	237	7%	0.14
Industrial Mineral	3,880	2515	65%	0.74
Miscellaneous lease	555	77	14%	0.03
Non-Ferrous	61,337	27,833	45%	8.75
Residue	57	3	5%	0.00
Peat	8,480	8100	96%	1.66
TOTAL	77,683	0	0	11.3

carries leached material such as sulfates that can be directly toxic to downstream ecosystems, and/or accelerate the mobilization of pollutants such as methylmercury (Myrbo et al., 2017). All of these impacts have implications for peat carbon storage, as well as downstream water quality and habitat.

The majority of the 27,000 peat soil acres intersecting with "non-ferrous" mining leases occur within the large active lease proposed by Talon for a nickel-copper-cobalt mine near Tamarack, Minnesota, which is currently under environmental review. Data also shows more than 8,000 acres of active peat mining leases, primarily on School Trust Lands, county tax forfeit, and state forestry lands. Many of these leases have lease terms ranging from 15-25 years, with terms running through 2043 or later. Data on historic leases also indicates approximately 4,000 acres of historic, no-longer-active peat leases.



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Key Takeaways

Estimated peatland soil carbon stocks. Previous peat carbon stock estimates of Minnesota did not account for wetlands in the central/south part of the state that also contain high percentages of peat soils.

- The amount of carbon stored in soils–particularly in the top layer most likely to be exposed or impacted by conversion, erosion, drainage, drought, or other water table impacts—also represents the amount of carbon that can be lost to the atmosphere as CO2, if wetland systems are degraded through drainage or natural disturbances such as peatland fires.
- We created a statewide map of soil organic carbon (SOC) in the top 100 cm of soils, and estimated total carbon in the top one meter statewide at 4.49 Petagrams (Pg). Of that, about 44% of total soil carbon was in histosols.

Land Ownership and Carbon Stocks. Of the 7.8 million acres of land identified as having peat soils (10% or more histosol content), roughly 4.5 million (~60%) are in public ownership. This includes: federal (approximately 3.8 million acres) and state lands (about 5.6 million acres).

Fully Converted Peatland. The majority of peat areas that have been fully drained and converted are concentrated south and west of a band that runs diagonally across the state from northwest to southeast, corresponding to the prairie forest border. For summaries, see Table 2.

Estimated Extent of Partially Drained Peatlands. We estimated the impacts of "Legacy Draining," or areas that have been ditched in the past but remain in natural vegetation cover, using a 150 m buffer around altered watercourses. For summaries, see Table 3.

- The majority of partially-drained peatlands are concentrated in two areas of northern Minnesota: (1) the Red Lake peatlands and adjacent Rainy River and Lake of the Woods drainages in northern Minnesota and (2) eastern Aitkin and southwestern St. Louis County, including portions of the Mississippi River and St. Louis River drainages (Figure 9).

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Estimating Carbon Mitigation Potential of Peatland Restoration in Minnesota

The climate mitigation benefit of any specific land use change, restoration or management practice (i.e. "NCS pathway") is often calculated as the sum of the changes in GHG emissions by gas for each of the individual emissions sources under the avoided conversion or restoration scenario, as compared with the 'counterfactual', i.e. baseline scenario without intervention, over some relevant time period.

Quantifying the climate mitigation potential of peatland restoration is particularly challenging for many reasons. The factors and processes that govern carbon inputs and outputs (collectively "fluxes") are highly variable and inconsistent at multiple spatial and temporal scales (Bedard-Haughn et al., 2006; Phillips and Beeri, 2008; Tangen et al., 2015; Tangen and Bansal, 2019).

As discussed earlier, because restoration of drained peatlands typically requires raising the water table to restore inundated conditions, re-wetting drained/degraded peatlands generally reduces CO2 emissions but increases CH4 emissions. This tradeoff is not straightforward, as CH4 is a near-term climate forcer, with a large radiative efficiency but a short atmospheric lifetime. CO2 however, is a long-term climate forcer, with a smaller radiative efficiency but a long atmospheric lifetime.

Increasingly, methodologies for estimating climate impacts from different scenarios recommend aggregating short-lived climate pollutants (e.g. CH4) separately from long-lived, stable climate pollutants (e.g. CO2). To account for the higher short-term warming potential of CH4, flux values for CH4 are often multiplied by a factor of 28-35 to express them as CO2 equivalent (CO2e). Wherever CH4 fluxes are within an order of magnitude of CO2 fluxes, the accuracy of estimates of GHG flux expressed as CO2e, particularly in the short-term, will be highly sensitive to CH4 flux, for which published values from Minnesota peatlands are limited and highly variable. At the same time, because the atmospheric lifetime of GHGs such as CH4 and CO2 differ significantly, their relative radiative forcing expressed as CO2-e also differ over time, because the warming effect of CH4 dissipates to zero over time, whereas the warming effect of long-lived pollutants is cumulative and largely perpetual. Therefore, metrics that equate emissions using a single scaling factor are overly simplistic and can be misleading particularly over longer time scales.

Recent guidance produced by MPCA (2022) reported avoided GHG emission from retirement and re-wetting of farmed peatlands based on the difference between emissions from drained cropped peatland soils (i.e., histosols) and re-wetted, restored histosols. GHG emissions reductions accounted for in calculating the baseline (pre-restoration) were comprehensive and included CO2 emissions from drainage

Table 6. Estimated climate mitigation potential from re-wetting and restoring peatlands on cropped and pastured histosols

Scenario	Restoration potential (acres)	Change in emissions from avoided loss + restored sequestration (Mt CO2e/ac/yr)	Total Mt CO2e/year
Re-wet cropped histosols	326,600	13.4	4,376,000
Re-wet pastured histosols	151,900	9.5	1,443,000
Total			5,819,000

Emissions avoided from re-wetting and restoring peatlands drained for agriculture

(mineralization) plus tillage and nitrogen fertilization, N2O and CO2 emissions from fuel used in crop production and during the manufacture of synthetic agricultural fertilizers, pesticides, and fuels used on-farm. For the restoration scenario, the estimate accounted for CH4 release post re-wetting, using the 28x multiplier for CH4 warming potential. Avoided emissions were averaged over 20 years and summed as per the recommended approach for national emissions reporting. The implied annual emissions reductions from re-wetting are shown in Table 6 for both cropped and pastured histosols. Based on our estimate of the area of cropped and pastured histosols, our revised estimate of carbon emissions avoided from restoration and re-wetting of farmed histosols is ~5.82M Mt CO2e/year.

Assessing carbon mitigation potential of restoring partially drained peatlands

In our initial statewide NCS analysis (Ahlering et al., 2021), we reported combined avoided carbon emissions from avoided peatland conversion and peatland restoration at 450,000 Mt CO2e per year. This was based on applying a single avoided emissions factor—expressed in CO2 equivalents, CO2e—to one estimate of annual area at risk of conversion, and another single emissions factor for annual sequestration potential from peatland restoration and re-wetting, multiplied by our initial area estimate of half a million acres of restorable peatlands statewide. For estimating change in emissions from re-wetting partially drained peatlands, we used a relatively mid-range estimate based on a wide range of values reported in the literature for annual peatland sequestration potential. This was not, however, compared to a specific counterfactual, and was oversimplified with respect to CO2 versus CH4.

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For the purposes of this Peatland Playbook, our intent is not just to improve our areal estimates of restoration and re-wetting opportunity, but also to refine our estimates of avoided loss and sequestration potential subdivided by peatland type, land cover, restoration status, and other important biophysical variables reported in the literature. We had also hoped to assess the relative importance over time of the tradeoff between CO2 and CH4 emissions from different restoration approaches, and to incorporate initial results from our greenhouse gas (GHG) monitoring at restoration sites. However, those results will instead be included in future publications.

There is no shortage of relevant or representative estimates of annual sequestration and/or emissions reported in the literature for both

CO_2 and CH_4 from different peatland and land cover types in Minnesota, as summarized here. However, there is considerable overlap in the range of estimates reported for each. Furthermore, although research is ongoing, there are no completed comparable studies of GHG flux from re-wetted peatlands in Minnesota, on either fully or partially-drained sites.

There is a growing body of studies from Canada relevant to the restoration of fully drained peatlands that were previously converted for agriculture or peat mining, including a few approaches that do develop separate comprehensive estimates accounting for individual differences in radiative forcing and atmospheric lifetimes for CO_2 and CH_4 across different peatland types. Relevant estimates come from an extensive literature review conducted by Wilson and colleagues (2016), evaluating emissions factors associated with re-wetting, expanding on the 2013 Wetlands Supplement to the IPCC (Drösler et al., 2013). Their work confirmed the general trend of decreasing CO_2 emissions from re-wetting of drained organic soils, as well as the strong link between water table depth and both CO_2 and CH_4 emissions. They also reported separate emissions reductions estimates, incorporating all components of GHG emissions (CO_2, DOC, CH_4, N_2O), for re-wetting of drained nutrient poor versus nutrient rich forested peatlands (0.49 and 0.64 Mt CO_2e/ac /yr, respectively (Wilson et al., 2016). A selection of relevant flux values reported in the literature for CO_2 and CH_4 from Minnesota, neighboring regions, or similar peatland systems is summarized in Table 7. The published values reveal a considerable range in CO_2 flux, from -0.76 to 0.04 t CO_2e/ac/yr, and highlight uncertainties in developing climate mitigation estimates appropriate for our region. In general, variability in annual average estimates relates to the fact that emissions and fluxes are dynamic across the seasons in response to fluctuations in temperature, soil pH, water table, vegetation composition, and seasonal growth patterns.

Peatland vegetation, nutrient status, depth to water table, mean annual temperature, and pH are all important factors (Abdalla et al., 2016), but depth to water table and nutrient status/pH are generally reported to be the most significant (Turetsky et al., 2014). Based on these observed relationships, and the relative simplicity of monitoring vegetation compared with GHG flux, some researchers propose and pilot methods to index emissions factors based on vegetation type or water table (Bona et al., 2020; Couwenberg et al., 2011) .

In 2023, carbon advisory firm Terracarbon conducted a pilot analysis for TNC, assessing the potential for carbon markets to finance peatland re-wetting projects under the approved Verra VM0036 carbon standard (Verra VCS Carbon methodology standard, 2016). Although the standard was developed and approved for projects generating climate benefits via avoided emissions of peatlands that have been drained for forestry, peat extraction, or agriculture, to date we are unaware of any projects that have been fully piloted using this standard. The VM0036 methodology allows two methods for estimating GHG emissions due to peat drainage in the baseline scenario: the GEST approach, which estimates GHG fluxes based on indicator vegetation types, or the use of water table levels as a proxy. However, because we have not fully established significant models for indexing fluxes from Minnesota peatlands to mapped indicator vegetation types, TerraCarbon used the water table proxy approach based on the regression model developed by Couwenberg et al. (2011) using CO_4 and CH_4 emissions data from 10 different studies in northern temperate/hemi-boreal climates. Using an assumption for a hypothetical project area based loosely on an existing WMA and water level logger data from the Sax- Zim Bog restoration, they estimated an area-wide impact for ditch restoration on the water table of 5 cm, i.e., raising the water table from -20 cm to -15 cm. They applied a linear regression model for comparing pre- (drained) vs. post-restoration (plugging and filling ditches) fluxes based on the predicted increase in water table x across the restored site:

CO_2: y = -752 * (x – 4750)

unit: x1,000 kg CO_2 per hectare per year

CH_4: y = 16.7 * (x + 20)

unit: kg CH_4 per hectare per year

Using the above equations, they derived an estimated net difference in baseline versus post-restoration-project scenarios of 0.57 Mt CO_2e/ac/yr (1.4 Mg/ha/year), which is within the range of emission factors (EFs) from restored peatlands in Table 7.

Although the Couwenberg regression estimates used for the above analysis were preliminary and oversimplified, the approach does offer the potential for developing region-specific relationships for scaling as well as eventual project reporting and verification. Furthermore, Couwenberg also presented a regression for indexing the density of aerenchymous leaves containing specialized structures for providing oxygen to submerged roots within peat vegetation, which serves as the basis for the GEST approach outlined in VM0036. Using the vegetative assessment of the GEST approach in conjunction with improved statewide vegetation mapping and/or modeling may allow for a more accurate, spatially explicit, or dynamic statewide assessment of climate benefits from restoration over time and in response to changing climate and vegetation conditions, similar to the Canadian emissions modeling approach for peatlands described in Webster et al. (2018) and Bona et al. (2020).

In the context of carbon finance, re-wetting scenarios involving a reduction in emissions rather than restoration of a net carbon sink, are subject to the concept of "peat depletion" time, i.e., the amount of time until a drained peat soil is fully oxidized, recognizing there is a limit on the number of years that a project can claim emissions reductions from re-wetting. Regardless, the appropriate comparison for estimating climate mitigation benefits of re-wetting and restoration is the difference between the baseline (no action) scenario and the restoration scenario, as summarized by the "CO_2e emissions avoided" in Table 8.

Although we are continuing to develop more refined methods for estimating climate mitigation benefits of peatland restoration, we include here a revised range of estimates based on the potential climate mitigation impact reported by Krause et al. (2021). Based on updated estimates of the extent of histosol soils and other high carbon stock soil types statewide that are within the lateral effects zone of altered drainage channels, we estimate the total potential climate mitigation benefits of restoring all partially-drained peatland statewide at more than one-half million Mt per year. The potential for peatland restoration on public land alone would be 282,000 Mt (Table 9).

Our estimates assume, as did Krause and colleagues, that gains from avoided loss of existing carbon from partially drained peatlands and the potential sequestration of carbon at restored sites would be linearly additive (Krause et al., 2021; USFWS, 2010). Although this is likely a valid assumption over longer periods of time, we acknowledge that the bulk of carbon losses likely occurred in the initial decades following drainage.

Table 7. Review of carbon dioxide fluxes reported from published studies of peatlands in Minnesota and other relevant northern peatlands compared to Tier 1 IPCC default EF (IPCC, 2014).

Peatland system	Net CO_2 flux (MT CO2/ac/yr)[a]	Net CH_4 flux (MT CH_4/ac/yr)[a]	Location	Notes	Reference
Forested ombrotrophic bog		0.05	MEF, MN[b]		Crill et al. (1988)
		0.04	MEF, MN[b]		Crill et al. (1988)
		0.01	MEF, MN[b]	Hummock	Dise et al. (1993)
		0.05	MEF, MN[b]	Hollow	Dise et al. (1993)
	-0.57	0.09	MEF, MN[b]		Griffiths et al., (2017)
	0.04	0.01	MEF, MN[b]		Hanson et al., (2016)
Open ombrotrophic bog		0.23	MEF, MN[b]		Crill et al. (1988)
		0.17	MEF, MN[b]		Dise (1993)[c]
		0.15	MEF, MN[b]		Dise et al. (1993)
	-0.59	0.02	Mer Bleue, Canada		Roulet et al. (2007)[d]
Open poor fen		0.23	MEF, MN[b]		Crill et al. (1988)
		0.07	MEF, MN[b]		Dise (1992)[c]
		0.27	MEF, MN[b]		Dise (1993)[c]
		0.05	MEF, MN[b]		Dise (1993)[c]
		0.24	MEF, MN[b]		Dise et al. (1993)
	-0.52	0.09	MEF, MN[b]		Olson et al. (2013)[c]
Rich fen		0.09	MEF, MN[b]		Crill et al. (1988)
	-0.76	0.00	Northwestern Finland		Aurela et al. (2007)[d]
IPCC Tier 1 Default Emissions Factors					
Re-wetted nutrient-poor (temperate)	-0.34	0.05	Multiple locations		Hiraishi et al. (2014)
Re-wetted nutrient-rich (temperate)	0.74	0.12	Multiple locations		Hiraishi et al. (2014)
Drained forest land (temperate)	3.86	0.00	Multiple locations		Hiraishi et al. (2014)
Drained cropland (temperate/ boreal)	11.72	0.00	Multiple locations		Hiraishi et al. (2014)
Drainage ditch (temperate/ boreal)		0.09	Multiple locations		Hiraishi et al. (2014)

[a] Negative values indicate sequestration; positive values represent emissions or loss to the atmosphere
[b] Marcell Experimental Forest located in northern Minnesota
[c] Summarized in Kolka et al. (2018)
[d] Summarized in Strack l (2023)

Table 8. Review of GHG emissions avoided (expressed as CO2 equivalents, including C as CO2 and CH4 and N2O) reported for re-wetting and restoration of partially drained peatlands in Minnesota

System	Description	Net GHG flux or Δ from baseline (CO_2e MT /acre yr)	Reference
Restore/re-wet fully drained peatland	Mean[a]	-0.67	Anderson et al., (2008)
	Re-wet / restore cropped peat soils	-13.4	BWSR (2022)
	Re-wet / restore pastured peat soils	-9.5	BWSR (2022)
Re-wet partially drained peat soil		-1.01 – 0.09	IPCC, (2014)
	Avoided loss + restored sequestration (Ditched peat soils in Minnesota)	-0.85	Krause et al., (2021)
	Modeled net Δ in GHG flux from average 5 cm in water table	-0.57	Terracarbon (Unpublished),

[a] Mean values for peatland restoration reported in Appendix II, converted from g C m2/yr

[b] Positive number indicates source to atmosphere; negative indicates net uptake from atmosphere or net increase in sink)

In closing, it is worth reiterating that multiple recent comprehensive reviews have concluded that wetlands are a long-term natural climate solution, and that even when accounting for the higher short-term warming effect of CH4, the cumulative radiative forcing from CO2 (and sometimes N2O emissions) from unrestored wetlands far exceeds the temporary warming effect from CH4 emissions of restored wetlands, including peat lands (see Figure 3; Günther et al., 2020; Julie Loisel et al., 2021; Neubauer and Verhoeven, 2019; Nyberg et al., 2022; Strack et al., 2022). Thus, both protection and immediate active restoration of peatlands are still considered essential to reverse, slow or avoid irreversible carbon losses from these enormous global carbon stores (Humpenöder et al., 2020; Nugent et al., 2019); with the caveat that research evaluation and adaptive monitoring are also critical to resolve uncertainties and expedite learning around successful techniques (Loisel and Gallego-Sala, 2022).

Table 9. Estimated climate mitigation potential of restoring partially drained peatlands through ditch restoration and peatland re-wetting.

Estimates:	Restorable ditch impacted peat, acres (ha)	Avoided ongoing loss rate (Mt CO2e ac/yr)	Potential sequestration rate (Mt CO2e ac/yr)	Avoided loss + restored sequestration (Mt CO2e /ac/ yr)	Total Mt CO_2e /year
Public land	332,000	0.46	0.39	0.85	282,200
Minnesota Total	642,000	0.46	0.39	0.85	545,700
*compare to Krause et al 2021	306,532 (124,102)	0.46	0.39	0.85	260,500

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Key Takeaways

- Previous academic literature confirms a strong link between both re-wetting of drained organic soils and increasing the water table to a long-term reduction in CO2 emissions, but a short-term increase in CH4 emissions.
- Estimating which one has a stronger impact is difficult because of variation in carbon fluxes. However, general evidence indicates the long-term benefits of CO2 reduction outweighs the short-term impacts from CH4 emission and that re-wetting peatlands will result in a net carbon sink.
- Based on updated estimates of the extent of histosol soils and other high carbon stock soil types statewide that are within the lateral effects zone of altered drainage channels, we estimate the total potential climate mitigation benefits of restoring all partially-drained peatland statewide at more than one-half million Mt per year. The potential for peatland restoration on public land alone would be 282,000 Mt (Table 9).
- Re-wetting of partially drained northern temperate peatlands represents a significant NCS pathway in Minnesota due to the presence of high remaining carbon stocks, the ongoing threat of degradation from legacy drainage, and net positive GHG dynamics of restoring ditched peat.

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Scaling Up Implementation: Exploring the Biophysical, Economic, and Socio-political Feasibility of Peatland Restoration

Many factors affect the feasibility of peatland restoration, including ecological type, biophysical and landscape setting, technical complexity, and social, economic, institutional, and governance practices.

In addition to identifying priority areas for restoration, TNC is learning from past research and restoration efforts to improve the outcomes of future restoration projects. As part of this, we are working to synthesize lessons learned from initial field data from the TNC-led study and other research projects. This will help to design and implement an effective monitoring and evaluation study to address key remaining uncertainties associated with hydrologic restoration of restored peatlands in Minnesota (see Restoration Effectiveness Study). To improve our estimate of the potential climate benefits of peatland restoration, we are continuing to refine our understanding of carbon mitigation potential, biophysical feasibility, and co-benefits from ditch plugging and peatland re-wetting across the state's peatland ownership mix.

Biophysical feasibility

Biophysical feasibility refers to the influence of biological, landscape, chemical, and other physical conditions and settings on the potential for restoration success. Success in this case refers to restoring peatland ecosystems as a carbon sink, or at least substantially reducing net emissions. Peatland restoration is often centered around restoring hydrology and can be as simple and straightforward as plugging a ditch (something that might even happen naturally due to beaver activity or lack of maintenance). There are many examples of successful peatland restoration projects globally, including some in Minnesota, that have led to both technical guidance and a growing body of experience. These range from the simple restoration of partially drained peatlands where most of the peatland is intact to the extremely complicated technical and engineering designs needed to restore fully drained and converted peatlands that have been farmed, mined, or afforested. However, in most cases these examples have not been evaluated in terms of their net impact on greenhouse gas (GHG) flux, but instead for how well they have restored hydrology or vegetation. Fortunately, the evidence from Canada, northern Europe, and elsewhere (including our initial study findings in Minnesota) suggests that the latter in most cases is indicative of the former, particularly for Sphagnum-moss-dominated communities.

A number of physical, biological, and environmental factors affect the feasibility of peatland restoration. These include factors such as peatland type, the restoration size, ditch properties, catchment position, hydrologic complexity (e.g. drainage area, degree of hydrologic alteration, level of peat degradation, time since drainage and/or maintenance, and size (width, depth, and slope) and capacity of the ditches).

These physical factors affect the degree of difficulty in restoring the water table and pre-drainage hydrology as well.

Peatland plant communities play a critical role in the peatland carbon sink function, so restoration feasibility depends on the ability to reestablish vegetation. Vegetation reestablishment is influenced by many factors, including the availability of local seed source or transplants, the influence of invasive species are at the site (e.g. cattails, Typha sp.; or reed canary grass, Phalaris arundinacea), and the degree of difficulty in reestablishing the hydrology and chemistry that supported the pre-altered wetland vegetation communities. Because peatland vegetation type is structured by the interaction of water source, chemical properties, hydrologic regime, and peat characteristics, it can be difficult to restore the original vegetation type if the correct hydrology cannot be reestablished due to alterations from roads, drainage, or other factors. Plant communities can influence GHG flux directly, for example by transporting CH4 through structures for providing oxygen to roots called aerenchyma, or indirectly through changes to the soil environment (Escobar et al., 2022; Robroek et al., 2015; Ward et al., 2013) . While it's possible to say that generally Sphagnum tends to decrease and sedges and grasses increase GHG fluxes, studies have showed mixed results.

Some wetland/peatland types are likely easier to restore than others, both in terms of restoring peatland vegetation as well as reestablishing net GHG uptake. For example, restoration of a carbon sink in peatlands appears to have a greater probability of success for Minnesota's acid peatland or open Sphagnum-dominated communities than for fens and open rich peatlands. Sphagnum moss is a key plant genus, referred to by some as an "ecosystem engineer" (Rochefort, 2000) that strongly influences many of the hydrologic, biogeochemical, and carbon-accumulating functions of peatlands. Sphagnum moss can create conditions that few other plants can thrive in (acidic, nutrient-poor, and cold) making bogs much less vulnerable to invasion. Sphagnum mosses are more resistant to decomposition compared to sedges and other vascular plants and thereby retain more carbon over time (Rydin et al., 2013). Sphagnum moss forms a cap over bogs, limiting CH4 release where it grows across the surface of the water or forms hummocks above the water table, intercepting CH4 (Kox et al. 2021, Zhang et al. 2021, Tian et al. 2023).

On the other hand, CH4 emissions are generally higher from fens than from acidic nutrient-poor bogs (Abdalla et al., 2016; Moore and Knowles, 1989) due to higher pH, warmer subsurface temperatures from groundwater flow, and more emergent vegetation, such as sedges, which transmit CH4 to the air more effectively. Fens are often more difficult to restore because of complex groundwater flow paths from the watershed and their greater diversity of rare plants, and the complex fen and bog hydrology of northwestern Minnesota's extensive patterned peatlands have resulted in little natural recovery of pre-drainage peatland conditions even where ditches have not been maintained for many decades. This has also made it difficult to restore pre-impact vegetation and hydrology even in many places where restoration has been attempted.

The complex hydrology and higher pH of fens also makes them more vulnerable to invasion by non-peatland emergent wetland plants that can be significant CH4 emitters (phragmites, cattails, reed canary grass). Restoration projects with more open water favor more bubbling up of CH4 (ebullition) and/or transport in plants that can lead to higher and more variable CH4 release in fens compared to bogs. Turetsky et al. (2014) found that the CH4 flux from fens is more sensitive to the vegetation type present and less sensitive to soil temperature than fluxes from bog or swamp ecosystems. Still, fens are more often protected and restored for their unique and rare plant community assemblages, e.g. calcareous fens, a rare type of peatland fed by groundwater low in oxygen and rich in calcium and magnesium. These fragile ecosystems are afforded special

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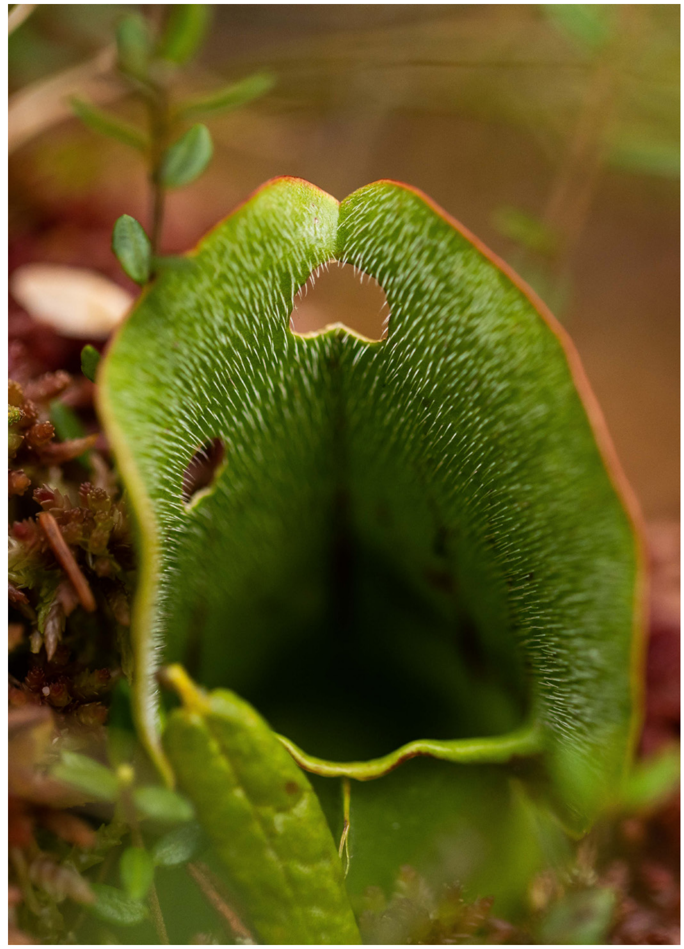
protections under the Minnesota Wetland Conservation Act.

Recognizing the importance of Sphagnum mosses to forested and open bog systems, BWSR provides technical guidance on peatland restoration both in locations where peat has been mined or where it is suitable to reestablish moss (MN BWSR, 2012). The guidance also discusses the equipment and materials needed to conduct large-scale peatland restoration, which also varies depending on how extensive physical and hydrologic alterations have been at the site, the degree and condition of peat remaining at the site, and the availability of nearby donor material such as Sphagnum and peatland plant communities needed to re-colonize the site. Restoration sites adjacent to larger intact peatland areas will likely require less time and fewer resources to reestablish, since they are likely less disturbed and have a nearby source of plants to colonize the site.

For peatlands mined for peat moss, considerable guidance and expertise has also been developed in Canada with the Moss Layer Transfer Technique for restoring peatlands, including demonstrating recovery of net carbon sequestration after 10-20 years (Quinty et al., 2020). This method should also work in many cases for drained, farmed, or cultivated peatlands once peatland hydrology has been restored. The BWSR guidance references the Canadian technique as well as experience gained from application of the approach in Minnesota at the Fens Wetland Bank site established by the Natural Resources Research Institute (NRRI; affiliated with University of Minnesota-Duluth).

Another major factor influencing restoration feasibility is the degree to which peat loss or degradation has already occurred. The rate of carbon loss appears to be most rapid during the initial phase after drainage or conversion, and therefore peatlands composed of less-degraded or decomposed fibric peat should be both a



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higher priority for avoiding irreversible carbon loss compared to hemic or sapric peats, as well as more technically feasible to restore (Krause, 2020). Because peatland drainage causes the land surface to shrink or subside over time, the ground surface can be lowered by over a meter in some cases where peatlands have been drained for many decades (Boelter, 1972; Hökkä et al., 2020; Nieminen et al., 2018; Reagan, 2023). The loss of peat volume and lower elevation creates several limitations for restoration. The loss of this amount of peat means that it would likely require decades or centuries to re-accumulate to the former elevation. From a practical standpoint, the lowered ground surface elevation means that when the ditch is blocked, the area is often re-flooded as open water. This changes the plant community type and has been found to favor CH4 release. It can be difficult to recover a Sphagnum-dominated bog in those open water areas, if it is too deep for the Sphagnum to re-colonize.

Blocking ditches is generally key to restoring peatland hydrology (Gatis et al., 2020; Holden et al., 2006; Price et al., 2003). While ditch blocking typically results in a more stable and sustainable hydrological regime by increasing baseflow from the peatland and reducing peak runoff rates and sediment export (Gatis et al., 2020)), this is not always guaranteed. One of the lessons learned from the restoration at Sax-Zim bog and other projects in the northern US and Canada is that blocking ditches alone does not restore all the ecological functions and benefits that intact peatlands provide. As previously mentioned, if blocking ditches creates large areas of open water this may create increased hotspots of CH_4 release.

Managers of future projects will want to consider the costs and benefits of simple ditch blocks versus more extensive restoration designs that require more earth-moving. If there are large, deep open ditches, they may need to be filled with logs, peat, or soil (see the BWSR wetland restoration guidance). Some ditches could be re-meandered into a shallower swale that could be revegetated more easily. Alternatively, or in addition, grading the filled ditches to make them shallower may also help reduce open water and accelerate vegetation recovery, though that adds considerably to the project cost.

For restoring partially drained peatlands through ditch closure, feasibility (and budgets) for restoration will likely vary significantly across restoration sites depending on factors such as ditch size, depth, conveyance capacity, and drainage slope. For partially-drained peatlands impacted by larger ditch networks, such as the Lake Superior Wetland Bank site in the Sax-Zim Bog it is likely necessary to do extensive filling of ditch segments in order to accelerate filling-in of open water areas and ditch-adjacent areas with peatland vegetation, especially reestablishment of Sphagnum moss communities. At the 24,000-acre Lake Superior Wetland Bank, ditch checks were required at intervals along the ditch coinciding with every one-foot drop in elevation.

"The minimum standard for ditch disablement is the construction of ditch checks, and the placement of a minimum of 200 contiguous linear feet upstream, and 100 contiguous feet downstream of natural material to completely fill the channel for the entire width and to the top of the natural bank." (EIP, 2015).
Active transplantation or seeding of moss cuttings may also help accelerate vegetation recovery, particularly if—as was done at the Lake Superior Wetland Bank—ditch fill materials are obtained on-site from areas adjacent to the ditches as part of the restoration itself where re-wetting would have likely led to some tree mortality in any case. Ditch fill materials can come, for example, from thinning of tamarack or spruce trees, together with their root wads and understory vegetation.

Feasibility factors that may be relevant to prioritizing based on degree of difficulty and complexity include watershed position and context, slope, and existing vegetation. Factors that maximize the carbon gains and co-benefits from hydrologic restoration of peat while minimizing the risk of impacts to adjacent working lands and infrastructure should in theory help identify better restoration opportunities. Factors such as the amount of road or other infrastructure that need to be preserved and the necessity of limiting impacts to adjacent properties may increase the cost, difficulty, and complexity, while lowering the feasibility of restoration success. Once restoration opportunity areas have been identified, each project typically requires a high degree of site-level detailed assessment. This includes LiDAR analysis of ditch depth, slopes, and orientation in relation to surface and subsurface flow hydrology. A hydrologic study typically has to be done to show that the project won't flood out adjacent roads, buildings or other infrastructure.

When assessing the effectiveness of restoration efforts, it is important to consider that the climate benefits of peatland re-wetting are time-dependent, with as much as 15-30 years required for re-wetted peatlands to resume functioning like intact peatlands (Escobar et al., 2022). During this time, changes in gas flux are not linear. Better accounting for temporal aspects of peatland recovery is key for accurately estimating climate benefits, as emissions factors are often derived from a short snapshot that may over- or underestimate rewetting GHG benefits depending on the post-restoration time of a peatland (Kalhori et al., 2024).

While our assessment of peatland restoration success focuses on climate mitigation, peatland restoration also offers a range of other potential co-benefits. For example, restoration can impact mercury export and improve water quality, reduce wildfire risk, and produce economic benefits. However, research focused on the climate impacts of peatland protection and restoration are rarely integrated with an investigation of co-impacts, and a better understanding co-benefits could help increase stakeholder buy-in and achieve greater implementation of protection and restoration projects.

Also impacting the effectiveness of peatland restoration efforts are the future impacts of climate change. Peatland responses to rising temperatures and changing precipitation patterns are complex, involving many feedbacks and non-linear responses between plant communities, soil properties, and soil microbial communities, which all affect carbon balance (Allison and Treseder, 2011). The SPRUCE (Spruce and Peatland Responses Under Changing Environments) project, a large-scale climate manipulation

experiment in northern Minnesota, is investigating changes to the entire peatland ecosystem above and belowground, and has shown the potential for significant disruption of peatland ecosystems and loss of carbon under projected warming scenarios (Hanson et al., 2020). However, climate manipulation experiments of this are rare, and studies examining interactions between peatland drainage and climate change are lacking. Climate change is also causing increased frequency and severity of wildfires (IPCC, 2022: Climate Change 2022:Impacts,AdaptationandVulnerabilityWorking Group II contribution to the IPCC Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 2022) and increase the susceptibility of peatlands to fire (Loisel et al., 2021; Turetsky et al., 2015, 2011), further threatening peatland carbon stocks, with fire potentially contributing peatland carbon emissions of the same order as peat decomposition (Turetsky et al., 2015). Restoring and protecting peatlands can decrease their fire susceptibility, but wildfire has not been well-incorporated into our understanding of Minnesota peatlands.

While significant guidance on peatland restoration techniques exists, many uncertainties remain with respect to the magnitude of the climate benefits of restoration in Minnesota, quantifying the underlying drivers of GHG flux, how these impacts may change under future climate change scenarios, and which co-benefits restoration may provide. TNC is conducting ongoing field research to fill these knowledge gaps, refining regionally-specific emissions factors, and developing models for estimating peatland GHG fluxes based on site-specific conditions. The findings of this work will help to assess the feasibility of future restoration projects and identify the highest priority peatlands.

Economic feasibility: Costs

Beyond the biophysical constraints, many factors impact the cost and feasibility of peatland restoration, including land ownership, land use, infrastructure such as roads and utility corridors, cultural history and beliefs, local and regional economic factors, taxation and drainage policy, and funding availability. Projects can range from relatively inexpensive options such as passive ditch abandonment to more costly interventions such as ditch plugging and active seeding of peat to ensure full restoration. While the costs described in this section represent key on-the-ground project estimates, they do not include other essential expenses related to project management, planning, and outreach.

For peatland restoration projects, whether on public or private land, the BWSR technical guide estimates costs for site preparation, donor material harvest, installation, and maintenance for peatland restoration at $1,200-$3,000 per acre. However, prices have likely increased in the years since the BWSR guide was published.

On private lands, the cost of purchasing the land or obtaining easements increases project costs considerably. In northern Minnesota, land may be $1,000-$3,000 per acre, but in southern Minnesota farmland land values can exceed $10,000 per acre. However, in Central Minnesota, TNC's partnership with the U.S. Fish and Wildlife Service (USFWS) has helped promote lower-cost restoration on private land by forgoing easements using low-tech designs and minimal seeding. For restoration, protection, and avoided conversion involving the acquisition of fee title, prices of $500-$1,000/acre can be expected for wetland acreage in Northern Minnesota.

Large-scale projects are typically more economical because of fixed costs for equipment mobilization, design, and erosion control. The fixed costs for mobilization often start in the range of $2,000-$5,000 for small equipment but can be as much as $10,000 or more for large pieces of earth-moving equipment.

The other major cost in peatland restoration is creating a ditch plug, which can range from a few thousand dollars to up to $20,000, as seen in a project in Anoka County, Minnesota. Drain tile plugs may also be required in southern agricultural wetlands of Minnesota, but are not usually present in northern Minnesota.

Most projects across the state will require a hydrologic analysis and modeling to demonstrate that the wetland restoration won't flood out adjacent roads, trails, homes, or other structures. This could add $5,000 to $20,000 or more for very complex projects. Management and long-term maintenance costs also need to be considered. This may be in the range of $1,000-$5,000 per year depending on the site. Hydrologic and carbon monitoring add additional costs. Currently, hydrologic monitoring is required for mitigation wetlands to demonstrate the establishment of wetland hydrology for a period of five years. For example, TNC is conducting monitoring of hydrology and CO_2 emissions from two sites at an estimated cost of $2,000-$5,000 per site per year.

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In theory, restoring drained peatlands on public lands through a legal ditch abandonment process has the potential to be most cost-effective because this strategy has the least opportunity cost and because producing climate benefits on publicly held peatlands is consistent with highest and best use of public lands. However, many ditches, even when not actively maintained, are not healing themselves. This strategy may work best in limited locations, or in conjunction with other restoration initiatives.

Sites on public lands often still contain some intact peat or native plant coverage, making them comparatively more cost-effective to restore. However, some peatlands on School Trust Lands support mining and forestry interests that make them more economically valuable and difficult to do peatland restoration on. In contrast, restoration on farmed sites (and peat mine reclamation sites) can sometimes be very expensive, as they often require peat revegetation and transplantation in addition to reestablishment of peat hydrology. However, these farmed peatlands are still important to consider for restoration, as described in Box 4.

Partially restored peatlands © TNC

Box. 4

Most farmed peatlands (cropped, pastured, or cultivated histosols, and organic soil wetlands) in Minnesota are in private ownership. Although peatland restoration in these contexts is often very expensive, due both to land/opportunity cost as well as extensive engineering, hydrologic, and technical costs of restoration, wetland restoration is a major strategy for the TNC's Resilient Waters program in Minnesota. Freshwater priorities for the chapter include promoting sustainable land and water management and climate resilience by restoring soil health, floodplain/riparian and wetland habitat. Restoring peatlands and wetlands in these more productive agricultural regions is often more costly, but wetland restoration projects in these contexts may produce, on a per-acre basis, higher carbon sequestration co-benefits in the short-term than restoration in northern peatlands, due to a warmer climate, more productive soils, and different vegetation types. In some cases, contrary to our initial assumptions, the lower legal and institutional complexity of smaller projects with less complex ownership patterns may even make the cost and feasibility comparable to restoration on public lands. In fact, multiple wetland restoration programs in Minnesota, from the WRP to wetland banking to FWS wetland easements— along with state Outdoor Heritage and Clean Water Funds generated by Minnesota's Clean Water, Land, and Legacy Amendment— have in recent years been driving significant increases in wetland restoration activities in southern and central Minnesota. A significant percentage of these projects have been completed on soils mapped as high organic/ histosols.

Economic feasibility: Funding opportunities

At present, state and federal funds have played a key role in funding many of the limited peatland restoration projects that are planned across the state. As regional and national climate priorities shift to include the importance of natural and working lands in climate change mitigation, we have seen some sources of funding set aside for peatland research and restoration. On the state level, this includes funding for the DNR's pilot restoration program, a state Legislative-Citizen Commission on Minnesota Resources (LCCMR) grant awarded to the University of Minnesota for research on northern peatlands, and BWSR's new RIM (Reinvest in Minnesota) program for peatland restoration on private lands. At the federal level, the Inflation Reduction Act provides some opportunities for securing funding for peatland restoration, and we hope to continue working with partners to secure and implement related proposals. Finally, there is a significant opportunity to engage directly with county drainage authorities seeking to reduce the long-term maintenance burden of public drainage systems on taxpayers, local and state government.

Though government funding has served as a key resource, we will likely need to pursue additional financial pathways in order to adequately scale peatland restoration. One such opportunity could be though the use of carbon markets, where project proponents could sell carbon credits from avoided carbon loss in peatlands after restoration. Carbon financing in Minnesota is in the early stages, even on private lands. There is a project piloting a Family Forest Carbon Program for financing carbon investments on private lands, which might provide a framework for compensating landowners for peatland restoration on private land in the future.

Given that a significant portion of publicly owned drainage-impacted peat is located on county tax forfeit or state School Trust Land, the state of Minnesota has been actively exploring a mechanism for Payments for Ecosystem Services (PES)—including participation in voluntary carbon markets—as a way to provide revenue to the counties or to the state School Trust Fund. Recent legislative changes allow for a county auditor, as directed by the county board, to lease tax-forfeited land under the terms and conditions prescribed by the county board for the purposes of investigating, analyzing, and developing conservation easements that provide ecosystem services.

However, to date there is no enabling legislation allowing for carbon financing on state-owned and administered lands. The OSTL is actively exploring the potential for carbon financing to generate revenue on School Trust Land as part of its 25-year asset management plan. The DNR, which is currently responsible for administering these lands, including revenue-generating activities such as peat mining and timber harvest, is coordinating internal discussions to understand the implications of pursuing this strategy.

As mentioned earlier, a verified carbon standard (VCS) for peatland restoration—the Verra VM0036 "Methodology for Re-wetting Drained Temperate Peatlands"—does already exist as a means to enable potential peat re-wetting projects through verified carbon markets.

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However, to date there are no examples of peatland restoration projects that have been piloted under this standard, in Minnesota or anywhere else. While more information would be needed before moving forward with a project, early analysis shows that this could work in some areas where the land use and history meets applicability considerations.

The Nature Conservancy, in partnership with TerraCarbon, recently conducted an exploratory analysis of the potential to fund restoration of partially drained peatlands in Minnesota under the VM0036 standard, as discussed in the previous section on estimating GHG reduction potential from restoration (Ericksen et al., Unpublished). The initial assessment confirmed that the largest restoration opportunity areas that meet conditions for a possible carbon project are on state-owned lands. Within the VM0036 standard, there are a few additional limiting applicability conditions that come into play. For example, carbon credits for peatland restoration must occur on land that was originally drained for one of the following: forestry that is no longer profitable, peat extraction that has been abandoned for at least two years prior to the project start, and/or agriculture that has been abandoned at least two years prior to the project start. The methodology also does not allow for projects on areas where commercial harvesting is considered to be part of the baseline scenario, which could be limiting for state-owned peatlands that are considered productive forestry lands.

Using an existing WMA with an estimated 3,109 acres of ditched peatlands as a hypothetical example, carbon market advisors suggest that a project proponent would need to keep restoration costs below $280 per hectare (~$690/ acre) for a site of that size to be economically viable as a carbon project under current market conditions. Based on the high cost and complexity of peatland restoration in Minnesota, our initial review suggests that most projects interested in using carbon markets to fund restoration would also need significant outside financial investments, such as grant funding or private philanthropy support. See Box 5 for more details about this analysis process, and Table 10 for a sample list of anticipated costs.

Table 10. Sample lists of cost types associated with a peatland restoration carbon project in Minnesota.

Carbon Operation and Certification Costs		
Project Component	Stage	Cost Type
Feasibility Study	Feasibility	Fixed
Field Data	Project Design	Fixed
Lab Analysis	Project Design	Variable
Baseline Development (USD)	Project Design	Fixed
Project Description (USD)	Project Design	Fixed
Validation Event (VVB)	Validation	Fixed
Registration Fee	Validation	Fixed
Field Data Collection	Verification	Fixed
Monitoring Report	Verification	Fixed
Verification Event (VVB)	Verification	Fixed
Issuance Levies	Verification	Variable
Hydrology Assessment Contract	Restoration	Variable
Permitting Fees	Restoration	Variable
Ditch Fill Contract (Excavation Company)	Restoration	Variable
Annual Maintenance Contract	Crediting	Variable
TNC Safeguards & FPIC Contract	Project Design	Fixed
Revenue Distribution Contract	Verification	Fixed
Revenue Distribution Contract	Verification	Fixed
Credit Marketing & Sales Contract	Project Design	Fixed
Outside Counsel Contract	All	Variable
Proponent’s Staff Costs	All	Variable

Box 5. Developing Sample Carbon Project Analysis

Phase 1: Identify eligible areas that fit with the applicability conditions of the VCS VM0036 methodology.

1. Identify parcels for further exploration, based on peatland status, ditch location, land ownership, and land use.
2. Some important applicability considerations relevant to Minnesota:
    1. Must be able to avoid leakage by ensuring that there is not meaningful hydrological connectivity with nearby areas.
    2. Verra methodology excludes locations that are being used for commercial forestry or agriculture, to avoid activity shifting and market leakage.
    3. In Minnesota, state forest lands contain large areas of ditched peatlands, but are commercially harvested and therefore not eligible for this methodology.

Phase 2: Complete feasibility analysis on a sample location.

Based on conditions determined in the phase 1 applicability analysis, the teams at TNC and TerraCarbon selected a WMA to create a hypothetical carbon project feasibility analysis.

Determine Site Characteristics:

1. Estimated 3,109 acres of ditched peatlands.
2. Originally ditched for agriculture and logging. Ditches are still in place and the legacy causes continued emissions.
3. Current land use: Wildlife Management Area managed by the DNR

Determine Project crediting period

1. Initial project crediting period of 20 years: 2025 to 2045. This could be renewed once, for a total crediting period of 40 years.
    1. validation and verification within 5 years of the project start date
    2. subsequent verifications at intervals of a maximum of 5 years

Estimate expenses from similar projects and models

1. Based on estimated expenses and revenues, calculations show that this project would need to keep restoration costs below $280 per hectare (~$690/ acre) for a site of that size to be economically viable as a carbon project.

Lessons Learned

1. Applicability conditions can have a large impact on eligible land (i.e. forestry designated land)
2. VM0036 carbon project methodology is evolving and possibly changeable.
3. In Minnesota, restoration is expensive. Under current conditions, peatland restoration carbon project would likely need additional funding from other sources in order to be financially viable.

The use of carbon financing to fund peatland restoration in Minnesota is unlikely to provide a long-term solution, nor is this appropriate or applicable for all locations and partners. However, in some cases, it may have the potential to serve as a short-term enabling factor, and to drive the kind of investments needed to develop restoration capacity in the short-term.

By contrast, wetland mitigation is well established in Minnesota as a regulatory mechanism that drives wetland restoration, including some peatlands. Mitigation banks are a special type of mitigation that creates larger, high-quality restored wetlands, where organizations can buy credits for wetland impacts incurred elsewhere. Most wetland banks aren't built on county or state-owned lands because private parties can't use public funding or resources to profit from the sale of mitigation bank credits. However, several wetland banks originally established on private lands have been later acquired by the state as public WMAs. Government agencies are not generally exempt from mitigation requirements and must also mitigate wetland impacts.

Ongoing market demand for additional wetland mitigation credits in the state of Minnesota is driven by permitted "unavoidable" impacts to existing wetlands, largely due to private and public road and infrastructure development. A significant amount of literature evaluating wetland mitigation effectiveness has raised significant and legitimate concerns about whether replacement wetlands are adequately compensating for lost wetland functions and values (Burgin, 2010), including carbon storage. In general, mitigation wetlands have been able to restore desired water levels but plant community re-establishment has been less successful. Despite their problems, mitigation wetlands have been a driving force behind a growing portfolio of peatland restoration case studies dating back at least thirty years, providing opportunities for an evaluation of impacts and co-benefits. Statewide, the most recent BWSR data layer shows more than 41,000 acres of approved wetland banks, of which more than 24,000 acres occur on soils mapped as histosols.


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Because Minnesota wetland law requires not just replacement of wetland acres, but "wetland functions and services," there is an opportunity to improve accounting for carbon functions through improved wetland mitigation approaches. State and federal wetland mitigation laws, recognizing that the quality and type of functions and services lost are difficult to replace and take time to recover, typically require replacement at ratios of 2:1 or larger (Jaschke and Larson, 1995), depending on wetland type and location within Minnesota. Because this requires restoring a larger area of wetland than the areas impacted, this does create the potential to address past wetland loss in terms of both extent and ecosystem services. According to the law, mitigation wetlands are also supposed to occur as close as possible to the lost wetlands, preferably in the same watershed, although this is frequently impractical. Regardless, due to the large lag time involved in restoring lost functions and services, a comprehensive peatland strategy should encourage siting and/or routing of linear infrastructure and other projects involving construction, conversion, etc. to avoid impacts to peatlands whenever possible. Achieving that goal would require effective enforcement of the WCA and implementation of the (wetland) mitigation hierarchy: avoid, minimize/reduce, and restore.

Efforts are ongoing to establish additional workable mechanisms for enabling ecosystem services payments on state and county lands. This is particularly relevant for School Trust Lands that are constitutionally obligated to generate revenue to the School Trust Fund according to their "highest and best use." In the case of peatlands, this may indeed be carbon storage and climate mitigation. For peatlands on School Trust Lands, the bulk of revenue generated is through peat harvest and other mining leases. Some forestry revenue is also derived from some of the more productive lowland conifer stands. Ultimately, the Trust needs to be compensated for any land use designations or new protections that result in foregone revenue to the Trust, unless those are decisions are based on "sound natural resource principles." Some climate mitigation may also be achieved through improved forest management on lowland conifer forest peatlands. In particular, thinning of dense forest cover prior to re-wetting may allow for harvest of many trees that would be subject to mortality following re-wetting, while opening up the canopy to allow for Sphagnum mosses to recover.

Sociopolitical feasibility

In addition to the biophysical and economic feasibility considerations, sociopolitical attitudes, values, and acceptance also impact the feasibility of peatland restoration. Across Minnesota, many public and private ditch systems are still actively maintained and are largely promoted and perceived as providing benefits to landowners. State statute chapter 103E governs state drainage law, which is largely administered through county drainage authorities. Public ditches may be maintained or excavated to reestablish their original depth if petitioned by landowners and/or approved by the local government unit. Though attitudes and values about wetlands have changed considerably in the past decades, many landowners are understandably concerned about the potential of ditch abandonment or plugging to negatively impact their property value or affect their ability to use their own land. Even though peatlands can provide downstream water storage and water quality benefits, benefits do depend on factors such as location in relation to the restoration site. In most cases where proposed restoration may impact downstream or adjacent property owners, detailed hydrologic studies will be needed to ensure restoration or ditch closure designs will not impact neighboring properties or increase the risk of localized flooding in areas adjacent to the restoration site. Even with good studies and evidence supporting net local benefits, a proposed restoration project may still find it difficult to win community or neighboring landowner support. Regardless, peatland restoration projects need to be designed to avoid impacting nearby properties, which may increase the design cost. As such, restoration projects are likely more feasible where they involve limited ditch complexity or land ownership/administration, as well as where they provide clear co-benefits like water quality, water storage, and habitat for which there is a recognized need.

Though some attitudes related to drainage and ditching have changed, laws relating to drainage are largely designed to facilitate maintenance of drainage projects. For example, under existing drainage laws, abandonment of public ditches is a complex and burdensome process for drainage authorities (e.g. counties or watershed districts). The legal system also typically places a high burden of proof on individual landowners who opt out of drainage improvements or "benefits assessments," or to pursue restoration on their own properties, even in some cases on privately maintained ditches. This is especially true if adjacent landowners want to maintain the drainage function of the ditch.

Institutional feasibility

Even on public land, the complexity of ownership and management is a consideration for potential restoration projects. Many potential restoration sites involve a complex matrix of federal, county, and state lands subject to different management goals, statutory obligations, and administrative policies and procedures, and sources and mechanisms for funding or financing or restoration. Coordinating such projects across multiple administrative interests is challenging, especially where restoration involves potential loss of revenue or other existing benefit streams, but not impossible.

As mentioned earlier, ongoing discussions between OSTL, DNR, counties, and others are exploring potential revenue streams from ecosystem services or conservation leases. School Trust Land managers have an opportunity to broaden their revenue portfolios by engaging with ecosystem service markets. A recent analysis, authored by Dovetail Partners with TNC input, identified opportunities to generate carbon revenue via "improved forest management" on forested School Trust Lands by managing for increased forest carbon storage and sequestration in forest biomass (Fernholz et al., 2021). The report recommended that ecosystem services criteria be used to conduct a strategic

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assessment of School Trust Lands to identify the best and most marketable opportunities for multiple ecosystem service payments, while acknowledging that these markets change over time. Though that report was focused on a different NCS pathway—Improved Forest Management (IFM)—as a means of generating carbon revenue, the large amount of peatland on School Trust Lands underscores the importance of evaluating the relative cost effectiveness of peatland restoration as compared with other NCS pathways such as IFM across the different peatland types.

Table 11. Tactics and options for a comprehensive statewide Strategy for Peatland Protection, Management, and Restoration

Strategy for Peatland Protection, Management, and Restoration		
Strategy	Applicability	Tactics/Options
Protect large remaining standing stocks of carbon in intact peatlands	Intact peatlands on private lands	• Quantify impacts and mitigation requirements for all new impacts to peatlands going forward (peat mining, wetland impacts, etc.) • Protect high quality at-risk peatlands through acquisition or easements • Support improved implementation of WCA • Expand wetland functional assessment to account for carbon functions and services • Adhere to the mitigation hierarchy (avoid/minimize/mitigate) in reference to carbon impacts
	Public (federal, state, and county lands)	• Identify and promote forestry best management practices (BMPs) and improved forest management (IFM) on lowland conifer/peat forestry lands to enhance carbon sequestration and/or minimize net above- and below-ground carbon loss, including reducing the risk of high-intensity peat fires
		• Develop public/private road/infrastructure BMPs that reduce drainage needs and carbon impacts to peatlands

Table 11. Cont.

Re-wet partially drained extensive peatlands in northern Minnesota	State-owned or administered: WMAs	• Public (federal and state) funding for DNR to conduct peat habitat restoration on WMA lands
	School Trust Land /State Forests	• Explore carbon finance and PES mechanisms (e.g., carbon leasing through voluntary/alternative carbon markets, peatland re-wetting and IFM Old growth buyout, additional SNA designation and buyout, exchange nonproductive School Trust Land peatlands for forestry lands with IFM/reforestation potential (e.g., through Strategic Land Asset Management (SLAM))
Restore large peat/muck wetlands throughout central Minnesota in areas degraded by drainage, agriculture, or other activities	Public	• WMA acquisition to enable larger peatland/wetland restoration complexes • Restoration of partially drained wetlands on existing WMAs and public land
	Private	• BWSR RIM • BWSR wetland and water storage easements • Federal wetland private lands programs (NRCS/USDA WRP, USFWS) including Partners for Fish and Wildlife • Minnesota Prairie Plan wetland restoration on perennial connection lands
	Public or private	• Identify additional peatland restoration opportunities where they provide water quality, water storage, biodiversity, or other co-benefits, especially where connected to existing programs and funding sources

Key Takeaways

Biophysical feasibility

- A number of physical, biological, and environmental factors affect the feasibility of peatland restoration. These include factors such as peatland type, restoration size, ditch properties, hydrologic complexity, level of peat degradation, time since drainage and/or maintenance, and size of the ditches.

Economic feasibility: costs

- Peatland restoration projects can range from relatively inexpensive options such as passive ditch abandonment to more costly interventions such as ditch plugging and active seeding of peat to ensure full restoration.
- Large-scale projects are typically more economical because of fixed costs for equipment mobilization, design, and planning.
- In northern Minnesota, large amounts of public land and cheaper land prices can make projects more financially feasible, as compared to southern Minnesota.

Economic feasibility: funding opportunities

- Carbon financing in Minnesota is in the early stages, but could play a role in funding peatland restoration projects.
- Initial assessments show the largest restoration opportunity areas that meet conditions for a possible carbon project are on state-owned lands, but that based on the high cost and complexity of peatland restoration in Minnesota, most projects interested in using carbon markets to fund restoration would also need significant outside financial investments (i.e. grant funding or private philanthropy support).
- Wetland mitigation is well-established in Minnesota as a regulatory mechanism that funds wetland restoration, including some peatlands.

Key Takeaways, continued

Sociopolitical feasibility

- Many landowners are understandably concerned about the potential of nearby ditch abandonment or plugging to negatively impact flooding on their property, though hydrologic studies will work to make sure that any project doesn't have negative offsite impacts.

Institutional feasibility

- Many potential restoration sites involve a complex matrix of federal, county, and state lands subject to different management goals, statutory obligations, and administrative policies and procedures, and sources and mechanisms for funding or financing or restoration.

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Scaling peat interventions to achieve measurable impacts

Peatland protection and restoration are complex and multi-sectoral initiatives that require ongoing communication and coordination among local landowners, Tribes, state and federal agencies, and NGOs. Globally, there is increasing recognition that taking action to monitor, assess, and restore peatland ecosystems is a point of urgency to meet global climate mitigation targets (Loisel and Gallego-Sala, 2022; UNEP, 2022). At the same time, there is broad recognition that scaling peatland protection and restoration will require action, policy, and science at multiple scales. A policy brief produced by the Ramsar Convention on Wetlands (2021) recognizes that restoring drained peatlands will be a critical part of achieving global climate goals, but acknowledges that scaling up globally will require additional work in each unique peatland context. New policies may also be needed in each jurisdiction to move from peatland degradation to peatland conservation and restoration. In Minnesota, this may include state support for re-wetting, reclamation, and restoration of drained sites, and improved policy frameworks for valuing the climate services of peatlands relative to alternative revenue generating activities. The allocation of more financial resources to peatland restoration is urgently needed because the lack of adequate financial incentives for sustainable peatland management remains a key barrier to progress.

In 2023, TNC hosted a peatland symposium in Minnesota to bring together these stakeholders, and consequently launched a series of working groups and partner conversations to amplify communication and knowledge, and to coordinate toward shared restoration goals. Though these groups are ongoing and changing, initial lessons show that there is a lot of energy and interest in peatlands in Minnesota, but need for more coordination among groups. As part of this coordination, it will be important to make sure that interested parties are ready to propose or implement potential projects when funding arises, including being comfortable with prioritizing sites and understanding potential restoration techniques and expenses. We are continuing to work with partners and collaborators to prioritize implementation opportunities across the suite of peatland types and settings in our region. In particular, we are working closely with the Minnesota DNR, which administers the largest area of peatlands statewide, to develop management plans in collaboration with other key partners. We are also working to support restoration on private lands within more agricultural areas in central and southern Minnesota.

Beyond Minnesota, national and international partnerships also provide an opportunity for sharing knowledge and resources. In North Carolina, TNC has helped lead development of an approved carbon market framework to finance restoration of "pocosin" peatlands in the southeastern United States, and lessons from this pilot program could translate to Minnesota's temperate and boreal peatland ecosystems. In Canada's southern peatland extents, where peat mining operations have been far more extensive than in Minnesota, researchers have developed a "Moss Layer Transfer Technique" to successfully restore Sphagnum mosses. Canadian researchers have also made great strides in understanding peatland and wildfire dynamics, and developing suggestions for ecosystem management to prevent carbon loss in catastrophic blazes. Due to the similarity of southern Canada's peatland systems with those in Minnesota, the Canadian experience offers many relevant insights, evaluation frameworks and research methods, research findings, and lessons learned from applied restoration that can be brought to prioritizing and scaling restoration and management here.

Outside of North America, many countries are also promoting, developing, and supporting science, strategy, and policies for the restoration of drained and degraded peatlands. These include Finland, Scotland, and other northern European countries such as Germany and Estonia, and elsewhere in several Andean nations and Indonesia. Finland's experience with developing restoration and improved forestry management approaches for drained peatlands, as well as its focus on Indigenous, locally-led and community driven restoration, is especially relevant to Minnesota.

The 2021 Ramsar policy brief also called for "more precise measurement and reporting and more coherent documentation of biodiversity values and climate change impacts, combined with socio-economic information" in order to help expand policy options and cultivate broader support from society at large. Our chapter's ongoing monitoring and assessment of existing restoration sites continues to improve our understanding of the benefits of peatland restoration. To support the chapter's freshwater program priorities, which include targeting wetland restoration (including peatlands) for multiple benefits, we are continuing to assess and evaluate vegetation recovery, nutrient reduction, hydrologic, and carbon benefits at multiple sites, and to expand our partnerships and learning from other on-the-ground peatland restoration and related projects. Although further work is required to quantify the effectiveness of peatland restoration as climate mitigation in Minnesota, we also recognize the important role these ecosystems play in supporting biodiversity and other co-benefits.

Healthy peatlands bolster climate change resilience, adaptation, and mitigation

Shifts in precipitation patterns and rising temperatures from anthropogenic climate change may cause significant disruption of peatland ecosystems, including loss of carbon under projected warming scenarios (Hanson et al., 2020). Despite this uncertainty, peatland protection and restoration are important conservation strategies because of the important roles that healthy peatlands can play in bolstering climate change resilience and adaptation, in addition to mitigation. Research suggests that the current ecological condition of peatlands will affect how they respond to climate change, and that early action is important. Peatlands with high peat moss (Sphagnum spp.) cover are likely to exhibit greater resilience to climate change (Alshammari et al., 2020; Glenk et al., 2014). Conversely, peatland areas in poor ecological condition are likely to be more vulnerable to climate change (Turetsky et al., 2015). Thus, restoration that occurs sooner rather than later to improve the health of peatlands, may be more likely to increase climate change resilience, as restored sites will have more time to recover vegetation and ecological functioning (see Swindles et al., 2019).

This is especially important because bogs grow vegetation very slowly compared to warmer, more nutrient-rich environments and therefore require long timescales to accumulate significant amounts of carbon in peat. Due to the slow rate of carbon sequestration, peatland protection is particularly important because intact peatlands contain so much of the world's carbon. Furthermore, intact, functioning peatlands offer many ecosystem services that the enhance climate change resilience of people and nature. For example, they provide water storage capacity, buffering against both flooding and drought (Waddington et al., 2015) and can act as fire refugia, preventing carbon loss from wildfires (Harris et al., 2022; Krawchuk et al., 2016; Kuntzemann et al., 2023).

Conclusion

It is clear that Natural Climate Solutions, including peatland restoration and management, are a critical strategy to address climate change. Minnesota has more peatland area than any of the lower 48 states and so peatlands play an especially important role in Minnesota's NCS strategies. However, many of Minnesota's peatlands have been altered by drainage and/or agriculture, causing significant GHG emissions and loss of stored carbon. Through re-wetting and restoring affected peatlands and protecting intact peatlands, we can reduce or even reverse the loss of stored carbon. Though the science of wetlands' role in climate change mitigation is fairly new, recent studies have taught us many lessons, and evidence suggests that the restoration and protection of peatlands has strong climate mitigation potential. This has led to the creation of TNC's peatland strategy: protect large standing carbon stocks, re-wet partially drained peatlands, and restore fully drained peat wetlands for multiple benefits. TNC has found significant climate mitigation potential in Minnesota's peatlands, particularly on publicly-owned land, presenting a strong opportunity to scale up peatland protection and restoration with unprecedented levels of interest and funding in the state. Although some scientific uncertainties around the magnitude of peatland restoration benefits still exist, we need to act now to capitalize on the opportunities. TNC is actively engaged in researching the climate impacts of Minnesota's peatlands and bringing together partners and stakeholders to capitalize on the current momentum. This playbook provides a resource for identifying opportunities and addressing some of the key challenges and next steps to move the ball forward on scaling up peatland protection and restoration as a key part of Minnesota's NCS strategy.

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Acronyms

BMP–Best management practices

BWSR–Board of Water and Soil Resources. The Minnesota soil and water conservation agency, which works to improve and protect soil and water resources primarily on private lands. They administer state wetland programs.

DOC–Dissolved Organic Carbon. The carbon content of dissolved organic matter, which is the smallest size of organic particle present in water.

EF–Emissions factor. An estimate of the greenhouse gas (GHG) emissions produced by an activity or land use type. For land use, emissions factors are given in GHG emissions (often CO2 equivalents) per unit land area.

GEST–Greenhouse gas Emission Site Type. Plant community type used in conjunction with water levels to estimate GHG emissions factors. System published in Couwenberg et al., 2011.

GHG–Greenhouse Gas. Gases that trap heat and contribute to climate change when present in the atmosphere. In peatlands, carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) are the three most common GHGs.

IPCC–Intergovernmental Panel on Climate Change. International organization of governments that provides climate-related scientific information to assist with climate policy. This group creates regular climate assessment reports.

(MN) DNR–(Minnesota) Department of Natural Resources. Minnesota state agency responsible for managing the state's natural lands and waters.

MMT–Million metric tons. 1 billion kilograms.

MPCA–Minnesota Pollution Control Agency. Minnesota state agency responsible for regulating and preventing pollution and climate change impacts.

N2O–Nitrous oxide. An important GHG. It is found in low concentrations in the atmosphere, but is highly efficient at trapping heat.

NASIS–National Soil Information System. Information system for entering and storing soils information for the National Cooperative Soil Survey.

NCS–Natural Climate Solutions. Strategies for management of natural and working lands to decrease GHG emissions or increase GHG sequestration. NCS include three levels of action: protect, manage, and restore.

NLCD–National Land Cover Database. National database describing land cover characteristics including land use type, tree cover, and impervious surface cover.

NWI–National Wetland Inventory. National database of the locations and types of wetlands using the Cowardin classification system.

PADUS–Protected Areas Database of the United States. National database of lands protected for conservation, recreation, or other uses.

SNA–Scientific and Natural Areas. This is a class of land managed by the Minnesota Department of Natural Resources to minimize disturbance and protect scientifically or educationally valuable natural features.

SOC–Soil Organic Carbon. The fraction of carbon in soils derived from living and dead and decomposed organisms. Peat soils have high SOC content, which can exceed 50%.

SOCCR2–State of the Carbon Cycle Report version 2. This report provides a comprehensive assessment of the current science of the carbon cycle in North America and feedbacks with climate change.

SSURGO–Soil Survey Geographic Database. National database of soil classification and soil property data produced and managed by the Natural Resource Conservation Service.

STL–School Trust Lands. A class of state-owned land originally granted by the federal government and managed to generate long-term economic return to fund K-12 education. Minnesota has 2.5 million acres of School Trust Lands, which generate income primarily through iron mining and timber harvest, as well as aggregate and peat mining, mineral leases, land sales, and licensing utility crossings.

STATSGO–State Soil Geographic dataset. National soil database, which offers more coverage but less detailed information than SSURGO.

USDA-NRCS–United States Department of Agriculture Natural Resources Conservation Service. As the land conservation agency of the USDA, the NRCS works with partners and landowners to implement management practices that promote healthy soil and water. The NRCS also leads the soil survey.

USFWS–United States Fish and Wildlife Service. Federal agency tasked with protecting fish, wildlife, plants, and their habitat.

WCA–Wetland Conservation Act. State statute promoting the conservation of Minnesota's wetlands. A key piece is the requirement for no net loss of wetland area or quality.

WMA–Wildlife Management Area. State lands managed to provide wildlife habitat, focused on management for hunting, fishing, and trapping.

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