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Thaw-induced impacts on land and water in discontinuous permafrost: A review of the Taiga Plains and Taiga Shield, northwestern Canada

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ABSTRACT

Rising air temperatures, intensifying wildfire activity, and human disturbance are driving rapid permafrost thaw across the subarctic, particularly for thaw-sensitive discontinuous permafrost. The Taiga Plains and Taiga Shield ecozones of northwestern Canada have experienced rapid and widespread permafrost thaw over recent decades, creating significant community concerns and knowledge gaps. In direct response, this review: (1) outlines the observed thaw-induced changes in landcover, hydrology, and water quality; (2) discusses the underlying drivers and mechanisms of these changes; and (3) identifies knowledge gaps to guide future research in the discontinuous permafrost zone of the Taiga Plains and Shield (study region). In the Taiga Plains, permafrost is mainly associated with peatlands where its thaw increases the extent of thermokarst wetlands at the expense of treed peatlands underlain by permafrost. This thaw-induced landcover change enhances the hydrologic connectivity of the landscape, which increases basin-scale runoff and annual streamflow, and enables wetland drainage such that permafrost-free treed wetlands develop. Thaw-induced landcover changes in the lake- and bedrock-dominated Taiga Shield are not well known but are expected to occur as limited or minor thermokarst pond development and changing lake extent due to the low (<5%) peatland coverage of this ecozone. Permafrost thaw also increases the connectivity between surface water and groundwater, leading to increasing winter baseflows and possibly icing (aufeis) development. Such increases in hydrologic connectivity can enhance the mobilization of parameters of concern for water quality, both in the Taiga Plains and Shield. The thawing of peatlands will likely increase the transport and concentrations of dissolved organic carbon and metals bound to organic compounds, including methylmercury. Further work is needed to fully understand the biogeochemical processes operating in these systems and the degree to which thawing peatlands will impact water quality and quantity at the larger basin scale. The greatest knowledge gaps across the study region surround the evolution of thaw-activated groundwater flow systems and the consequences for wetland biogeochemistry, the rates and patterns of permafrost thaw, contaminant transport, and streamflow of larger river systems. This synthesis not only informs future research directions in the study region but extends to similar subarctic peatland and Shield environments common throughout the circumpolar north.

1. Introduction

Northwestern Canada is warming at nearly twice the global rate (Box et al., 2019; Vincent et al., 2015), leading to widespread permafrost thaw (Gibson et al., 2021). Discontinuous permafrost is highly vulnerable to thaw (Spence et al., 2020b) since fragmented permafrost bodies receive vertical and lateral conduction (Devoie et al., 2021). It is also relatively thin and warm (isothermal at the freezing point), so even slight increases in temperature or changes in the surface energy balance from anthropogenic or natural disturbance can lead to permafrost thaw (Quinton et al., 2009). As such, the southern fringe of the discontinuous permafrost zone is experiencing some of the highest rates of areal permafrost thaw (Helbig et al., 2016). Here, permafrost extent has decreased between ~10–50% over the last 50–60 years (Beilman and

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Robinson, 2003; Chasmer and Hopkinson, 2017; Holloway and Lewkowicz, 2020; Quinton et al., 2011; Zhang et al., 2014), with evidence suggesting the southern permafrost boundary is migrating northward (Kwong and Gan, 1994). In addition, wildfires in the northern hemisphere are increasing in frequency, severity, and quantity (Hanes et al., 2019; Jafarov et al., 2013; Wotton et al., 2017; Zhang et al., 2015) which is further accelerating rates of permafrost thaw (Gibson et al., 2018).

There are growing concerns from Indigenous groups in this region who have occupied their lands since time immemorial and are directly impacted by climate change (Mackenzie River Basin Board, 2021). Permafrost thaw is rapidly transforming terrestrial and aquatic ecosystems and changing water quantity and quality, which impact wildlife and fish, and threaten to change traditional access routes. These changes, combined with expanding resource development projects and increasing road access, have stimulated new research within the region, including Indigenous-led land monitoring (e.g., Dene Tha' First Nation, 2021; Government of the Northwest Territories, 2020; Indigenous Leadership Initiative, 2021) and initiatives that document climate-driven changes (e.g., Christensen, 2015; Guyot et al., 2006; Parlee and Maloney, 2017). Several recent reviews have focussed on broad-scale thaw-induced terrestrial impacts (Jin et al., 2020; Quinton et al., 2009), hydrology (e.g., Bring et al., 2016; Kokelj and Jorgenson, 2013; McKenzie et al., 2021; Walvoord and Kurylyk, 2016; Woo et al., 2008), and water quality (Cochand et al., 2019; Frey and McClelland, 2009; Miner et al., 2021; Tank et al., 2020; Vonk et al., 2015, 2019), all of which note that region-specific characteristics control landscape response to permafrost thaw. However, due to interdisciplinary barriers, how changes in landcover, hydrology, and water quality affect each other is rarely discussed. Considering this region is one of the most rapidly warming (Vincent et al., 2015) and hydrologically evolving on Earth (Mack et al., 2021), an in-depth and region-specific review for the southern Taiga Plains and Taiga Shield is necessary to identify knowledge gaps and guide future research in the region. Here, we provide a detailed overview of permafrost thaw impacts that account for feedback and linkages among landcover, hydrology, and water quality components.

2. Study region

This review focuses on the southern portion of the discontinuous permafrost zone of the Taiga Plains and Taiga Shield ecozones of western Canada (Fig. 1). The study region lies within the traditional

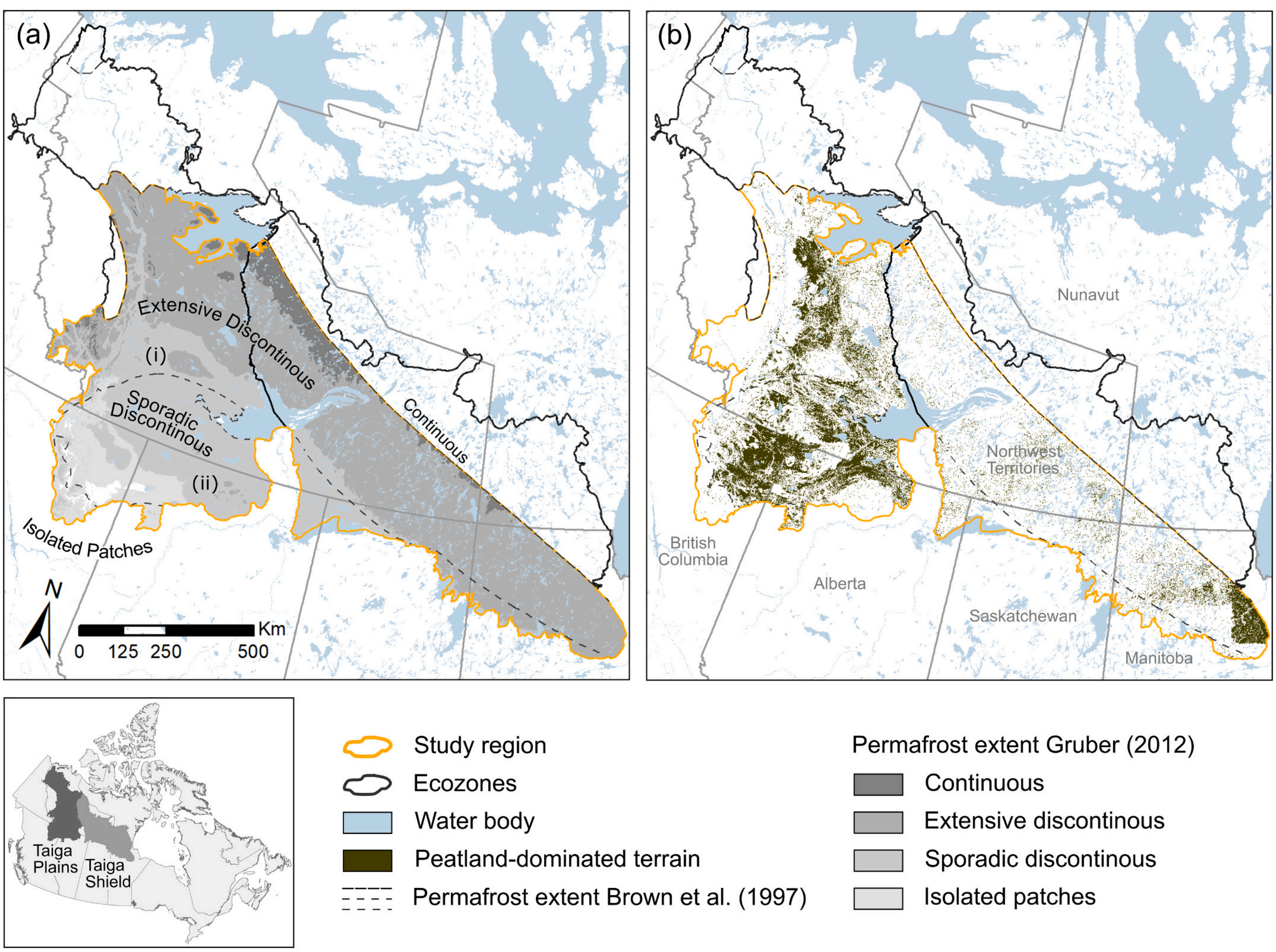

Fig. 1. (a) Permafrost extent within the Taiga Plains and Taiga Shield ecozones after Gruber (2012) and compared to Brown et al., 1997. The study region excludes the continuous permafrost zone based on the extent from Brown et al., 1997, but includes sporadic (<10% areal coverage), isolated (10-50% areal coverage), and extensive discontinuous permafrost (50-90% areal coverage). The influence of topography on permafrost extent can be seen over the (i) Horn Plateau and (ii) Caribou Mountains. (b) Predicted distribution of peatland-dominated terrain in the Taiga Plains and Taiga Shield. Peatland-dominated terrain was mapped using a saturated soils dataset (Natural Resources Canada, 2017) following methods described in Carpino et al. (2021). Note that ecozone boundaries are based on the National Ecological Framework for Canada, where the Slave River corridor falls outside the Taiga Plains (Ecological Stratification Working Group, 1995).

lands of many Indigenous groups and Nations including the Denendeh (Dënësųłinë Nëné), Dene Tha', Michif Piyii (Métis), Northwest Territory Métis Nation, Dehcho Dene, Acho Dene Koe, Akaitcho Dene, Kátł'odeeche First Nation, Salt River First Nation, and Kaska Dena Kayeh, Sahtu Dene and Métis, Tłı̨chǫ Nation, Dahlu T'ua, Tes-He-Olie Twe, Kisipakamak, and Athabascan Chipewyan First Nations. These Nations have stewarded the land since time immemorial and have been disproportionately impacted by changing landscapes as a consequence of permafrost thaw, including disruption of hunting and on-the-land activities (Parlee and Maloney, 2017).

Permafrost extent (Fig. 1a) generally follows mean annual air temperature (MAAT) trends (Brown et al., 1997), with increased extent at higher elevations (Gruber, 2012). For example, the Horn Plateau (Fig. 1a-i) and the Caribou Mountains (Fig. 1a-ii) have greater predicted permafrost extents than surrounding areas. Permafrost maps for the northern hemisphere were also developed by Obu et al. (2019), but the sporadic permafrost zone of the Canadian subarctic had the lowest model accuracies for Canada and predicted mean annual ground temperatures (MAGT) overestimated borehole measurements. Higher resolution (e.g., 15 m) permafrost probability models have been generated for northern Alberta (Pawley and Utting, 2018) but are lacking for the rest of the study area. Excess ice abundance (i.e., segregated ice and wedge ice) in the top 5 m of permafrost is generally low (<15%) or absent (Brown et al., 1997; O'Neill et al., 2019), particularly in the bedrock of the Taiga Shield. Relatively high excess ice abundance (5–10%) is predicted in the eastern portion of the Taiga Plains south of Great Bear Lake (O'Neill et al., 2019). Due to the distinct characteristics of the Taiga Shield and Taiga Plains, separate detailed descriptions of the ecoregions are discussed below.

2.1. Taiga Plains

The Taiga Plains is characterized by low relief, poor drainage, and thick organic deposits (up to 8 m) with a peatland extent that covers 218,000 km^2, nearly half the total area (Ecosystem Classification Group, 2009; McClymont et al., 2013; Tarnocai et al., 2011). The Taiga Plains developed with the recession of the Laurentide Ice Sheet, as evidenced by the till plains in uplands and widespread lacustrine deposits remnant of the vast postglacial Lake McConnell (Lemmen et al., 1994). MAAT and average annual precipitation (1981–2010) generally decreases with increasing latitude ranging from -1.0°C to -5.1°C and 294 mm/yr to 451 mm/yr (ECCC, 2021).

Permafrost in the Taiga Plains study area is relatively thin (1.5 m to 17 m) and warm (-2°C to -0.2°C) with permafrost temperature decreasing and thickness increasing with latitude (Brown, 1964; Burgess and Smith, 2000; GTN-P, 2016; Holloway and Lewkowicz, 2020; Smith et al., 2013; Smith et al., 2010). Here, permafrost is strongly linked to peatlands with dry ground surfaces (e.g., peat plateaus, palsas), particularly in warmer regions, due to the thermal buffering provided by unsaturated peat (hereafter, permafrost peatlands). The low thermal conductivity of dry peat (~0.06 W/m·K) common in summer insulates against ground heating, and the high thermal conductivity of saturated/icy peat (~1.9 W/m·K) common in winter facilitates ground cooling (Brown, 1964; Camill, 1999; Quinton and Baltzer, 2013; Woo, 2012). The highest concentration of permafrost peatlands within the study region (Fig. 1b) is estimated at 118,000 km^2 and occurs along the central corridor of the Taiga Plains (Gibson et al., 2021; Hugelius et al., 2020; Tarnocai et al., 2011). The region has epigenetic permafrost conditions where peatland development began ~8,500 years ago while permafrost aggradation occurred 1,200–4,500 years ago (Heffernan et al., 2020; Pelletier et al., 2017).

Tree-covered peat plateaus are the predominant permafrost landform in the Taiga Plains, followed by palsas and polygonal peat plateaus (definitions in Table 1). Peat plateaus are commonly found in wetland environments covered by black spruce trees (*Picea mariana)* because the ground surface is raised 1–3 m above surrounding wetlands (Fig. 2a,c; Quinton et al., 2003; Zoltai and Tarnocai, 1974) and therefore provide sufficiently dry conditions to support its shallow (0.2 m) root system (Viereck and Johnston, 1990). Permafrost in the Taiga Plains also occurs in mixed-forest uplands with fine-grained mineral sediment (silts and clays) overlain by >0.3 m of organic cover (Holloway and Lewkowicz, 2020). Organic layers of sufficient thickness are the primary control on permafrost occurrence, followed by fine-grained substrate (Burgess and Smith, 2000).

Common permafrost thaw features in the Taiga Plains include collapse scar wetlands (bogs and poor fens; Fig. 2a,d) and lakes that develop as ice-rich permafrost thaws and the overlying ground surface subsides, causing peat plateaus to collapse internally and along plateau

Table 1
Characteristics of permafrost landforms found in the study region in order from most common to least common.

Permafrost Landform	Stratigraphy & Size	Active layer thickness	Permafrost thickness & temperature	Ice content (% by volume)	Segregated ice	Occurrence in study region
Peat Plateau (PP): a flat-topped expanse of frozen peat elevated (>1 m) above the general surface of a wetland. Segregated ice lenses may, or may not, extend into the underlying mineral soil [13].	1.5–8.0 m of peat overlying fine-grained sediment [1-4] 10s to 100s of meters wide [1].	0.3–1.3 m [1,2,11]	1.5–17 m [4, 10-12] >−0.4°C [10]	Up to 80% in peat [2] Avg. 20% in mineral soil & peat [2]	Uncommon, up to 0.2 m lenses [1] More common at peat-soil contact, up to 3 m thick [1,2]	Most common [6-8]
Palsa: A peaty permafrost mound with a core of alternating layers of segregated ice and peat or mineral soil [13].	3.5–6.5 m of peat overlying fine-grained sediment [1] 10–30 m wide, <5 m tall [1].	Similar to PP [1]	Similar to PP [1]	Similar to PP [1]	< 0.35 m lenses, up to 1 m at peat-soil contact. Pure ice layers common in mineral soil [1]	Less common [7,8]
Polygonal Peat Plateau: A peat plateau with ice-wedge polygons [13].	0.9–3.6 m of peat overlying fine-grained sediment [1] Polygonal patterns ~15 m in diameter [1].	Similar to PP [1]	Similar to PP [1]	Similar to PP [1]	Wedge of pure ice extending 2–4 m in depth [1]	Rare, only in coldest parts of the study region [7-9]
Lithalsa [5]: A permafrost mound or ridge forming in mineral-rich soils in warm discontinuous permafrost. Often beside water bodies.	10–15 m of silt and clay [5] 10–120 m wide, 0.5–8.0 m tall [5]	0.9–1.3 m [5]	5–10 m, ~-0.8°C [5]	50% [5]	Horizontal lenses up to 10 cm thick [5]	Only in Taiga Shield, most common in Great Slave Lowlands [5]

Sources: [1] Zoltai and Tarnocai (1974), [2] Aylsworth and Kettles (2000), [3] Quinton et al. (2019), [4] McClymont et al., 2013, [5] Wolfe et al. (2014), [6] Gibson et al. (2020), [7] Ecosystem Classification Group (2009), [8] Ecosystem Classification Group (2008), [9] Wolfe et al. (2021), 10] Smith et al., 2013, [11] Holloway and Lewkowicz (2020), 12] Brown (1964), 13] Harris et al. (1988).

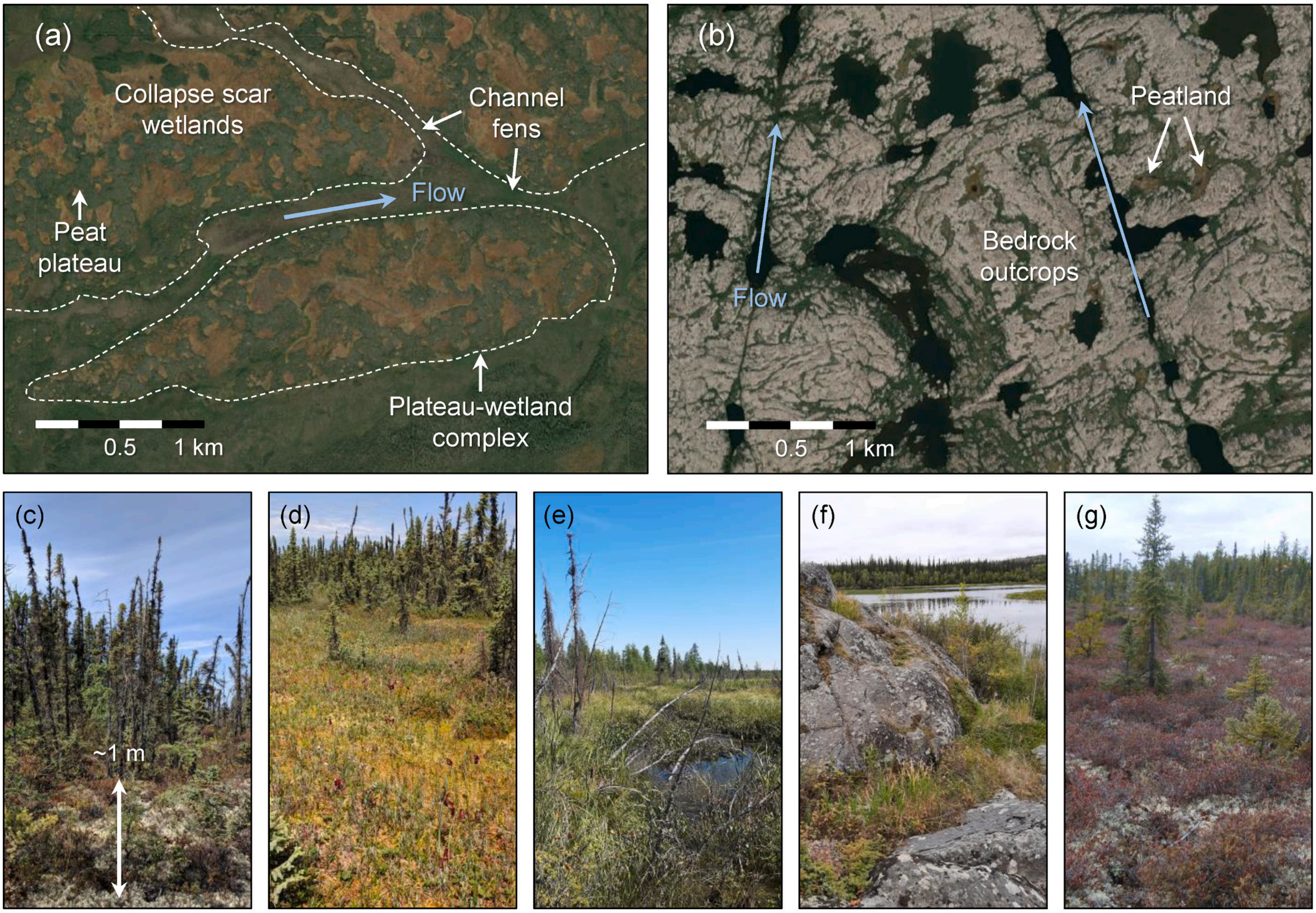

Fig. 2. (a) Plateau-wetland complexes in the Taiga Plains. Green areas are intact permafrost-underlain peat plateaus, dark grey areas are permafrost-free runoff-conveying channel fens, and orange/brown areas are permafrost-free collapse scar (thermokarst) bogs and poor fens. (b) Bedrock uplands and lakes in the Taiga Shield. Grey areas are permafrost-free bedrock outcrops, and green/brown areas are permafrost-underlain soil-filled valleys and peatlands. (c) A treed peat plateau, (d) thermokarst bog, and (e) channel fen in the Taiga Plains. (f) A permafrost-free bedrock outcrop adjacent to a lake and (g) permafrost peatland in the Taiga Shield. Satellite imagery from Esri Canada and photos by L. Thompson, S. Wright, and C. Spence.

margins (Zoltai, 1993). This thaw-induced ground surface subsidence/inundation and land-cover change is also referred to as thermokarst (Harris et al., 1988). Thermokarst wetlands can either be relatively small (tens of meters) and isolated within a peat plateau (i.e., isolated bog; Fig. 2d) or interconnected (i.e., poor fens) and eventually drain to broad, linear channel fens (Fig. 2a,e) that route water to the basin outlet (Connon et al., 2014; Quinton et al., 2009; Vitt et al., 1994). At the larger scale, these major landcovers form plateau-wetland complexes comprised of peat plateaus with internal thermokarst wetlands that are separated by channel fens (Fig. 2a). Most plateau-wetland complexes in the study region south of 62° latitude exhibit a high (67–100%) degree of thaw based on the area covered by thermokarst wetlands (Gibson et al., 2020), with 70% of permafrost projected to completely disappear by 2100 (Gibson et al., 2021). Cyclical permafrost aggradation and degradation of permafrost peatlands have been common throughout the Holocene period, but the rate of permafrost thaw has rapidly increased in recent decades (Chasmer and Hopkinson, 2017; Turetsky et al., 2020; Zoltai, 1993).

2.2. Taiga Shield

Surficial geology of the Taiga Shield includes lacustrine deposits and glacial till from post-glacial lakes, and bedrock plains and hills from eroded Precambrian mountains and volcanoes (Ecosystem Classification Group, 2008). Bedrock types include granite, migmatite, gneiss, metasedimentary and metavolcanic rock (Spence and Woo, 2002). The landscape consists of bedrock uplands (Fig. 2b,f) and soil-filled valleys that contain wetlands and lakes (Fig. 2b,f,g; Spence, 2000; Spence and Woo, 2002, Spence and Woo, 2003). Lakes cover nearly one-quarter of the total area, and peatlands cover less than 5% (Ecosystem Classification Group, 2008). The southern Taiga Shield has a continental climate with short, cool summers and cold winters. MAAT and average annual precipitation (1981–2010) generally decreases with increasing latitude ranging from -2.9°C to -4.3°C and 288 mm/yr to 509 mm/yr (ECCC, 2021).

Permafrost and hydrological process information for the Taiga Shield mainly stem from the North Slave region, where approximately 52% of the area is underlain by permafrost (Zhang et al., 2014). Shield hydrology has been described as a "fill-and-spill" process (Spence and Woo, 2003; Woo and Marsh, 2005) where runoff from bedrock uplands fills in valley bottoms until the valley storage threshold is exceeded and excess water drains (or spills) into the next valley or lake (Woo et al., 2008). Permafrost is associated with forests (mainly black spruce) and peatlands underlain by fine-grained silts and clays and consistently absent below bedrock outcrops (Brown, 1973; Morse et al., 2016). Black spruce peatlands may, or may not, be peat plateaus. In the North Slave region, reported values for permafrost thickness, active layer thickness (ALT), and MAGT at a depth of zero annual amplitude range from a few meters to 60 m, 0.3 m to 0.7 m, and -1.43°C to -0.02°C, respectively (Brown, 1973; Karunaratne et al., 2008; Morse et al., 2016). Ice content is negligible (0–2%) in bedrock (O'Neill et al., 2019), but segregated ice as horizontal lenses (0.1 to 8 cm thick) can be found in frozen lacustrine soils (Johnston et al., 1963). Lithalsas (Table 1) are widespread within the fine-grained sediment of the Great Slave Lowlands but quickly decrease in occurrence throughout the Great Slave Uplands (Wolfe et al., 2014).

Areal permafrost extent in the North Slave region has degraded by approximately 28% between 1950 and 2009 (Zhang et al., 2014). Morse et al. (2016) suggest permafrost in the fine-grained sediment beneath forests is presently being protected by considerable latent heat effects and the insulative properties of organic ground cover, which combine to slow permafrost thaw. However, these landscapes are still increasingly vulnerable to climate change, and a considerable reduction in permafrost extent can be expected in a warmer climate. Zhang et al. (2014) estimated that minimal permafrost will remain in the North Slave region by 2090.

3. Mechanisms and drivers of permafrost thaw

Air temperature is a considered the dominant large-scale control on the state of permafrost (Biskaborn, 2019). The study area is undergoing warming at 0.46°C per decade (1948–2012), which is approximately twice the national and global average (Vincent et al., 2015). Higher air temperatures result in higher energy availability, which increases ground surface temperature and downward heat conduction (Koven et al., 2013; Pastick et al., 2015; Slater and Lawrence, 2013). Warming from anthropogenic greenhouse gas (GHG) emissions has significantly decreased the areal extent of near-surface permafrost (0.46×10^6 km^2/decade) between 1921–2005 across the Northern Hemisphere (Guo et al., 2020). Anthropogenic aerosols can also influence large-scale climate by absorbing or scattering incident solar radiation, resulting in either cooling or warming of the ground surface (Im et al., 2021). Anthropogenic aerosols have been correlated to decreasing air temperatures and increasing near-surface permafrost area, but not enough to offset warming from GHG forcings (Guo et al., 2020). Additionally, Guo et al. (2020) found natural large-scale forcings like volcanic aerosols and solar variability share weak relationships with changes in permafrost.

In addition to large-scale drivers, there are many local-scale drivers of permafrost thaw. Water bodies and permafrost-free wetlands adjacent to permafrost drive lateral thaw through conduction as well as advection if surface water flows year-round (Devoie et al., 2021; Kurylyk et al., 2016). Groundwater flow, particularly when hydrologically connected to warmer surface water, can contribute to heat advection above, below, or adjacent to permafrost bodies (Devoie et al., 2021; Devoie et al., 2019; Kurylyk et al., 2016; Sjöberg et al., 2016). Thaw at the base of the permafrost can also be driven by conduction from geothermal heat from the Earth's core (reported at 0.08 W/m^2 at 50 m depth; McClymont et al., 2013). If the ground cannot lose enough energy in winter to balance heat gains from summer, then the net result is progressive permafrost thaw. In permafrost peatlands of the Taiga Plains, Devoie et al. (2021) found that thaw rates from heat advection (115 cm/yr) were an order of magnitude higher than both downward thaw from the ground surface and thaw from below due to geothermal gradients (both 10 cm/yr, assuming isothermal permafrost conditions).

Permafrost temperatures are at or near 0°C in many locations within the study area, indicating that permafrost is currently thawing and/or is highly susceptible to thaw (Morse and Spence, 2017; Quinton et al., 2019). Processes that can initiate or accelerate permafrost thaw include wildfire, windthrow, surface flooding, resource exploration, human land development, and other ecosystem stressors that perturb or remove insulative vegetation (e.g., game trails, foot paths, all-terrain vehicle tracks, etc.), alter snow distribution, increase surface albedo, or increase soil moisture (Gibson et al., 2018; Holloway et al., 2020; Vitt et al., 1994; Williams et al., 2013). Snow cover is an excellent insulator, limiting heat loss from the ground (Woo, 2012). By affecting snow interception and redistribution processes, vegetation cover also affects the spatial distributions of snow (Connon et al., 2021) and, therefore, ground temperatures.

Changes in rainfall intensity, duration, and frequency also affect the rate of permafrost thaw (Douglas et al., 2020; van Huissteden, 2020) due to heat advection from warm summer rain (Douglas et al., 2020) and, more importantly, increases to the soil moisture and bulk thermal conductivity of soil. For example, end-of-summer frost table depths for peat plateaus and palsas are deepest in years with greater precipitation (Seppälä, 2011; Wright et al., 2009), because the higher thermal conductivity of saturated peat increases heat transfer to the frost table (van Huissteden, 2020; Walvoord and Kurylyk, 2016). However, when evaluating an active layer monitoring network in Alaska, Clayton et al. (2021) found that increased latent heat effect of wetter soils can also decrease active layer thickness, suggesting that soil heterogeneity can play a large role in how permafrost responds to changes in precipitation. Douglas et al. (2020) suggest a multi-year memory effect from anomalously wet summers that slow winter freeze-back, limiting ground cooling and supporting warmer subsurface conditions in subsequent summers. Yet, the relatively high thermal conductivity of frozen-saturated peat is highly effective at cooling the ground in winter (Woo, 2012). These opposing effects suggest a poorly understood threshold for the timing and degree of saturation that either: (1) result in effective heat loss in winter that protects permafrost; or (2) stores excess heat that subsequently thaws permafrost. Further work is needed to understand the thresholds and competing effects of soil moisture and changing precipitation patterns on permafrost thaw.

Wildfires have been observed to accelerate permafrost thaw throughout the study region (e.g., Smith et al., 2015; Spence et al., 2020b; Zhang et al., 2015), particularly in the peatlands of the Taiga Plains, where ~40% of peat plateaus have burned in the last 60 years (Gibson et al., 2018). Since wildfire can remove insulative/shading vegetation and alter snow cover distribution and albedo, the supra-permafrost layer (Connon et al., 2018) and talik (perennially unfrozen soil) coverage typically increase following wildfire (Gibson et al., 2018; Holloway et al., 2020). In some cases, permafrost thaw in the study region from old wildfires (>30 years old) has recovered to pre-fire conditions, but thaw resulting from more recent fire disturbance may be irreversible under current climate warming trends (Gibson et al., 2018; Holloway and Lewkowicz, 2020; Zhang et al., 2015). Regions of the Taiga Shield with little forest cover and more exposed bedrock and lakes are "hydrologically resilient" to forest fires, meaning wildfires result in little hydrologic change since pre-fire conditions have little vegetation and permafrost to begin with (Spence et al., 2020a).

It is well documented that human-induced land cover change through the construction of roads, pipelines, communities, mines/gravel pits, oil and gas infrastructure, and seismic lines thaw underlying permafrost (Cao et al., 2016; de Grandpré et al., 2012; Huntington et al., 2007; Smith et al., 2008; Smith and Riseborough, 2010; Williams et al., 2013; Wolfe, 2015). Solar sheltering from the canopy is removed upon land clearing, increasing the ground heat flux. Soil compaction from construction can promote higher soil moisture contents, increasing heat transfer rates from the surface to the subsurface. (Sub) surface drainage is driven toward the depression, increasing soil moisture content and consequent permafrost thaw. Surface runoff can also enhance heat transport to the margins of linear disturbances that are compacted or paved (i.e., roads, cut lines, or pipeline corridors; Chen et al., 2020). In areas with warm and thin permafrost (MAGT >-2°C; < 20m thick), the combined effect of a pipeline corridor and climate warming is predicted to completely degrade underlying permafrost between 2030 and 2050, with effects possibly extending beyond the clearing and into the larger landscape (Smith and Riseborough, 2010). Some of the highest densities (>2.0 km/km^2) of seismic lines and linear infrastructure in the study region occur in the peatland-rich nexus of the British Columbia, Alberta, NWT borders (Strack et al., 2019), but the cumulative impacts of seismic lines on permafrost thaw, hydrology, and water quality remain poorly understood.

4. Observed impacts of permafrost thaw

Significant thaw-induced landcover, hydrologic, and water quality changes have been observed in the study region over the last half-century (Table 2). Many of these observations come from studies conducted since 1999 at the Scotty Creek Research Station (61.3°N, 121.3°W), approximately 50 km south of Fort Simpson, NWT (Fig. 3a; Quinton et al., 2019), and sites located along transportation corridors such as the Mackenzie Highway and the Mackenzie Valley pipeline from Norman Wells, NWT to Zama, Alberta. In the Taiga Shield, studies are generally limited to the North Slave region (Fig. 3b), including the Baker Creek Research Basin located 7 km north of Yellowknife, NWT (62.5°N, 114.4°W). The drivers and processes that explain the observed changes are discussed in the proceeding sections.

Table 2
Observed changes in landcover, hydrology, and water quality in the study area directly tied to permafrost thaw. Note that this is not an exhaustive list but includes representative changes and trajectories.

Observed change	Location in study area	Trajectory	Stressors/drivers	Selected references
Landcover				
Forest area	N-S transect from northern BC to Scotty Creek [1]; Scotty Creek, NWT [2-4]; Taiga Plains [5]	Loss and gain, 1970-2010 [1]; 2012–2018 [3]; 1947–2018 [4] Loss, 1977–2010 [2]; 2000 – 2014 [5]	Climate warming, inundation leading to forest loss [1-5]; Wetland drainage leading to afforestation [3,4]	[1] Carpino et al., 2018; [2] Baltzer et al., 2014; [3] Dearborn and Baltzer, 2021; [4] Carpino et al., 2021; [5] Helbig et al., 2016
Wetland area	Scotty Creek, NWT [1,2]	Increase, 1970–2008 [1]; 1955–2015 [2]	Climate warming, land disturbance	[1] Quinton et al., 2011; [2] Gibson et al., 2018
Lake and pond area	Southern Shield [1]; Northern Shield [2,6]; Upper Mackenzie [3]; Northern Alberta [4]; Kakisa Basin, NWT [5]	Decrease, 2000–2009 [1,5]; Increase, 2000–2009; [2,3,4]; Stable, 1947–2012 [5]; increase in ponds, 1945–2005 [6]	Changing precipitation, increased temperature, permafrost thaw.	[1–4] Carroll et al., 2011; [5] Coleman et al., 2015; [6] Morse et al., 2017
Hydrology				
End-of-season thaw depth (supra-permafrost layer thickness)	Hay River, AB-NWT [1]; Petitot River, NWT [2]; Scotty Creek, NWT [3,4]; Mackenzie River Valley [5]	Stable/Increase, 1963–2017 [1]; Stable, 1988–2000 [2]; Increase, 1998–2018, 1955–2015, 1990s–2010s [3,4,5]	Organic layer thickness supports stable conditions [1,2]. Climate warming, wildfire, changing precipitation, land disturbance [1,3,4,5].	[1] Holloway and Lewkowicz, 2020; [2] Nixon et al., 2003; [3] Quinton et al., 2011; [4] Gibson et al., 2018; [5] CALM, 2020
Spatial distribution of taliks	Scotty Creek, NWT [1,2]	Increase, 2011–2015, 1955–2015 [1,2]	Climate warming, human disturbance [1], wildfire [2]	[1] Connon et al., 2018; [2] Gibson et al., 2018
Surface-subsurface connectivity	Scotty Creek, NWT	Increase at local scale, 1996–2012	Climate warming, landcover change	Connon et al., 2014
Icings (Aufeis)	North Slave Region, NWT [1]; Central Mackenzie Valley near Normal Wells, NWT [2]	Variable, 1985–2014 [1]; Stable, 2004–2016 [2]	Changing autumn rainfall, and mid-winter melts [1]	[1] Morse and Wolfe, 2015; [2] Glass et al., 2021
Wetland Storage	Scotty Creek, NWT	Decrease, 2003–2017	Climate warming, increasing hydrologic connectivity	Haynes et al., 2018
Lake Runoff	Caribou Mountains, AB	Increase, 2015	Changing precipitation and increasing temperature	Gibson et al., 2015
Winter baseflow (only significant trends presented)	Taiga Plains; Taiga Shield north of Yellowknife [1]; Lower Liard River Valley, NWT [2]; Liard River Basin, NWT [3]	Increases, 1939-2007; 1996–2012; 1972–2012 [1-3];	Climate warming, wildfire, changing precipitation [1-3]	[1] St Jacques and Sauchyn, 2009; [2] Connon et al., 2014; [3] Shrestha et al., 2019
Annual Streamflow (only significant trends presented)	*Taiga Plains Rivers:* Birch [1,2], Blackstone [2], Scotty [2], Jean-Marie [1, 2] Trout, Martin, La Martre; *Taiga Shield River:* Camsell [1]	Increase 1970s–2007 [1]; 1996–2012 [2];	Climate warming, groundwater activation [1]; Landcover change, groundwater activation [2]	[1,3] St Jacques and Sauchyn, 2009; [2] Connon et al., 2014
Water Quality				
DOC concentrations	Hay River, Buffalo River and other rivers from Fort Providence to Slave Lake, AB.	Highest in non-permafrost basins, 2011	Presence of permafrost dampened DOC while peatlands increased DOC	Olefeldt et al., 2014
Nitrogen concentrations	Scotty Creek [1], Boundary Creek [2]	Increasing, 2016 [1]; 2015–2017 [2]	Permafrost thaw, wildfire	[1] Ackley et al., 2021; [2] Spence et al., 2020a
Phosphorus flux	Liard River	Increasing, seasonal, 1970s–2010s	Winter trend follows streamflow trends	Shrestha et al., 2019
Phosphorus concentrations	Notawhoka Creek [1], Scotty Creek, NWT [1, 2]	Increasing, 2016	Permafrost thaw, wildfire	[1] Burd et al., 2018; [2] Ackley et al., 2021
Methylmercury concentrations	Scotty Creek, NWT [1], Hay River basin [2], Taiga Plains and Mackenzie Valley [3]	Increasing in wetlands, 2013 [1]; 2019 [2]; Stable at catchment scale, 2019 [3]	Permafrost thaw, groundwater connectivity	[1] Gordon et al., 2016; [2] Figure 9; [3] Thompson and Olefeldt, 2020; Thompson et al., Submitted
Mercury concentrations	Taiga Plains and Mackenzie Valley	Stable at catchment scale, 2019	Permafrost thaw, hydrologic connectivity	Thompson and Olefeldt, 2020; Thompson et al., Submitted

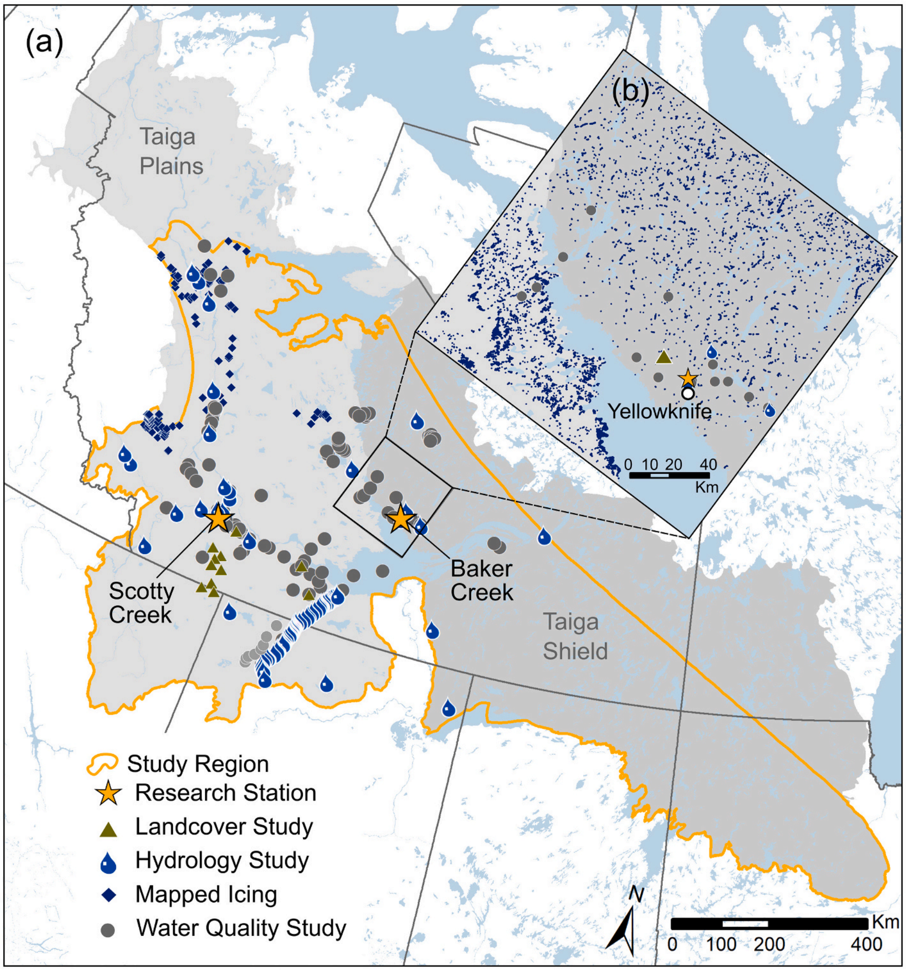

Fig. 3. (a) Locations of data collection sites and field studies in the study region related to thaw-induced impacts to landcover, hydrology, and water quality. The location of icing studies and mapped icings have been given a unique symbol but still fall under the hydrology category. Note that larger remote sensing studies are not shown. (b) The North Slave region with mapped icings (blue) from 1985–2014 from Morse and Wolfe (2015). See supplementary material for study citations and coordinates.

5. Impacts of permafrost thaw on landcover

Permafrost can support certain ecosystems by controlling soil temperature, soil moisture, root zones, and subsurface hydrology (Woo, 2012). Thaw of ice-rich permafrost can lead to ground surface subsidence and inundation (thermokarst), and the wholesale replacement of one plant community with another (Sannel and Kuhry, 2011; Vallée and Payette, 2007; Vitt et al., 1994), as seen in the Taiga Plains (Table 2). The resulting landcover changes have direct impacts for Indigenous land users such as changing traditional access routes, wildlife habitat and populations, traditional medicines, and country foods. In the Taiga Shield, the impacts of permafrost thaw on landcovers are less well understood. However, it is reasonable to assume that since the region is dominated by ice-poor, consolidated bedrock, permafrost thaw is not coupled with ground surface subsidence and would therefore be less disruptive to landcovers. Although permafrost thaw would not result in considerable surface subsidence, thaw may alter the hydrologic connectivity of Shield basins, thereby impacting lake levels and altering shoreline landcover.

Methods of delineating permafrost terrain from optical imagery have advanced significantly in recent years (e.g., Nguyen et al., 2009; Nitze et al., 2018; Panda et al., 2010). A detailed discussion of such techniques is beyond the scope of this review; however, many of the thaw-induced landcover changes observed in the study area were initially identified and measured from remote sensing. These included documented shrinkage of peat plateaus (Quinton et al., 2011; Robinson and Moore, 2000), forest cover changes throughout the southern margin of discontinuous permafrost (Carpino et al., 2018), delineation of lake expansion (Korosi et al., 2017) and contraction (Carroll et al., 2011), and thermokarst features (Gibson et al., 2021; Morse et al., 2017).

5.1. Peatlands

Climate warming has accelerated permafrost thaw in the Taiga Plains and transformed forest- and permafrost-dominated landscapes to those that are increasingly wetland-dominated and permafrost-free (Table 2; Gibson et al., 2020; Quinton et al., 2011). Natural or anthropogenic land disturbances accelerate this landscape transformation (Fig. 4a-i), including forest fires (Gibson et al., 2018), land clearing for seismic line surveys (Braverman and Quinton, 2016; Williams et al., 2013), and community infrastructure (Haynes et al., 2019). Since peat plateaus also occur in the Taiga Shield, it is suspected similar changes occur (Fig. 4b-iii), but the relatively small proportion of peatlands in this ecoregion likely prevents this process from having an impact at regional scales. However, further investigation is needed to confirm this.

Permafrost thaw following a disturbance, and surface warming first presents as a depression in the permafrost table, which leads to a small supra-permafrost talik within a peat plateau, a layer directly above permafrost that remains unfrozen year-round (Fig. 4a-i; Carpino et al., 2021; Connon et al., 2018). Surface and subsurface water is driven toward these depressions, increasing heat transfer and deepening the depressions. The impacted permafrost continues to degrade vertically until the eventual loss of the forested plateau, and a thermokarst wetland (bog or poor fen) is formed in its place (Fig. 4b-ii; Gordon et al., 2016; Chasmer et al., 2011; Quinton et al., 2011). Permafrost can also be degraded laterally by heat transfer from neighbouring surface water,

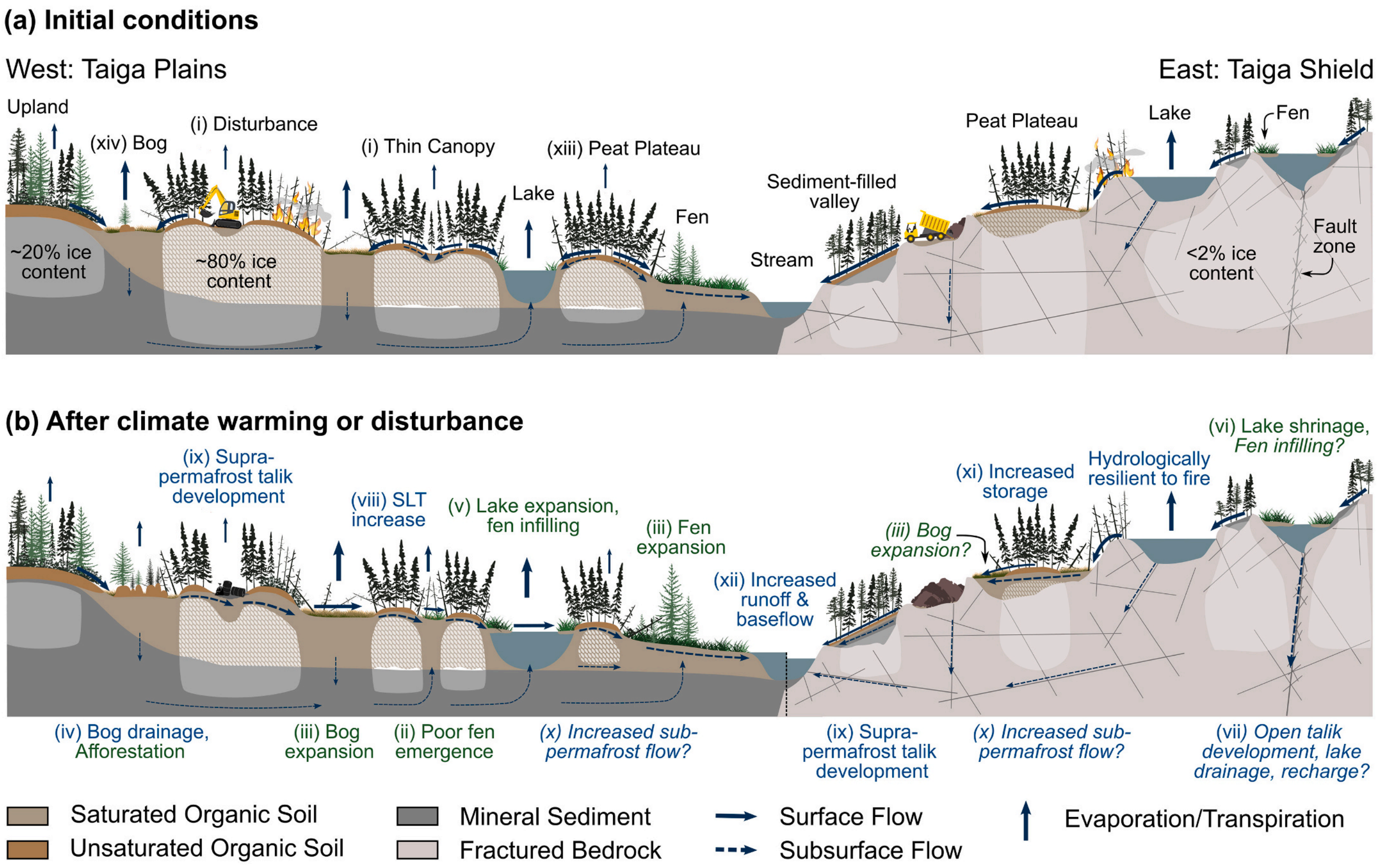

Fig. 4. (a) Initial discontinuous permafrost conditions for a conceptual cross-section from the peatland-dominated Taiga Plains in the west to the bedrock/lake-dominated Taiga Shield in the east. The thickness of blue arrows indicates the relative magnitude of hydrologic fluxes. (b) Permafrost conditions and resulting changes to landcover (green text) and hydrology (blue text) following progressive climate warming and/or disturbance. Italicized text with a question mark indicates a high degree of uncertainty and requires further investigation. SLT = Supra-permafrost layer thickness. All labels are described and referenced in text.

which similarly expands bogs, lakes, and fens at the expense of plateaus (Fig. 4b-iii). Plateaus continue to degrade and collapse until isolated bogs coalesce and form an interconnected network of bogs with interspersed and fragmented peat plateaus (Chasmer and Hopkinson, 2017; Connon et al., 2015; Hayashi et al., 2011). Permafrost thaw, therefore, allows wetlands to develop hydrologic connections with the basin drainage network (Connon et al., 2014) and partially drain (Haynes et al., 2018). Progressive drainage of wetlands supports the development of hummocks (Haynes et al., 2020) that are sufficiently dry to support the growth of black spruce trees (Disher et al., 2021) and eventual forest regeneration (Fig. 4b-iv; Carpino et al., 2021). Despite black spruce forests experiencing a net decline throughout the Taiga Plains from permafrost thaw (Carpino et al., 2018), forest productivity is still increasing due, in part, to the new growth of non-dominant species like tamarack trees (*Larix laricina*) (Dearborn and Baltzer, 2021) and the continued growth of larger black spruce in the middle of plateaus (Chasmer et al., 2011).

The cycle of peat plateau and palsa collapse followed by forest regeneration has been described by Zoltai (1993) and occurs over approximately a 600-year period under a stable climate. In this model, forest regeneration is associated with the redevelopment of permafrost that provides conditions for tree growth. However, rising surface temperatures in the Taiga Plains have likely resulted in the disruption of this cycle (Camill, 1999), where far greater permafrost degradation occurs than aggradation (Quinton et al., 2011). Thus, Carpino et al. (2021) suggested a conceptual model where the re-emergence of a forest cover (due to thaw-enhanced wetland drainage) occurs without the redevelopment of permafrost. Since the timeframe of forest recovery does not depend on the slow process of permafrost aggradation, the trajectory of forest regeneration following permafrost thaw may be on the scale of decades rather than centuries (Carpino et al., 2021). However, the transition to a permanent permafrost-free environment is highly uncertain in terms of the intermediate stages, timing, and the resulting landcover.

5.2. *Lake and pond area*

As permafrost thaws, the opening of hydrologic pathways can result in either: (1) an influx of water leading to lake expansion; or (2) newly activated pathways that promote lake drainage and shrinkage (Walvoord and Kurylyk, 2016). Additionally, gradual lateral permafrost thaw of terrestrial features can lead to lake expansion (Fig. 4b-v). At the national scale, Carroll et al. (2011) found surface water gains in the Hay-Zama lakes area, Alberta, and a small reduction in the Kakisa basin, NWT (Taiga Plains) between 2000–2009. In contrast, no lake expansion (1950s–2012) was observed from remote sensing and paleo-reconstruction of two lakes in the Kakisa basin, although fen cover had significantly increased (Coleman et al., 2015). As Kokelj and Jorgenson (2013) noted, fen infilling can be a significant factor in lake shrinkage and complicate directional detection (Fig. 4b-v), which may be a factor for the lakes in the Kakisa basin. A mechanism for the expansion of lakes in the Hay-Zama lakes area was not described by Carroll et al. (2011), but lake area on the nearby Boreal Plains is strongly influenced by inter-annual wet and dry periods (Pugh, 2021), which likely dominates over thaw-driven effects. In the Mackenzie Wood Bison Sanctuary, NWT, remote sensing coupled with paleo-reconstruction showed that lake expansion since the 1980s represented a positive net change in the water balance (Korosi et al., 2017). The primary factors leading to lake expansion were increased temperature and precipitation, while increased groundwater inputs from permafrost thaw were not predominant (Korosi et al., 2017).

Recent studies of lithalsa permafrost features in the North Slave suggest that lithalsa thaw will expand the surface area of thermokarst ponds (Table 2; Morse et al., 2017). An inventory of thermokarst ponds indicated 3138 ponds expanded or developed within the 1430 km^2 study area between 1945–2005, but the increase in aerial extent (3.57 km^2) remained relatively low (~0.25% of the study area, Morse et al., 2017). Ponding was most commonly observed in the low elevation glaciolacustrine deposits within the North Slave Lowland (Morse et al., 2017). At the national scale, remote sensing analysis by Carroll et al. (2011) showed net losses in lake area in the Taiga Shield between 2000–2009. The observed lake declines are not well known and may relate to potential changes in permafrost coverage, decadal atmospheric circulation, and precipitation patterns (Bonsal and Shabbar, 2011) or fen infilling (Fig. 4b-vi). The development of open taliks beneath lakes, which typically form along structural zones of weakness like fault zones (Woo, 2012), could also enable the drainage of lakes in upland areas (Fig. 4b-vii). However, the long-term trajectory and drivers of thaw-induced lake extent changes in the Taiga Shield require further investigation.

6. Impacts of permafrost thaw on hydrology

The thaw-induced landcover changes discussed have implications on the routing, storage, and connectivity of surface and subsurface water. Each landcover serves a particular hydrologic function, so when there is a shift away from one cover to another, there is a concurrent change in the hydrologic behavior. Inadequate baseline and historical data remain a challenge in the study region and globally. There is a general lack of understanding of large-scale and longer-term impacts of permafrost thaw, particularly in peatlands outside the Liard River basin in western NWT (Mack et al., 2021) and throughout most of the Taiga Shield.

6.1. Snowmelt and evapotranspiration

Vegetation can influence snow cover dynamics, where forested areas, particularly along margins, can maintain thicker snow cover than open areas exposed to wind and solar radiation (Woo, 2012). Thus, when landcover is altered due to permafrost thaw, it has implications for snow cover, associated snow water equivalents (SWE), and snowmelt dynamics. For example, Connon et al. (2021) recently found statistically different end-of-winter SWE between wetlands and plateau forests in the lower Liard River valley. However, these differences were not large enough to measurably impact basin-scale averages in SWE. As such, it is unlikely that shifting snow distributions due to thaw-induced landcover change will considerably alter basin-scale runoff dynamics. However, the resulting increase in hydrologic connectivity will likely alter the timing and magnitude of snowmelt runoff, commonly the largest annual runoff event in the study region.

Transforming landcovers have direct influences on evapotranspiration rates. With black spruce dominating the landcover of permafrost peatlands (Fig. 4a), evapotranspiration rates are relatively low due to its low transpiration rates (Warren et al., 2018) making understory vegetation the primary contributor to evapotranspiration (Chasmer et al., 2011). As bogs expand with thaw (Fig. 4b-iii), the extent of low-transpiration black spruce decreases, and the extent of saturated wetland vegetation increases (including *Sphagnum* mosses) resulting in increased evapotranspiration (ET) rates (Carpino et al., 2021; Warren et al., 2018). Even though mosses are non-vascular and non-transpiring, the expansion of wetland areas covered by these mosses results in evaporation through capillary rise, becoming a dominant component of the ET budget (Waddington et al., 2015). However, under progressive permafrost thaw and sustained wetland drainage (Haynes et al., 2018), both lower water tables (Waddington et al., 2015) and increased coverage of permafrost-free treed bogs (Strilesky and Humphreys, 2012; Warren et al., 2018) would likely decrease ET rates (Fig. 4b-iv). The afforestation following wetland drainage would return the landcover to a low-transpiration forest cover (Carpino et al., 2021), but this has not been as well studied as collapse bogs or permafrost plateaus (Disher et al., 2021; Haynes et al., 2020). Changes in lake extent would also influence the ET component of the water balance.

6.2. Groundwater

Deepening of the active layer from climate warming has been reported in the literature (Walvoord and Kurylyk, 2016), but caution is needed when interpreting ALT data, given the wide interpretation of how the active layer is defined. The long-standing definition (used herein) refers to the layer of ground above permafrost that thaws and refreezes each year (Muller, 1943). However, ALT is sometimes used synonymously with "end-of-season thaw depth," even if a perennially thawed layer (talik) exists (Harris et al., 1988). To avoid confusion, the term supra-permafrost layer thickness (SLT) is used to define the thickness of the layer between the ground surface and the permafrost table. In the Taiga Plains, SLTs near the Ochre River, Willowlake River, and Fort Simpson have all significantly increased since the 1990s (Fig. 5; CALM, 2020). In contrast to these findings, Holloway and Lewkowicz (2020) found that SLTs in the uplands along the Mackenzie Highway (Taiga Plains) exhibited little change between 1962 and 2017/2018 due to insulation from thick organic layers (>50 cm). In the Taiga Shield, there is a lack of knowledge regarding the trends in SLT. It is possible that where the ground is thermally buffered by thick organic cover and fine-grained substrate (Morse et al., 2016), SLT has remained relatively stable over the past several decades, as observed by Holloway and Lewkowicz (2020). However, further investigation is required to assess multi-decadal changes in ALT/SLT in the Taiga Shield region.

Sustained increases in SLTs lead to the development of supra-permafrost taliks (Fig. 4b-ix). Such taliks have been well characterized in the permafrost peatlands of the Taiga Plains (e.g., Connon et al., 2018; Devoie et al., 2019; Gibson et al., 2018) and are suspected of having developed in soil-filled valleys following wildfire in the Taiga Shield (Spence et al., 2020a). As taliks expand at the expense of permafrost, they become hydrologically connected with adjacent permafrost-free wetlands and/or surface water bodies, promoting heat advection and

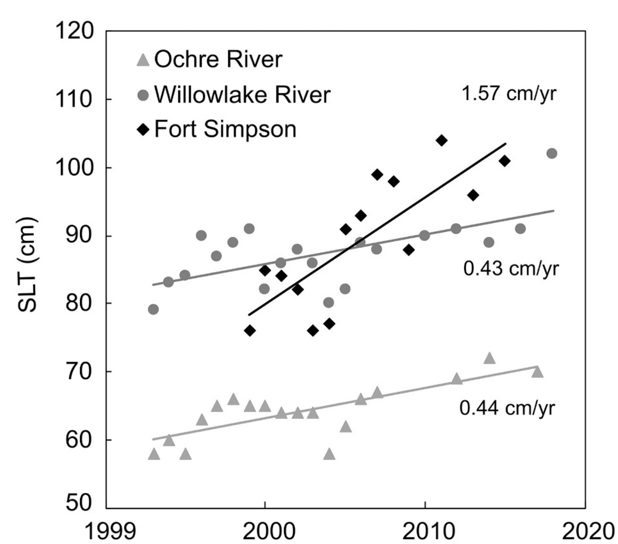

Fig. 5. Monitoring of average SLT between 1993–2017 for the Ochre River (63.466, -123.693), 1993–2018 for Willowlake River (62.697, -123.065), and 1999–2015 for Fort Simpson (61.888, -121.602). Data sourced from CALM (2020). All trends are significant ($p \leq 0.01$) as determined from a Mann-Kendall trend test.

accelerating thaw (Connon et al., 2018; Devoie et al., 2021; Kurylyk et al., 2016; Sjöberg et al., 2016). Supra-permafrost groundwater flow can irreversibly thaw underlying permafrost (Devoie et al., 2019), leading to a positive feedback loop that intensifies summer thaw rates and increases winter groundwater contributions to streams and rivers (Connon et al., 2014). Connon et al. (2018) also found that as supra-permafrost taliks increase on peat plateaus, the ALT decreases due to the increased heat capacity introduced by a saturated talik layer and rising winter temperatures that reduce the depth of re-freeze.

At regional scales in the Taiga Plains (i.e., the Mackenzie Valley), permafrost impacts the location of groundwater recharge but does not appear to influence groundwater discharge (Michel, 1986). Depending on the location of permafrost thaw relative to local and regional groundwater flow systems, either groundwater recharge or discharge zones can emerge following a complete loss of permafrost (Fig. 4b-ii; Gordon et al., 2016). However, predicting how these systems will continue to evolve and integrate with surface water systems is not well known. Sub-permafrost groundwater flow (i.e., groundwater flow below permafrost) also occurs in peatlands in the Taiga Plains (Fig. 4a). Here, the thin (typically <10 m) and discontinuous nature of permafrost results in numerous open taliks beneath water bodies and thermokarst wetlands that allow for the exchange of supra- and sub-permafrost groundwater. Since much of the southern Taiga Plains are underlain by low permeability silts and clays with low vertical hydraulic gradients, sub-permafrost groundwater contributions in these areas are anticipated to be relatively low (Hayashi et al., 2004). However, relatively higher sub-permafrost groundwater flows are possible within higher permeability peat, mineral sediment, and fractured bedrock. These groundwater flows may continue to increase as permafrost thaws, and new pathways are activated (Fig. 4b-x) or may already be well developed, particularly in zones of sporadic permafrost. Additionally, thaw-induced landcover changes that alter evapotranspiration rates and snow cover dynamics have implications for groundwater recharge and extraction. For example, recharge can increase beneath newly permafrost-free forested areas due to greater snow capture relative to open areas (Young et al., 2020). Further research is needed to understand the influences of thaw-induced landcover change on groundwater recharge/discharge dynamics and the basin-scale implications.

The thaw-induced impacts to groundwater systems in the Taiga Shield are not well understood. The relatively shallow permafrost (<50 m) and abundance of permafrost-free lakes and bedrock outcrops likely result in a highly connected subsurface system. Localized groundwater flow systems can occur through fractured rock networks (Spence and Woo, 2002; Thorne et al., 1998; Woo, 2012) and highly conductive fault zones that commonly underlie lakes (Woo, 2012). As permafrost thaws in the soil-filled bedrock valleys, groundwater recharge and storage are likely to increase (Fig. 4b-xi; Morse and Spence, 2017). Thawing of bedrock may lead to increased sub-permafrost groundwater flow through the reactivation of fracture networks and fault zones (Fig. 4b-x) and the development or expansion of supra- and inter-permafrost (i.e., between permafrost) taliks (Morse and Spence, 2017; Rouse, 2000). However, evidence for this is lacking, and the resulting changes to larger-scale basin behaviour are unknown. Morse and Spence (2017) suggest flow can also occur through taliks below lakes, but the configuration of these taliks is not well documented. Sub-permafrost aquifers may also receive more recharge sourced from overlying lakes due to the development of open taliks (Fig. 4b-vii). The altered flow system with increased hydrologic connectivity may impact discharge rates to streams and rivers (Fig. 4b-xii).

6.3. Icings (Aufeis)

Groundwater discharging through taliks along river and stream banks in winter can result in riverine icings (sheet-like masses of layered ice), which affect the seasonal water balance (Reedyk et al., 2011). Since river baseflow is the primary water source for riverine icings (Crites et al., 2020), increasing baseflow may increase riverine icing occurrence in areas where permafrost previously inhibited groundwater flow and discharge over the winter months. However, icing occurrence is closely related to low winter air temperatures and the presence of frozen ground (Crites et al., 2020; Ensom et al., 2020), so as winter air temperatures increase and permafrost thaw continues, the primary zones of icing occurrences may migrate northward. Additionally, riverine icings are unlikely to develop if baseflows increase to the point that an open water channel is maintained over the winter. There is generally a lower occurrence of icings in the extensive discontinuous permafrost zone of the Taiga Plains than continuous permafrost zones (Crites et al., 2020). Icing investigations in the Taiga Plains have been sparse and limited to north of Fort Simpson, NWT (Fig. 3; Crites et al., 2020; Glass et al., 2021; Reedyk et al., 2011). Therefore, the influence of changing baseflows on riverine icing development remains a knowledge gap for most of the Taiga Plains study region.

In the subarctic Canadian Shield, icing development is related to high autumn rainfall and frequent mid-winter warming events (Morse and Wolfe, 2015; Sladen, 2017). Continued increases in autumn rainfall (1943–2013) may promote icing development in the Taiga Shield study region, but this could be counteracted by rising air temperatures and continued decreases in mid-winter warming events (≥5°C) (Morse and Wolfe, 2017). At present, the highest icing density is associated with highly fractured bedrock in the Shield that is likely permafrost free (Fig. 3b; Morse and Wolfe, 2015), suggesting icing occurrence could increase as permafrost thaws in the future and basins become more hydrologically connected (Spence et al., 2020b; Spence et al., 2014). Longer-term changes of icings in the Taiga Shield remain highly uncertain (Morse and Wolfe, 2017; Morse and Wolfe, 2015).

6.4. Peatlands

Thaw-induced landcover changes observed in peatlands of the Taiga Plains impact both local- and basin-scale hydrology. Surface and subsurface runoff from peat plateaus are directed along sloped margins into adjacent collapsed bogs and poor fens, which store or route water to the stream network (Fig. 4a-xiii). Greater surface runoff occurs in spring when the active layer is frozen, and the freshet generates large volumes of snowmelt (Woo, 2012; Wright et al., 2009). As the landscape undergoes thaw-induced land cover change, the relative proportion of storage features (thermokarst wetlands) and routing features (fens) changes, which impacts how much water can reach the stream network (discussed in detail in Section 6.6).

In the initial stages of permafrost thaw, collapsed bogs are generally disconnected from the hydrologic network (Carpino et al., 2021; Connon et al., 2014). Runoff and precipitation added to isolated bogs and depressions within the plateau are primarily removed through evaporation and/or possibly groundwater recharge since surrounding permafrost plateaus act as hydrologic dams (Fig. 4a-xiv; Quinton et al., 2009). Thus, groundwater storage temporarily increases under isolated bog expansion (Carpino et al., 2021). During periods of high water availability, isolated bogs can become ephemerally connected and follow a fill-and-spill process, similar to Shield hydrology, to activate hydrologic connectivity to adjacent collapsed bogs and channel fens (Connon et al., 2015). The expansion and deepening of supra-permafrost taliks on permafrost plateaus enables year-round hydrologic connectivity between landcovers (Fig. 4b-ix; Connon et al., 2014). The thawing and shrinking of permafrost plateaus that previously acted as a subsurface hydrogeologic barrier enable drainage of isolated bogs (Connon et al., 2014) and a decline in basin storage as the landscape is converted to higher runoff-producing wetlands (Haynes et al., 2018).

Similarly, when water availability and frost tables are high during the snowmelt period, linear disturbances (e.g., seismic lines and winter roads) become filled with water and behave like isolated bogs on peat plateaus with a fill-and-spill drainage pattern (Braverman and Quinton, 2016; Williams et al., 2013). Williams et al. (2013) hypothesized that linear disturbances might begin to function more like channel fens and increase basin drainage with progressive permafrost thaw, but further research is needed to confirm this. Similarly, subsurface flow could become increasingly important with the development of supra-permafrost taliks, but the low hydraulic conductivity of the catotelmic peat makes this unlikely (Braverman and Quinton, 2016).

6.5. Lakes

Lateral lake expansion can contribute to the toppling of trees and other vegetation, soil erosion on shorelines, and changes to lake water quality. Lateral subsurface thaw beneath the shoreline can also accelerate shoreline collapse and permafrost thaw (Fig. 4b-v; Kokelj et al., 2009). Thermokarst lake contraction or expansion impacts water storage, routing, and landscape connectivity. Lake drainage has been associated with decreased surface water storage, where subsurface flow paths are enhanced at the expense of surface waters (Karlsson et al., 2012). In contrast, lake expansion may increase surface water storage, reflect enhanced groundwater recharge (Walvoord and Kurylyk, 2016), and increase evaporation rates (Song et al., 2020). In boreal Alberta, more runoff was generated from permafrost thaw-influenced lakes in the Caribou Mountains relative to lower elevation sites with lesser peatland/permafrost influence (Gibson et al., 2015). However, this response may wane as permafrost becomes extensively thawed.

The Taiga Shield has the highest proportion of lakes in the study area, which can attenuate surface runoff, such that streamflow responses from spring freshet or storm events are delayed (Morse and Spence, 2017). For example, the Taltson River typically experiences peak flows in early July (Kokelj, 2003), which is notable from the snowmelt peaks in early May in the Taiga Plains (Hayashi et al., 2004). Due to the fill-and-spill process that controls basin runoff, thaw-induced increases in the storage capacity of soil-filled bedrock valleys (Fig. 4b-xi) during dry periods could mean less water contributes to basin runoff and, therefore, reduced lake inflow (Morse and Spence, 2017). The volume of water from melting ice in permafrost is unlikely to dramatically affect lake levels due to the relatively low ice content in the Taiga Shield (Spence et al., 2014). However, water routing and storage changes resulting from permafrost thaw may affect the network of lakes. As open taliks develop beneath lakes, particularly at higher latitudes, lake levels may decline by connecting surface water to deeper flow systems and increasing sub-permafrost groundwater recharge (Fig. 4b-vii). Thaw-enhanced groundwater flow beneath lakes in the Taiga Shield could explain the declines in lake levels observed by Carroll et al. (2011), but the configuration of taliks in this area is unknown.

6.6. Streamflow

Streamflow increases have been observed for many (but not all) gauged basins in the study region (Table 2) and across the circumpolar north at varying basin scales (e.g., Connon et al., 2014; McClelland et al., 2004; Peterson et al., 2002; St Jacques and Sauchyn, 2009; Walvoord and Striegl, 2007). Three explanations for increasing streamflow in discontinuous permafrost terrain in a warmer climate have been proposed in the literature and will be further discussed below: (i) water released from thawing permafrost; (ii) reactivation of subsurface flow paths; and (iii) thaw-induced landcover changes.

(i) An early explanation for rising streamflow was that permafrost thaw supplied additional water inputs to streams from ice converting to liquid water (St Jacques and Sauchyn, 2009; Walvoord and Striegl, 2007). However, recent studies have shown that the estimated volume of water sourced from thawing permafrost, particularly in low ice content terrain, is insufficient to account for all or most observed increases in river discharge (McClelland et al., 2004), including studies in the Taiga Plains (Connon et al., 2014) and Taiga Shield (Spence et al., 2014). Although some component of increasing streamflow can stem from the thawing of ice-rich peat plateaus in the Taiga Plains, it is considered a secondary factor (Connon et al., 2014).

(ii) Thaw-induced reactivation of groundwater flow paths that increase groundwater discharge to rivers is the second explanation for rising streamflow (Crites et al., 2020; Smith et al., 2007; St Jacques and Sauchyn, 2009; Walvoord and Striegl, 2007). Increases in streamflow are occurring in low-flow winter months (Peterson et al., 2002), including the Liard River valley where winter baseflow has increased between 1964–2012, with increases ranging from 0.7%–94.6% per year over each basin's period of record (Table 2; Connon et al., 2014; Shrestha et al., 2019; St Jacques and Sauchyn, 2009). Thaw-induced talik development is likely to enable wintertime groundwater discharge to streams (Fig. 4b-xii). Sources of groundwater discharge may be from deeper flow systems or reopened flow paths that enable drainage of wetlands and lakes to occur year-round (Smith et al., 2007; Walvoord and Kurylyk, 2016; Yoshikawa and Hinzman, 2003). Although increased talik development has been observed on peat plateaus in the Taiga Plains (Connon et al., 2018; Gibson et al., 2018), baseflow was found to be a relatively small (<7%) component of annual streamflow, insufficient to explain the observed increases to streamflow (Connon et al., 2014).

(iii) The third explanation for rising streamflow is that thaw-induced landcover changes are altering the basin runoff dynamics. For the lower Liard River valley, liquid water inputs from thawing peat plateaus and subsurface reactivation could not fully explain increases in annual runoff (Connon et al., 2014). Precipitation also did not increase during periods of increased runoff. Instead, permafrost thaw resulted in a landscape shift to a higher runoff producing landcover (Connon et al., 2014). This shift likely needs to happen in tandem with either reduced evapotranspiration (somewhat permanent), or reduced water storage (transient), where the latter is documented in Haynes et al. (2018). The low permeability of the underlying mineral soil may be why increased subsurface connectivity was not a dominating factor in streamflow rises in this environment compared to others (Kurylyk and Walvoord, 2021). However, the cumulative and/or competing effects of landcover change and groundwater reactivation on streamflow and how this varies across landscapes require additional investigation to predict hydrologic change across the region.

Evidence for landcover change driving streamflow increases is supported by runoff ratios in the Liard River valley increasing between 1996–2012 (Connon et al., 2014). Fig. 6 illustrates that, despite non-significant changes in annual precipitation between 1978 and 2017, annual runoff significantly increased for basins in the Taiga Plains underlain by permafrost. However, significant changes in annual runoff were not observed for basins in the Taiga Shield with similar proportions of permafrost, likely due to limited thaw-induced landcover changes associated with the bedrock-dominated terrain and low storage crystalline bedrock.

As noted in Section 6.5, thaw-induced increases in bedrock valley storage in the Taiga Shield (Fig. 4b-xi; Morse and Spence, 2017) may reduce the hydrologic connectivity of the fill-and-spill drainage network and lead to more intermittent and delayed streamflow responses to nival freshet or summer rainfall events. Streamflow changes from climate-driven thaw in the Taiga Shield may be similar to the hydrologic

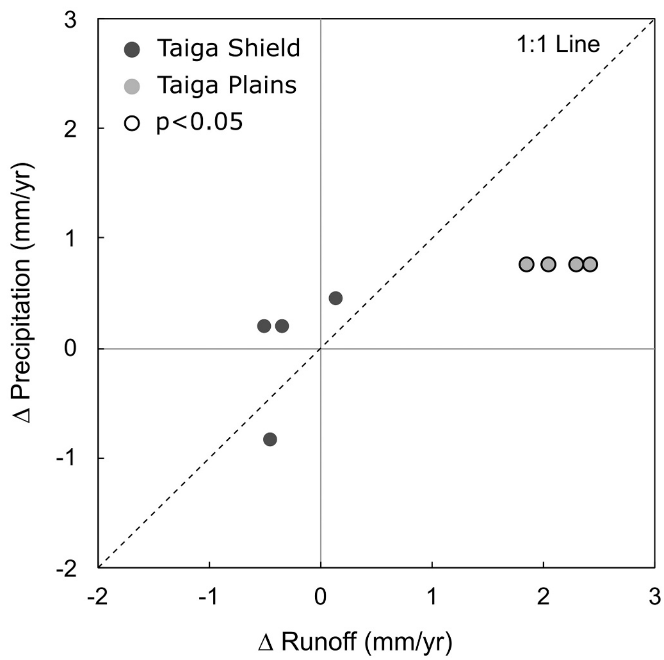

Fig. 6. Changes in annual precipitation versus changes in runoff between 1978 and 2017 for basins in the Taiga Plains and Taiga Shield with similar proportions of permafrost coverage. The 1:1 line indicates where a unit change in precipitation will result in an equal unit change in runoff. Plotting off the line, like the basins shown in the Taiga Plains, suggest other factors like thaw-induced landcover change are altering runoff patterns. Significance (circled marker) and magnitude of change were determined from a Mann Kendall test. Runoff data were obtained from gauges operated by the Water Survey of Canada within the transboundary region. Precipitation records were obtained from the closest community with a long-term record. No change in precipitation was statistically significant.

effects of wildfires investigated in two Shield basins by Spence et al. (2020a). Differences in annual streamflow between unburned and burned basins were insignificant. However, winter baseflow was higher in the previously burned basin, evidenced by considerable icing at the stream outlet. Since icings form from groundwater discharge, these results suggested that forest fire promoted talik development and increased hydrologic connectivity (Fig. 4b-ix).

7. Impacts of permafrost thaw on water quality and biogeochemistry

Permafrost thaw and the resulting alterations to landcover and hydrology can impact downstream water quality. Stores of organic matter, nutrients, metals, and point-source anthropogenic contaminants previously locked in permafrost may become mobilized due to thaw (AMAP, 2015; Frey and McClelland, 2009; Miner et al., 2021; Vonk et al., 2015), with implications ranging from ecosystem health to drinking water quality and the toxicity of country foods. Here, site-specific studies are summarized regarding the potential impacts of permafrost thaw and wildfire on water quality within the Taiga Plains, and to a lesser extent, in the Taiga Shield. The studies utilized space-for-time approaches (e.g., Olefeldt et al., 2014) and paired catchment comparisons (e.g., Tank et al., 2018). Where aspects of water quality and biogeochemistry have not been investigated in the study region, studies from representative external regions are drawn upon, such as the peatland-rich Western Siberian Lowlands or Fennoscandia.

7.1. Physical parameters

Permafrost thaw and increased connectivity to groundwater may influence the electrical conductivity (EC) and pH of surface water bodies. EC is influenced by water movement through mineral sediment, and where landcover shifts from peat plateau to minerotrophic wetlands with high groundwater connectivity (e.g., channel fens), EC increases (Fig. 7-i). Thermokarst bogs are defined by lower groundwater connectivity and therefore have lower EC than fens (Hayashi et al., 2004; Olefeldt and Roulet, 2012). While peatlands are often acidic environments, nutrient-poor peatlands (e.g., bogs and peat plateaus) have a substantially lower pH than nutrient-rich fens (Vitt and Chee, 1990). Groundwater connection and the buffering capacity of carbonate bedrock/sediment can thus lead to a higher pH in peat-rich catchments, as observed in Western Siberian Lowlands catchments with a latitudinal decrease of pH (Frey et al., 2007a; Pokrovsky et al., 2015). The predicted increase of pH and EC with permafrost thaw (Frey and McClelland, 2009) will likely be most pronounced in the continuous and extensive discontinuous permafrost regions of the Taiga Plain as new groundwater pathways develop (Fig. 8a; Mertens, 2018; Thompson and Olefeldt, 2020).

It is unlikely that permafrost thaw in the permafrost fringe of the Taiga Plains and Shield will increase suspended sediment loads. Large-

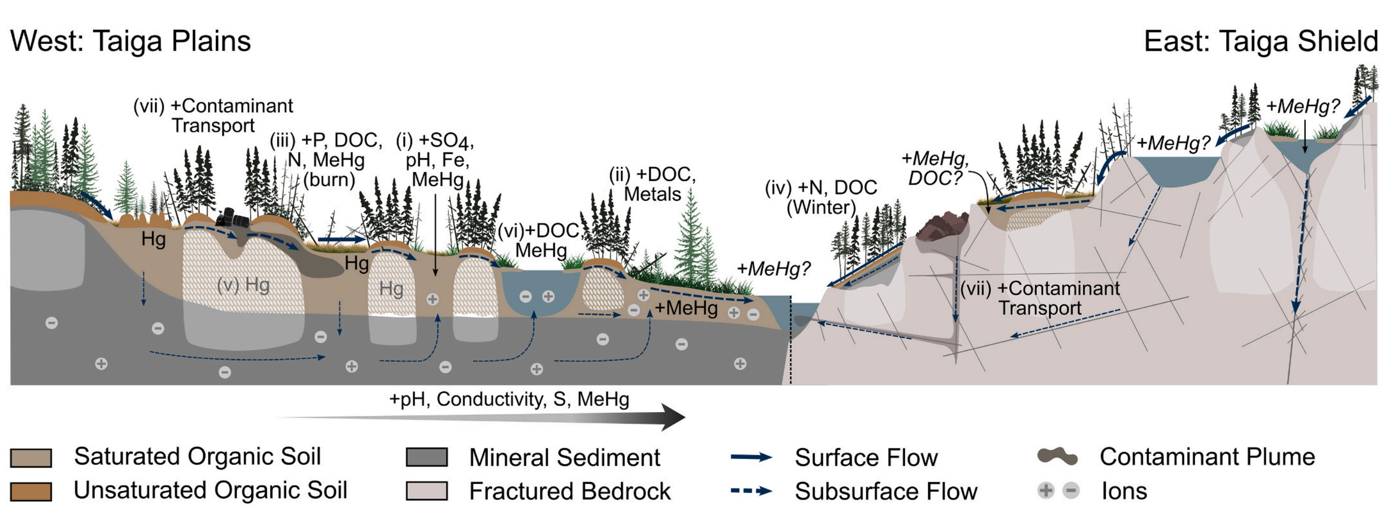

Fig. 7. Conceptual cross-section of the impacts to water quality in the Taiga Plains and Taiga Shield following progressive permafrost thaw from climate warming and/or land disturbance. Refer to Fig. 4a for initial permafrost conditions and landcover descriptions. The '+' before text indicates an increase in concentration and/or mobilization of the specified water quality parameter. Italicized text with a question mark indicates a high degree of uncertainty and requires further investigation. P: phosphorus, N: nitrogen, S: sulfur, Fe: iron, Hg: mercury, DOC: dissolved organic carbon, MeHg: methylmercury.

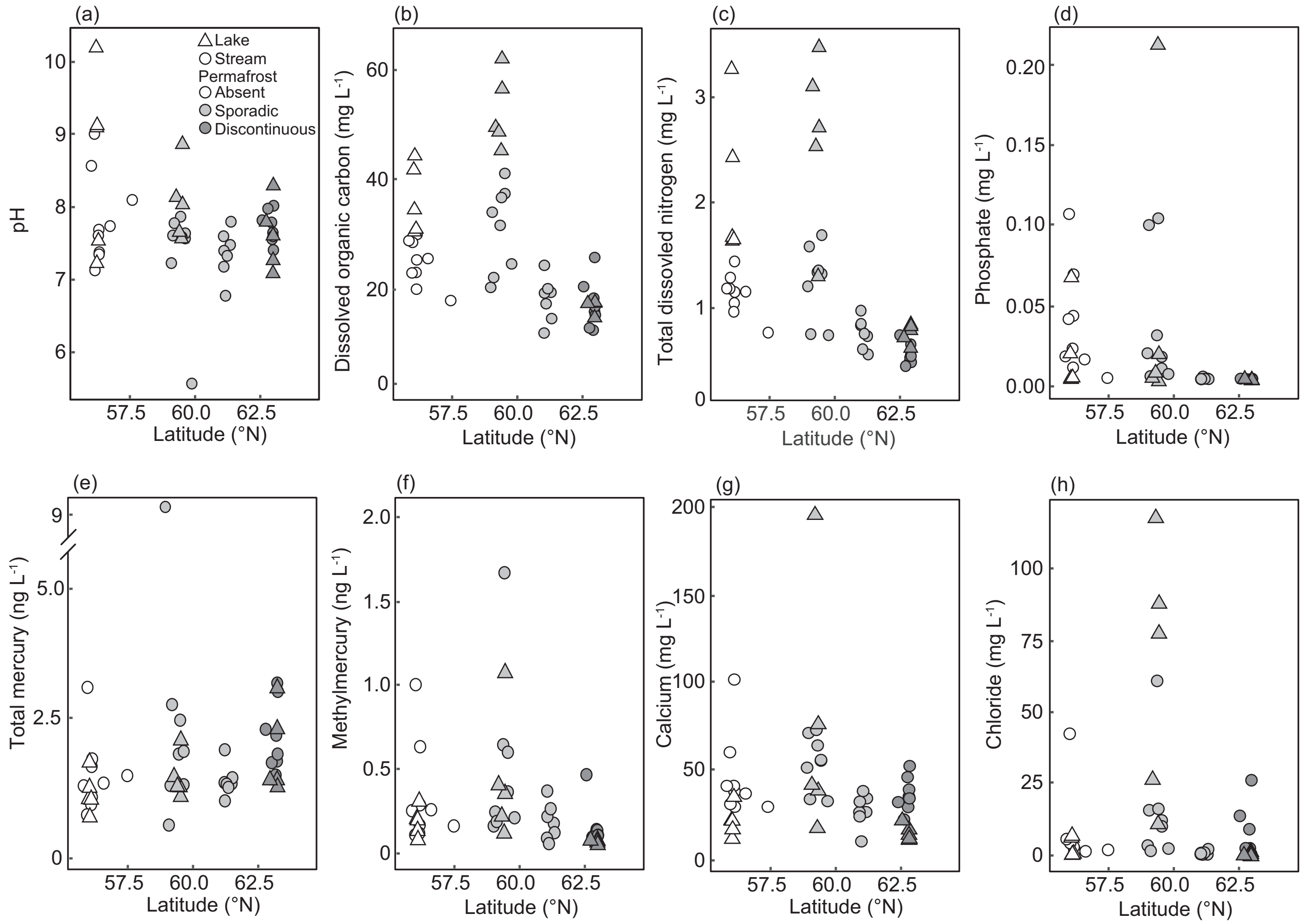

Fig. 8. Water chemistry variables as a function of latitude for streams and small lakes within the Boreal Plains and Taiga Plains of Alberta and the Northwest Territories, including (a) pH, (b) dissolved organic carbon, (c) total dissolved nitrogen, (d) phosphate-as-phorphorus, (e) total mercury, (f) methylmercury, (g) calcium, and (h) chloride (data from Thompson and Olefeldt, 2020).

scale disturbances and mass movements that increase downstream suspended sediment loads by several orders of magnitude (e.g., retrogressive thaw slumps and active layer detachments; Kokelj et al., 2013) are uncommon in the region, especially on lower Strahler-order streams and rivers (Kokelj et al., 2017; Olefeldt et al., 2016). While increased suspended sediment loads downstream from permafrost peatlands are not expected, increased runoff and intensity of peak flows (Section 6.6) could potentially increase sediment transfer and turbidity, such as from bank abrasion and resuspension of channel sediment stores (Krickov et al., 2020).

7.2. Organic matter

Peatlands are major sources of dissolved organic carbon (DOC) to boreal streams (Moore, 2013), and the magnitude of annual DOC export to the Mackenzie River is amongst the highest in the world (Li et al., 2017). DOC is a substrate for microbial activity and plays an important role in water quality. Dissolved organic matter (DOM) controls light penetration in water bodies, with implications for phototransformations of neurotoxic methylmercury (MeHg) (Klapstein and O'Driscoll, 2018; Thompson et al., Submitted) and light conditions that control fish growth, predation, and reproduction (Solomon et al., 2015). Metals such as mercury can bind to DOM, and DOM can alter drinking water color, taste, and odor. During water treatment processes, DOC can interact with chlorine to produce potentially carcinogenic disinfection by-products and interfere with the effectiveness of disinfection (Teixeira and Nunes, 2011). As such, there is a strong interest in understanding how DOC concentrations in northern streams may be affected by permafrost thaw.

Permafrost presence and peatland cover are important controls on DOC concentrations in waterbodies (Fig. 7-ii). A survey of rivers in northern Alberta and southern NWT found DOC concentrations increased with basin peatland cover but were consistently lower north of the permafrost boundary (Olefeldt et al., 2014). Patterns of DOC concentrations within peatland lakes across the Taiga Plains were also higher in the sporadic and permafrost-free zones than further north (Fig. 8b; Thompson and Olefeldt, 2020). Similar patterns have been observed in the Western Siberian Lowlands, where permafrost-influenced rivers had low DOC concentrations, and permafrost-free basins had significantly higher DOC concentrations that increased with peatland cover (Frey and Smith, 2005). These studies suggest that ongoing permafrost thaw may increase DOC concentrations in permafrost peatland basins. Furthermore, both solute concentrations and the hydrologic regimes of rivers control DOC export. Therefore, the increasing runoff regimes due to thaw-induced landcover change (Section 6.6) could further contribute to higher DOC export in the Taiga Plains, but further research is needed.

Wildfire may also influence DOC concentrations, but the Taiga Plains and Shield evidence suggest that the influence is muted through the continuum of soil porewater to catchment outlet (Tank et al., 2018). While higher DOC concentrations have been observed in the porewater of burned peatlands in the Taiga Plains (Fig. 7-iii; Ackley et al., 2021;

Burd et al., 2018), catchment export was only modestly higher in a burned site compared to a paired unburned catchment (Burd et al., 2018). At a paired burned/unburned catchment in the Taiga Shield, concentrations of DOC in ice-free seasons were similar but were elevated during winter in the burned catchment (Fig. 7-iv; Spence et al., 2020a). In a survey of 50 sites across the Taiga Plains and Taiga Shield, there was no significant difference in DOC concentrations between burned and unburned sites (Tank et al., 2018).

In non-peatland environments, enhanced groundwater flow paths from thaw have resulted in decreases of DOC from basins in Alaska (Douglas et al., 2013; Petrone et al., 2006) and Yukon (Shatilla and Carey, 2019) as mineral soil can readily adsorb DOC (Kothawala et al., 2012). In northern Sweden, groundwater influence (inferred from EC) was related to lower DOC concentrations and aromatic quality relative to peatland sources, with increased groundwater contributions in wetter years (Olefeldt and Roulet, 2012). While DOC export has decreased in the Yukon River (1978-1980 compared to 2001-2003), attributed to increasing groundwater connections that adsorb DOC (Striegl et al., 2005; Walvoord and Striegl, 2007), longer-term carbon (C) export has increased in the peatland-influenced Mackenzie River (Tank et al., 2016). This increase may be due to limited groundwater contributions from the underlying low-permeability glacial till despite groundwater activation with permafrost thaw. Instead, the surface water and wetland-dominated systems become increasingly effective at delivering peatland DOC to the main river system, with minimal dilution from deepened groundwater flow paths through thick peat deposits (Fig. 7).

To identify permafrost thaw and the mobilization of organic matter, radiocarbon dating of DOC determines whether the source of C is from the decomposition of relatively young plant or peat matter (modern C) or the decomposition of plant or peat matter previously frozen in permafrost (aged C). Currently, DOC in Taiga Plains streams is predominately modern, with only a minor contribution from millennial-aged peatland soil C (Burd et al., 2018; Tanentzap et al., 2021). However, an abrupt DOC aging event in 2018 was detected in the Mackenzie River north of Tsiigehtchic, NWT (Schwab et al., 2020). This was also detected in two large tributaries to the Mackenzie River (Peace and Liard rivers), which was attributed to petrogenic organic C stores and mobilization from permafrost peat (Campeau et al., 2020). In contrast, more modern DOC was detected in the Taiga Shield rivers and attributed to aquatic biomass, thinner organic soils, and a low presence of DOC-adsorbent sediment (Campeau et al., 2020). However, as noted in a recent synthesis of radiocarbon DOC and particulate organic C across the pan-Arctic, it is difficult to conclude whether aged organic matter released from deep soils is generated because of terrestrial disturbance or regular permafrost C cycling (Estop-Aragonés et al., 2020).

7.3. Nutrients

Terrestrial disturbances due to permafrost thaw, wildfire, and increasing human influence (i.e., agriculture and wastewater, Section 7.6) may enhance nutrient (i.e., nitrogen (N), and phosphorus (P)) fluxes in the Taiga Plains. Peatlands are nutrient-limited systems, dominated by organic forms rather than more bioavailable inorganic forms (Moore et al., 2019). The changes in organic nutrient forms resulting from permafrost thaw are likely to mirror DOC (Frey et al., 2007b; Section 6.2), while alteration of inorganic nutrient concentrations remains more uncertain (Vorobyev et al., 2017). Lakes and rivers in the Taiga Plains showed the highest total N concentrations (dominated by organic N forms) and phosphate (PO_4^{3-}) concentrations in permafrost-free and sporadic permafrost zones relative to discontinuous and continuous permafrost (Fig. 8c-d; Thompson and Olefeldt, 2020). Particulate N in the Western Siberian Lowlands rivers had the highest concentrations and fluxes in the sporadic and discontinuous permafrost, attributed to thawing, deeper peat soils (Krickov et al., 2018), although PO_4^{3-} and inorganic N concentrations were not significantly impacted by extent of permafrost (Vorobyev et al., 2017). Chemical extractions from peatland soils in the sporadic permafrost region of northern Sweden showed that thawing peatlands mobilized high quantities of inorganic N, which was suggested to be taken up by plants rather than delivered to downstream environments (Keuper et al., 2012). However, downstream delivery of PO_4^{3-} was observed in lakes of the southern Taiga Plains, resulting in enhanced algal productivity (i.e., chlorophyll-α concentrations) (Kuhn et al., 2021); inorganic N may be likewise "leaky" in the Taiga Plains. Wildfire disturbances may also enhance the mobilization of nutrients from peatlands. For example, a comparison of burned and unburned catchments near Jean Marie River, NWT, found higher P yields from the burned catchment, with limited effects on N forms (Fig. 7-iii; Burd et al., 2018). Both N and P increased in porewater of a burned peat plateau in Scotty Creek relative to unburned soils, which was attributed to release during peat combustion along with increased water residence time and decreased nutrient uptake by plants due to vegetation loss (Fig. 7-iii; Ackley et al., 2021).

Few studies have examined the effects of permafrost thaw on nutrient cycling in the Taiga Shield, although wildfire effects have been explored. At a paired burned/unburned catchment in the Taiga Shield, wintertime dissolved N concentrations were elevated during winter at the burned catchment (Fig. 7-iv; Spence et al., 2020a). A larger survey of water quality in streams across the Taiga Plains and Taiga Shield showed that the influence of wildfire on both P and N was only detected for smaller headwater basins, with no effect for larger rivers (Tank et al., 2018). Thus, the spatial scale at which permafrost thaw impacts nutrient mobilization is important to consider, with effects appearing to be muted at greater catchment scales.

7.4. Mercury

Atmospheric mercury (Hg) deposition from distant sources becomes bound to organic matter and accumulates in soils, especially organic-rich peatland soils (Fig. 7-v; Grigal, 2003). Stocks of Hg in the permafrost and active layer (top 3 m) of organic soils are estimated to be 85 Gg Hg (top 3 m, interquartile range of 55–106), ~17% of the total Hg sequestered in pan-Arctic permafrost soils (Lim et al., 2020). Permafrost inhibits any further cycling of Hg, but permafrost thaw makes Hg potentially sequestered in the peatlands of the study region vulnerable to mobilization. Hg release has been detected in Swedish thaw ponds (Klaminder et al., 2008; Rydberg et al., 2010) and downstream of thawing peatlands in the Western Siberian Lowlands (Lim et al., 2019). Hg-related fish consumption advisories have been enacted for NWT lakes (Government of the Northwest Territories, Health and Social Services, 2020). Numerous advisories in the peatland-rich Dehcho region are related to high Hg burdens, particularly in predatory species (e.g., northern pike and walleye) (Evans et al., 2013; Evans et al., 2005; Laird et al., 2018). Evidence suggests that Hg concentrations in biota are associated with the terrestrial delivery of DOC and Hg to lakes from lowlands (Fig. 7-vi; Evans et al., 2005; Moslemi-Aqdam et al., 2022), implying that thaw-mobilized DOC (Section 7.2) and Hg may influence Hg burdens in fish. In contrast, studies of fish in Yukon and Nunavut have not observed increasing Hg bioaccumulation (Chételat et al., 2015), potentially relating to the lesser influence of permafrost peatlands in those regions.

The transition of relatively dry peat plateaus into saturated fens and bogs enhances the microbial transformation of mercury's most toxic form,MeHg (Fahnestock et al., 2019; Gordon et al., 2016; Poulin et al., 2019). MeHg is a neurotoxin that biomagnifies in concentrations as it travels from primary producers and consumers to higher trophic level organisms and bioaccumulates in tissues over the lifetime of aquatic biota (McIntyre and Beauchamp, 2007). Human intake of MeHg may impact the central nervous system, the cardiovascular system, reduce reproductive outcomes, suppress immune function, and during gestation, can pass across the placenta to the fetus (Mergler et al., 2007). However, current monitoring programs in the study region do not include MeHg as a regularly sampled parameter.

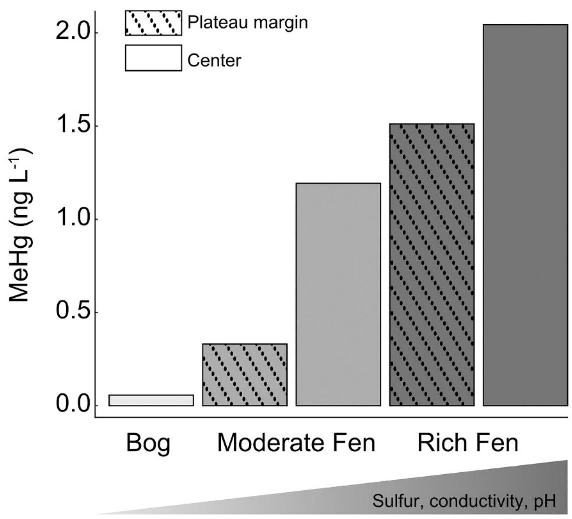

Fig. 9. Barplot of methylmercury (MeHg) concentrations in permafrost-free wetlands draining to the Hay River, AB, where concentrations increased with wetland trophic status (L. Thompson, unpublished data).

Permafrost thaw and the development of thermokarst wetlands have been shown to create hotspots of MeHg production (Fig. 7-i). However, whether these hotspots can influence concentrations and fluxes at the basin level is unclear, and peatland MeHg dynamics have not been investigated in the Taiga Shield. The production of MeHg (methylation) is tied to the microbial community structure, DOM quantity and quality, Hg bioavailability, and the abundance of electron receptors (Bravo and Cosio, 2020). The nutrient-rich environment of thermokarst fens is more productive for methylation than nutrient-poor thermokarst bogs within the study area (Gordon et al., 2016) and other peatland-rich regions in Europe and North America (Fig. 9; Fahnestock et al., 2019; Poulin et al., 2019). MeHg concentrations at a burned peat plateau were also elevated relative to a nearby unburned site, attributed to elevated DOC concentrations and favourable sulfate (SO_4^{2-}) concentrations (Ackley et al., 2021; Fig. 7-iii). However, MeHg and total Hg concentrations were not significantly elevated in rivers and lakes in the sporadic and discontinuous permafrost regions relative to the continuous permafrost zone of the Taiga Plains (Fig. 8e-f; Thompson and Olefeldt, 2020; Thompson et al., Submitted). Still, peatland cover and DOC concentrations were key drivers for MeHg concentrations (Thompson et al., Submitted). Thermokarst peatland lakes show increasing Hg inputs (Klaminder et al., 2008; Korosi et al., 2015), and northern lakes in other regions have been methylation hotspots (Lehnherr et al., 2012; MacMillan et al., 2015; St Louis et al., 2005; Varty et al., 2021). However, in the Taiga Plains, MeHg bound to DOM is likely delivered from surrounding wetlands rather than produced in situ (Branfireun et al., 2020; Bravo et al., 2017; Thompson et al., Submitted). Downstream aquatic environments will likely receive increased inputs of Hg forms in the Taiga Plains as permafrost thaw advances and landscapes transition to thermokarst wetlands, with greater uncertainty in the Taiga Shield due to a lack of existing data.

7.5. *Other metals*

Some evidence from external regions indicates that permafrost thaw in peatlands can lead to increased mobilization and downstream transport of metals complexed to DOM, such as lead (Pb), iron (Fe), and selenium (Se) that can impact aquatic biota (Fig. 7-ii; Klaminder et al., 2010; Patzner et al., 2020; Pokrovsky et al., 2018). In northern Sweden, peatland thermokarst development led to an increased flux of Pb into the sediment of adjacent lakes (Klaminder et al., 2010), and Pb concentrations in peatland porewater increased as permafrost extent decreased (Raudina et al., 2017). A study of Fe release through permafrost thaw in Sweden found that large quantities of organic matter are bound to reactive Fe; with waterlogging and oxygen limitation after permafrost thaw, Fe-reducing bacteria begin mobilizing both Fe and C (Patzner et al., 2020). In thaw lakes and rivers of the Western Siberian Lowlands, Se concentrations were highest in the discontinuous permafrost zone and attributed to peat thawing, although concentrations did not exceed toxic thresholds. Substances that readily bind with Se, including DOC and Fe, were shown to be linearly correlated with Se concentrations (Pokrovsky et al., 2018). Since the primary driver of increased mobilization of these metals is the shift to anoxic conditions associated with thermokarst wetland development, similar trends may occur within the Taiga Plains. Ground ice in peatlands is another potential source of metals yet unexplored in the study region, as high trace element concentrations were observed in peat ice in the Western Siberian Lowlands (Lim et al., 2021). Thawing wetlands may likewise mobilize metals accumulated in peat within the Taiga Shield, although downstream effects may be less pronounced due to lower peatland coverage.

7.6. *Point-source contaminants*

Indigenous communities in the permafrost-fringe of the Taiga Plains and Taiga Shield have reported degraded water quality and expressed concern of water contamination from landfills, oil and gas facilities, and mine tailings (Christensen, 2015; Guyot et al., 2006; Mackenzie River Basin Board, 2021; Parlee and Maloney, 2017). Permafrost thaw can interact with the storage and transport of contaminants and potentially impact water quality (Fig. 7-vii; Grebenets et al., 2021; Miner et al., 2021). For example, solid waste facilities in the NWT do not have engineered liners to contain leachate, so thaw-induced changes to hydrology may alter leachate transport to surface water receptors (Ripley, 2009). Additionally, solutes alter the freezing point of water (Woo, 2012), which could in turn, delay freeze back and enhance permafrost thaw. Recent modelling of a community sewage lagoon in the study region (undisclosed location) indicated that permafrost thaw increased hydrologic connectivity and transport of conservative/non-reactive solutes (e.g., chloride) to the nearby river (Mohammed et al., 2021). However, the authors also found that thaw-enhanced deep groundwater flow paths increased the residence times of reactive solutes, causing them to naturally degrade before reaching the river. Additional field investigations of point source contaminants like waste sites and lagoons are needed to support model development and assess risk to drinking water supplies from waste facilities.

Current and historic mining operations in the region include diamond, gold, lead, zinc, and silver mines in the Taiga Shield (Silke, 2009). A well-known case study of permafrost thaw interacting with mining activity is the Giant Mine in Yellowknife, NWT, which has posed significant health risks to nearby communities. During operation (1948-2004), arsenic trioxide (As_2O_3) dust (a by-product of gold ore roasting) was blown underground with the assumption that permafrost would contain the carcinogen (Jamieson, 2014; O'Reilly, 2015). However, permafrost is now largely absent from the site due to mine workings, so a thermosyphon system is needed to maintain frozen ground conditions (Jamieson, 2014). Still, seepages from the underground chambers are ongoing sources of arsenic to groundwater (Jamieson et al., 2013). Other point-source contaminants from mine sites that may be impacted from permafrost thaw include various hydrocarbons from fuel spills (Fig. 7-vii) like at the abandoned Colomac mine in the Taiga Shield (Iwakun et al., 2008).

Persistent organic pollutants (PoPs) are toxic chemicals known to bioaccumulate and biomagnify in food webs. PoPs have been detected in northern environments in air, biota, water, ice, snow, and sediments and can originate from natural or industrial sources, delivered locally, or from long-distant atmospheric transport (AMAP, 2015). Freshwater cycling of PoPs is a current knowledge gap, and mobilization of PoPs with permafrost thaw is a concern for food web health (AMAP, 2015;

Vonk et al., 2015). While studies are limited, PoPs have been found to revolatilize from permafrost soils to the atmosphere (Cabrerizo et al., 2018; Ren et al., 2019), and permafrost thaw is expected to release PoPs into aquatic systems (Ma et al., 2016). Similarly, recent work has highlighted projected increases in the thaw-induced emission of polycyclic aromatic compounds (PACs) (Muir and Galarneau, 2021), which are environmental pollutants generated from combustion, such as fossil fuels or wildfires (Abdel-Shafy and Mansour, 2016). PACs have been detected in the Hay River and Liard River, but levels were below water quality guidelines, and sources of the PACs were attributed to natural seeping from oil deposits in the environment and contributions from forest fires (Golder Associates, 2017; Stantec, 2016).

7.7. Groundwater geochemistry

Re-activation of shallow and deep groundwater systems as permafrost thaws imposes uncertainty to high latitude water quantity and quality (McKenzie et al., 2021). Our understanding of Arctic and sub-Arctic hydrology is almost entirely based on surface water observations, but new thaw-activated subsurface pathways often drive surface processes (IPCC, 2019; McKenzie et al., 2021). Groundwater knowledge in the southern permafrost-fringe of the Taiga Plains and Shield is largely deficient (Golder Associates, 2017; VanGluck, 2016); many groundwater quality studies are concentrated in the western Canadian Arctic and Alaska and are lacking in peatland-dominated basins (Cochand et al., 2019). Few studies in the region directly measure groundwater geochemistry and instead make inferences based on surface water. For example, high concentrations of major ions in lakes and rivers of the Taiga Plains (Fig. 8g-h; Mertens, 2018; Thompson and Olefeldt, 2020) indicate that connectivity of contemporary surface waters to groundwater sources rich with major ions is common in the sporadic and discontinuous permafrost regions.

Thaw-induced increases in groundwater discharge and connectivity with surface waters (Section 5.2) may increase dissolved solids, EC, and ion concentrations in streams and lakes (Frey and McClelland, 2009). In addition, as the delivery of electron receptors such as SO_4^{2-} increases with groundwater connectivity in wetlands, a consequence may be enhanced MeHg production (e.g., through SO_4^{2-}-reducing bacteria) (Fig. 7-i; Gordon et al., 2016). With thaw-enhanced hydrologic connectivity between wetlands, lakes, and streams, MeHg may be more easily transported to downstream waters. However, the impacts will likely be greatest in regions with widespread permafrost, such as the northern Taiga Plains, where thermokarst wetlands are not yet well connected to the basin drainage network. In general, more research utilizing a “space-for-time” approach is needed to understand the groundwater geochemistry changes in the southern reaches of the study area which may inform future changes in the north.

8. Summary and knowledge gaps

Rapid warming across the study region has resulted in permafrost thaw-driven landcover changes with direct impacts on the hydrology and water quality within and downstream of disturbed landscapes (Table 2). These changes are particularly pronounced for the peatland-dominated terrain of the Canadian Taiga Plains, where permafrost thaw is transforming black spruce forests underlain by permafrost to permafrost-free thermokarst wetlands. Here, in the initial stages of permafrost thaw, thermokarst bogs are hydrologically disconnected from other wetlands. Their formation temporarily increases groundwater storage, but their continued expansion results in an interconnected drainage network that forms a higher runoff-producing landcover. This landcover shift, along with increased supra-permafrost taliks, are considered the primary factors contributing to the observed increases in annual and winter streamflows in wetland-dominated basins. However, predicting the evolution and longer-term trajectory of increasingly integrated groundwater-surface water systems and the basin-scale implications remains a challenge. Sustained drainage of thermokarst wetlands can result in dry enough conditions to support the re-growth of permafrost-free black spruce forests, but this is a relatively recent advancement in landscape trajectory. As such, there are growing research opportunities for investigating the hydro(geo)logic and biogeochemical implications of afforested areas following permafrost thaw. Although considerable progress has been made in understanding the thaw-induced landcover impacts to discontinuous permafrost peatlands of the Taiga Plains, process-based studies largely stem from the Scotty Creek Research Station (Fig. 3). Existing knowledge gaps should continue to be addressed here and at new locations in the study region to determine the transferability of these processes and fill spatial and temporal data gaps.

In the Taiga Shield, similar thaw-induced landcover changes as the Taiga Plains may occur in the peatlands that cover approximately 5% of the region, but this has not been well studied. Additional landcover changes stem from thermokarst pond development due to thawing lithalsas and changes in the areal extent of lakes that dominate the region. In contrast to the Taiga Plains, lake levels and streamflow in the Taiga Shield appear to be dominated by changes in precipitation instead of thaw-induced landcover change. However, permafrost thaw in soil-filled bedrock valleys may increase basin storage and alter the timing and magnitude of runoff events. Increased supra-permafrost taliks are also linked to icings which are most common in the Taiga Shield but remain relatively unstudied in the southern Taiga Plains. The development of open taliks beneath lakes may be a driver for observed declines in lake levels in the Taiga Shield, where lake drainage is facilitated through the thaw of highly conductive fracture zones resulting in sub-permafrost groundwater recharge. In both the Taiga Plains and Shield, thaw-induced activation of sub-permafrost flow systems may also increase with implications for stream baseflow, particularly where higher permeability substrate exists. However, direct evidence of this is lacking, limiting our understanding of flow and transport in these environments. Studies in the Taiga Shield primarily stem from the North Slave region, with limited groundwater investigation due to the logistical challenges and cost-prohibitive nature of such research in remote bedrock environments. Advancements in remote sensing will continue to provide invaluable information for remote areas, but new tools are needed to investigate remote and challenging subsurface environments.

As permafrost thaws in peatlands, the release of DOC, Fe, and contaminants may increase, while wildfire may enhance the aquatic release of nutrients. Waterlogged bogs and fens are environments that are more suited for the microbial production of MeHg than dry peat plateaus; thus, lakes and rivers may see increased concentrations of MeHg. As such, continued and expanded monitoring of MeHg in the region is needed. Additionally, studies that examine the potential release of PoPs and PACs with permafrost thaw in the region are lacking, although preliminary work has shown low concentrations of PACs in the Taiga Plains. Groundwater quality is a key knowledge gap in the thawing-permafrost fringe of the Taiga Plains and Shield, and further studies are needed to determine baseline groundwater quality in addition to impacts to downstream systems at much larger basin scales. The thaw-induced increase in hydrologic connectivity between landscapes means the potential for enhanced mobilization of contaminants, particularly non-reactive solutes. Additionally, fracture networks in the Taiga Shield pose a risk for rapid contaminant transport to receptors, but further research is needed on thaw-activated groundwater flow systems to understand the coupled transport in this environment. The increased connectivity between ground and surface waters and enhanced groundwater flow can alter residence times for solute reactions to take place, thereby increasing or decreasing the natural attenuation of contaminants and the resulting impact on aquatic ecosystems and water supplies. Additional field investigations of point-source contaminants, such as community waste facilities and lagoons, are needed to improve our understanding of thaw-impacted contaminant transport.

Indigenous people who have lived in the study region for millennia are experiencing direct impacts of permafrost thaw-influenced land-cover change and subsequent impacts on hydrology and water quality. Communities and Nations of the region are monitoring the land, sharing local and traditional knowledge, and producing data that document climate-driven changes. Such stewardship of the land through current/proposed Indigenous Protected and Conserved Areas (e.g., Edéhzhíe and Thaidene Nëné in NWT, Bistcho Lake in Alberta) are contributing to sustaining and monitoring waters in the study region. To fill knowledge gaps in our current understanding of landcover, hydrology, and water quality trajectories and re-orient from harmful research practices, western scientific institutions must prioritize engaging and collaborating with Indigenous-led and directed programs in a non-extractive way (Latulippe and Klenk, 2020). In doing so, monitoring and research efforts will have the maximum benefit to those who live and rely on the land and those who study it.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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