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Significant underestimation of peatland permafrost along the Labrador Sea coastline

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Abstract. Northern peatlands cover approximately four million km², and about half of these peatlands are estimated to contain permafrost and periglacial landforms, like palsas and peat plateaux. In northeastern Canada, peatland permafrost is predicted to be spatially concentrated in the western interior of Labrador and largely absent along the Labrador Sea and Gulf of St. Lawrence coastline. However, the paucity of observations of peatland permafrost in the interior, coupled with ongoing use of perennially frozen peatlands along the coast by Labrador Inuit and Innu, casts doubt on the reliability of existing maps of peatland permafrost distribution in the region. In this study, we develop a multi-stage consensus-based inventory of peatland permafrost complexes in coastal Labrador and adjacent parts of Quebec using high-resolution satellite imagery and validate it with extensive field visits and low-altitude aerial photography and videography. A total of 1885 wetland complexes were inventoried, of which 1023 were interpreted as likely containing peatland permafrost. Likely peatland permafrost complexes were mostly found in lowlands within 40 km of the coastline where mean annual air temperatures of up to +1.2 °C are recorded. Evaluation of the geographic distribution of peatland permafrost complexes reveals a clear gradient from the outer coasts, where peatland permafrost is more abundant, to inland peatlands, where permafrost is generally absent. This coastal gradient may be attributed to a combination of climatic and geomorphological influences which lead to lower insolation, thinner snowpacks, and more frost-susceptible materials along the coast. The results of this study also suggest that existing maps of permafrost distribution for southeastern Labrador require adjustment to better reflect the abundance of peatland permafrost complexes which are located to the south of the regional sporadic discontinuous permafrost limit. This study constitutes the first dedicated peatland permafrost inventory for Labrador, and our results provide an important baseline for future mapping, modelling, and climate change adaptation strategy development in the region.

1 Introduction

Near the southern boundary of latitudinal permafrost zonation, lowland perennially frozen ground is primarily restricted to peatlands as palsas (peat mounds with a frozen core of mineral and organic material) and peat plateaux (large, elevated fields of frozen peat) (Payette, 2004; van Everdingen, 2005; Zoltai, 1972; Zoltai and Tarnocai, 1975). Persistence of these cryotic landforms at the extreme limits of their viability is facilitated by a large offset between the ground surface and

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the top of permafrost, caused by the thermal properties of thick layers of overlying peat (Burn and Smith, 1988; Williams and Smith, 1989). In recent years, many studies have shown that peatland permafrost can be very sensitive to climate warming and ecosystem modifications (Beilman et al., 2001; Borge et al., 2017; Thibault and Payette, 2009). Understanding the distribution of these ice-rich, thaw-sensitive periglacial environments is important for predicting thermokarst potential (Gibson et al., 2021; Olefeldt et al., 2016), local hydrological and vegetation change (Zuidhoff and Kolstrup, 2005), regional infrastructure and land-use planning, and global carbon stores and cycling activities (Hugelius et al., 2014).

Palsas and related landforms are primarily thought to occur in continental locations (Fewster et al., 2020; Hustich, 1939) where colder winters allow deeper frost penetration and drier summers promote less thaw. For example, palsas and peat plateaux have been described in many continental locations in Canada, including Yukon Territory, the Northwest Territories, and the Prairie provinces (e.g., Beilman et al., 2001; Coultish and Lewkowicz, 2003; Mamet et al., 2017; Thie, 1974; Zoltai, 1972), but they have also been documented in coastal locations including the Hudson Bay Lowlands in northern Manitoba, Ontario, and Quebec (e.g., McLaughlin and Webster, 2014; Ou et al., 2016; Pironkova, 2017). In the Labrador region of northeastern Canada, continental- to hemispheric-scale studies have suggested that peatland permafrost is present in the region's continental interior but is far less abundant or completely absent along most of the Labrador Sea coastline (Fewster et al., 2020; Hugelius et al., 2020; Olefeldt et al., 2021). However, historic and contemporary use of coastal peatland permafrost environments by Labrador Inuit and Innu is well documented (Anderson et al., 2018; Karst and Turner, 2011), and published field-based observations (e.g., Anderson et al., 2018; Andrews, 1961; Brown, 1975, 1979; Davis et al., 2020; Dionne, 1984; Elias, 1982; Hustich, 1939; Seguin and Dionne, 1992; Smith, 2003; Way et al., 2018; Wenner, 1947) suggest that peatland permafrost is more abundant along the coast than in the interior. This ongoing underestimation of peatland permafrost in the region has led to predictions of low ground ice content (O'Neill et al., 2019), thermokarst potential (Olefeldt et al., 2016), and carbon content (Hugelius et al., 2014).

Locally, preservation of peatland permafrost complexes is also relevant to Labrador Inuit and Innu because these areas are frequented for traditional activities such as bakeapple (cloudberry; appik; *Rubus chamaemorus*) berry-picking (Anderson et al., 2018; Karst and Turner, 2011), goose hunting, and fox trapping. Improvements to our understanding of regional peatland permafrost distribution will provide an important baseline for local and regional climate change adaptation strategy development, while better representation of the distribution of thaw-sensitive terrain will inform future development of linear and built infrastructure in and around Labrador's coastal communities.

Previous peatland permafrost mapping efforts in Labrador have been limited to scattered observations of palsa bogs through the National Topographic Database (Natural Resources Canada, 2005) and the Ecological Land Classification (Environment Canada, 1999), and no dedicated peatland permafrost inventorying efforts have been completed to date (Way et al., 2018). In this study, we develop a multi-stage, consensus-based inventory of contemporary peatland permafrost along the Labrador Sea and part of the Gulf of St. Lawrence coastline, comprising the region of Nunatsiavut and surrounding areas claimed by the Innu Nation (Nitassinan) and NunatuKavut Community Council (NunatuKavut). The goal of this inventory is to map and contextualize the contemporary distribution of peatland permafrost complexes throughout coastal Labrador, using

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extensive validation efforts from a combination of field visits and low-altitude imagery acquisition methods. This point-based inventory will refine our understanding of peatland permafrost distribution at local to regional scales and will be relevant for carbon modelling, land use planning, infrastructure development, and climate change adaptation strategies in northeastern Canada. This contribution will also provide insights into the reliability of existing peatland permafrost and permafrost distribution maps in eastern Canada, which will help to refine regional and global estimates of ground ice content, thermokarst potential, and carbon storage.

2 Study area

2.1 Bioclimatic setting

Labrador's long, cold winters and short, cool summers are largely dictated by the Labrador Current that carries cold Arctic waters down the eastern coast of mainland Canada (Banfield and Jacobs, 1998; Foster, 1983; Roberts et al., 2006). Mean annual air temperatures (1980-2010) decrease with continentality and latitude, ranging from -11.9 °C to +1.5 °C (Karger et al., 2017, 2021). Labrador is also characterized by some of the highest precipitation amounts in the North American boreal zone (Banfield and Jacobs, 1998; Hare, 1950) due to its varying relief, high moisture availability from the adjacent Atlantic Ocean, and high frequency of passing winter storm systems (Brown and Lemay, 2012).

Labrador exhibits a combination of taiga forests in the interior, tundra in the north, and wind-swept coastal barrens along the coastline of the Labrador Sea (Roberts et al., 2006). Tree cover is sparse in the coastal barrens due to a combination of climatic and physiographic limitations, but dense patches of black spruce (*Picea mariana*), white spruce (*Picea glauca*), tamarack (*Larix laricina*), and balsam fir (*Abies balsamea*), interspersed with deciduous trees, like paper birch (*Betula papyrifera*) and trembling aspen (*Populus tremuloides*), do exist in sheltered locations and on some slopes (Roberts et al., 2006).

2.2 Physical environment

Labrador is mostly underlain by igneous and metamorphic bedrock (Roberts et al., 2006). Extensive blankets of glacial till were deposited during and following the retreat of the Laurentide Ice Sheet (12-6 k years BP) (Bell et al., 2011; Dyke, 2004), along with thin layers of medium- to fine-grained marine and glaciomarine sediments in coastal lowland areas below the marine limit (Fulton, 1995). The post-glacial marine limit decreases with latitude, from ~150 m a.s.l. in southeastern Labrador and along the Quebec Lower North Shore to 0 m a.s.l. at the northernmost tip of Labrador in the Torngat Mountains (Occhietti et al., 2011; Vacchi et al., 2018). The broad distribution of near-surface bedrock and hardpans (Smith, 2003) results in poor drainage that has facilitated peatland development across large areas of Labrador, following a general gradient of string and blanket bogs in the interior to raised bogs along the coast (Foster and Glaser, 1986).

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2.3 Permafrost distribution

While permafrost conditions in Labrador, including the occurrence of peatland permafrost landforms, have been noted during ecological, palynological, glaciological, and archaeological surveys and studies (Anderson et al., 2018; Andrews, 1961; Hustich, 1939; Smith, 2003; Wenner, 1947), permafrost-specific field investigations are limited to R.J.E. Brown's (1975) helicopter survey of permafrost conditions in the late 1960s and the Labrador Permafrost Project from 2013 to 2017 (Way, 2017). Compared to other parts of Canada, where permafrost-focused studies are more concentrated, our understanding of permafrost distribution in Labrador has relied on extensive extrapolation of limited field observations and broad assumptions of the interactions between air temperature, vegetation cover, snow cover, and permafrost presence (Ives, 1979). According to the Permafrost Map of Canada (Heginbottom et al., 1995), permafrost area in Labrador is relatively low, with approximately two-thirds of Labrador classified in the isolated patches of permafrost (<10% permafrost by area) zone. Permafrost distribution in Labrador follows a latitudinal gradient, with extensive discontinuous (50-90% permafrost by area) and sporadic discontinuous (10-50% permafrost by area) permafrost zones in the north, and the isolated patches of permafrost zone in the south (Figure 1). Along the coastline, the sporadic discontinuous permafrost zone extends slightly further south along the outer edge of the Akami−Uapishk^{u}−KakKasuak−Mealy Mountains National Park Reserve than in the interior, though the rationale for this departure is unclear. Continuous permafrost (>90% permafrost by area) is expected to persist only at high elevations and latitudes, mostly in the Torngat Mountains (Heginbottom et al., 1995).

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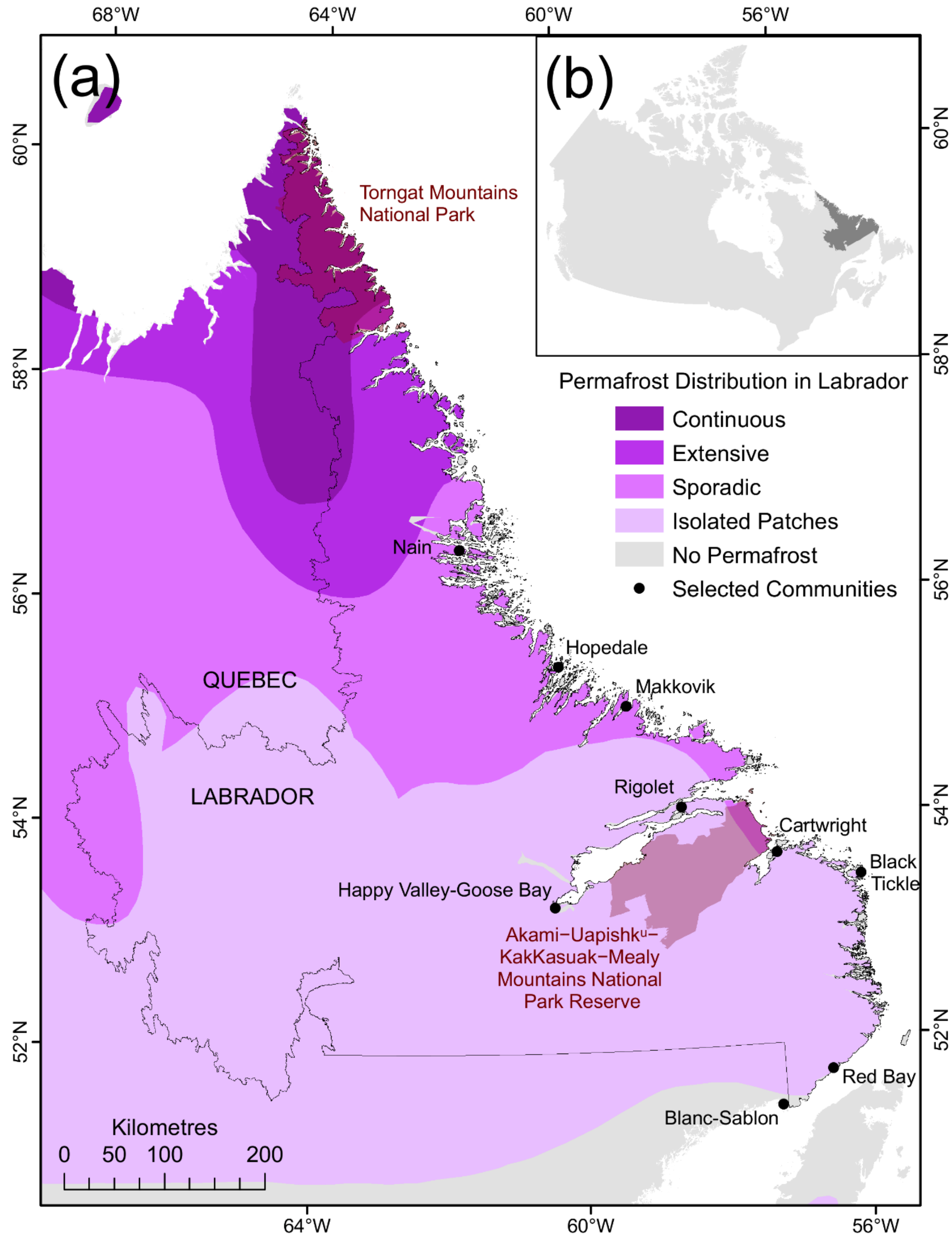

Figure 1. (a) Permafrost zonation in Labrador according to the Permafrost Map of Canada (Heginbottom et al., 1995) and locations of the Torngat Mountains National Park, Akami−Uapishkᵘ−KakKasuak−Mealy Mountains National Park Reserve, and communities mentioned in the text; (b) Location of Labrador in relation to Canada.

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3 Methods

Palsas and peat plateaux in the region may measure up to 4 m higher than their surrounding wetlands, so large peatland permafrost landforms can be identified and mapped from high-resolution satellite imagery (Borge et al., 2017; Gibson et al., 2020, 2021). Our inventory of large peatland permafrost complexes along the Labrador Sea and Gulf of St. Lawrence coastline was generated through a multi-stage mapping and consensus-based review process, supported by extensive validation efforts completed between 2013 and 2021. Prospective peatland permafrost complexes were identified from high-resolution satellite imagery, resulting in an initial database of wetlands of interest (WOIs). The presence of peatland permafrost landforms within these WOIs was evaluated through a consensus-based review process involving three mappers with permafrost-specific field experience in the region. Final interpretation of peatland permafrost presence or absence within the WOIs was based on reviewer agreement and was informed by field- and imagery-based validation of peatland permafrost landforms in the region.

3.1 Data sources

WOIs were identified and evaluated using Maxar (Vivid) optical satellite imagery, available as the World Imagery basemap via ArcGIS Online (0.5 m ground sampling distance; 5 m absolute spatial accuracy) (Esri, 2022). These satellite imagery mosaics consisted of summer imagery with minimal cloud and snow cover and acquisition dates for Labrador that ranged from 2010 to 2020.

Topographic data from Natural Resources Canada covering the WOIs were extracted from the Canadian Digital Elevation Data (CDED; 50 m spatial resolution), with a small gap near the provincial border between Labrador and the Quebec Lower North Shore that was filled in using the Canadian Digital Surface Model (CDSM). Gridded mean annual air temperature (MAAT) and mean annual thawing degree days (TDD) for the 1981 to 2010 climate normal were extracted from CHELSA V2.1 (~1 km spatial resolution) (Karger et al., 2017, 2021) at the WOI locations. Mean annual freezing degree days (FDD) for the WOI locations for 1981 to 2010 were calculated from MAAT and TDD over the same climate normal, following prior work in the region (Way et al., 2017; Way and Lewkowicz, 2018).

3.2 Inventorying peatland permafrost complexes

3.2.1 Identifying wetlands of interest (WOIs)

A team of three mappers used ArcGIS Online to identify WOIs throughout coastal Labrador (Supplement Sect. S1). Mapping and identification activities were mainly restricted to WOIs that contained prospective peatland permafrost landforms that exceeded ~2 m in length or width due to the 0.5 m spatial resolution of the satellite imagery. Some prospective peatland permafrost locations in interior Labrador and along the Labrador-Quebec interior border were included in the inventory (Brown, 1955, 1975; Way, 2017; Way and Lewkowicz, 2014), but mapping activities were primarily concentrated along the coast. This focus on the coastal barrens ecozone was based on an evaluation of existing literature-based observations (Anderson et al., 2018; Andrews, 1961; Brown, 1975, 1979; Davis et al., 2020; Dionne, 1984; Elias, 1982; Hustich, 1939; Seguin and

Dionne, 1992; Smith, 2003; Way, 2017; Way et al., 2018; Wenner, 1947) and records of palsa bogs from the National Topographic Database (Natural Resources Canada, 2005) that favoured the coastline, and a lack of identified features during extensive field activities in the interior (Way, 2017; Way and Lewkowicz, 2016, 2018) (Supplement Sect. S2). Mappers were instructed to identify WOIs based on local geomorphology, the presence of a white or grey surface cover corresponding to *Cladonia* spp. lichens, evident shadows indicative of elevated landform edges, and the presence of thermokarst ponds or exposed peat that may indicate ongoing thaw processes. The inventory sought to only include active peatland permafrost landforms, so WOIs with extensive thermokarst ponds but no evident peatland permafrost landforms were not included in the database. Mappers assigned each WOI a ranking of 1 (low confidence) to 3 (high confidence) to reflect their self-assessed confidence in their interpretation of permafrost presence within the wetland complex.

3.2.2 Quality control of WOI database

The WOI inventory was subjected to a quality control check, during which each complex was reviewed and duplicates or points clearly not corresponding to wetlands were removed. In some cases, non-wetland locations may have been retained because of difficulties discerning peat plateaux from peat-covered bedrock or flat coastal tundra.

3.2.3 Consensus-based review of WOI database

The quality-controlled WOI inventory was sent back to the mappers for a consensus-based review, following a similar method used by Way et al. (2021a) for rock glacier inventorying in northern Labrador. Each WOI was independently reviewed by two team members, both of whom had access to the mapper's initial confidence rating, and one of whom had access to a field-validated dataset of WOIs (see Sect. 3.3 Validation of subset of WOI database). Both team members were asked to indicate whether each WOI contained peatland permafrost landforms. WOIs that were evaluated by both reviewers as containing peatland permafrost were considered likely to contain palsas or peat plateaux, while WOIs that were evaluated by both reviewers as not containing peatland permafrost were considered unlikely to contain palsas or peat plateaux. WOIs with conflicting classifications were considered to possibly contain palsas or peat plateaux. This consensus-based review process resulted in a full inventory of WOIs that were classified as likely, possibly, or unlikely to contain peatland permafrost landforms.

3.3 Validation of subset of WOI database

The full, consensus-based inventory results were compared with a field-validated dataset of 281 WOIs, with and without contemporary peatland permafrost landforms. From July to September 2021, field evaluations of WOIs were undertaken via in-person field visits, remotely piloted aircraft (RPA) image acquisitions (DJI Mini 2), video clip acquisition from a helicopter survey, and image acquisitions from commercial Twin Otter aircraft flights. Interpretation of the presence or absence of permafrost landforms within each WOI that was visited or aerially surveyed was determined following a

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consensus-based approach between two mappers. Any disagreements in interpretation were discussed on a wetland complex by complex basis until consensus could be reached.

Field visits to peatland complexes were undertaken at road-accessible locations via truck or ATV and at coastal locations via speedboat from nearby communities. During field visits, team members probed the soil to the depth of refusal (maximum of 125 cm). The nature of refusal, interpreted as frozen ground, compact sediment, clasts, rock, or not applicable (N/A; >125 cm), was noted and used to assess permafrost presence. Where the cause of probe refusal was unclear, instantaneous ground temperature measurements were collected using vertically arranged thermistors connected to an Onset Hobo UX120-006M 4-Channel Analog Data Logger (accuracy ±0.15 °C) (Davis et al., 2020; Holloway and Lewkowicz, 2020; Way et al., 2021b; Way and Lewkowicz, 2015). Ground temperatures were recorded at the base of the probed hole for a minimum of 10 minutes to allow for thermal equilibration. Frost probing and instantaneous ground temperature measurements aimed to sample locations that were most likely to contain frozen ground and thus mostly occurred on elevated peat-covered microtopography within each complex.

Low-altitude RPA imagery of prospective peatland permafrost complexes was collected using a DJI Mini 2 minidrone when weather conditions were suitable (i.e., no rain, no fog, low wind). Imagery of WOIs was able to be collected within 2 km of the take-off location, allowing for many coastal sites to be viewed without having to come ashore from the speedboat.

Low-altitude georeferenced video footage was collected using a GoPro Hero9 camera that was mounted onto a helicopter during a fuel cache cleaning mission throughout northern Labrador, led by the Torngat Wildlife, Plants, and Fisheries Secretariat. The camera was set to record real-time video (1080 p, 60 fps, wide) at an oblique angle (~45°). The flight altitude was between 90 m and 120 m a.g.l., similar to Boisson and Allard (2018), and the flight plan between the Goose Bay Airport and the Torngat Mountains National Park was designed to fly over WOIs in coastal locations north of the community of Hopedale (55.5° N).

Low-altitude georeferenced aerial images were also collected using handheld digital cameras (Nikon Coolpix W300 or Olympus Tough TG-6) during commercial Air Borealis Twin Otter flight segments between Cartwright and Black Tickle and between Goose Bay, Rigolet, Makkovik, Postville, Hopedale, Natuashish, and Nain. The Twin Otter flights only crossed over WOIs along existing commercial flight routes.

3.4 Statistical analyses of WOI database

ANOVA (analysis of variance) and *post hoc* Tukey's HSD (honest significant difference) tests were performed to determine whether the mean latitude, distance from coastline, elevation, MAAT, TDD, and FDD were statistically significantly different between the final classes of likely, possibly, and unlikely peatland permafrost complexes. Statistical analyses were performed in R 4.0.3 (R Core Team, 2020).

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4 Results

4.1 Peatland permafrost complex identification and review

A total of 1885 unique WOIs were included in the full inventory. In the consensus-building review process, reviewer agreement was very high (88%), with 1016 complexes classified by both reviewers as likely containing peatland permafrost and 643 complexes classified by both reviewers as not likely containing peatland permafrost, and only 226 complexes with conflicting classifications of permafrost presence or absence (12%) (Supplement Sect. S3).

4.2 Validation of peatland permafrost complexes

In Summer 2021, in-person field visits (n=60 WOIs), RPA visits (n=97 WOIs), helicopter video clips (n=69 WOIs), and Twin Otter images (n=97 WOIs) were combined to evaluate peatland permafrost presence at 271 WOIs, 47 of which were cross-validated using multiple methods (Figure 2; Supplement Sect. S1). Previous work from 2013 to 2020, including field visits (n=7 WOIs) and RPA image collection (n=10 WOIs), were also used to validate palsa or peat plateau presence at an additional 10 complexes (Way, 2017). Out of the 281 WOIs evaluated via field and/or imagery validation methods, 161 were interpreted as containing peatland permafrost landforms. Comparison between the validation dataset and the consensus-based inventory resulted in re-classification of 34 of the 226 possible peatland permafrost complexes (15%) to either likely (n=7) or unlikely (n=27) peatland permafrost complexes.

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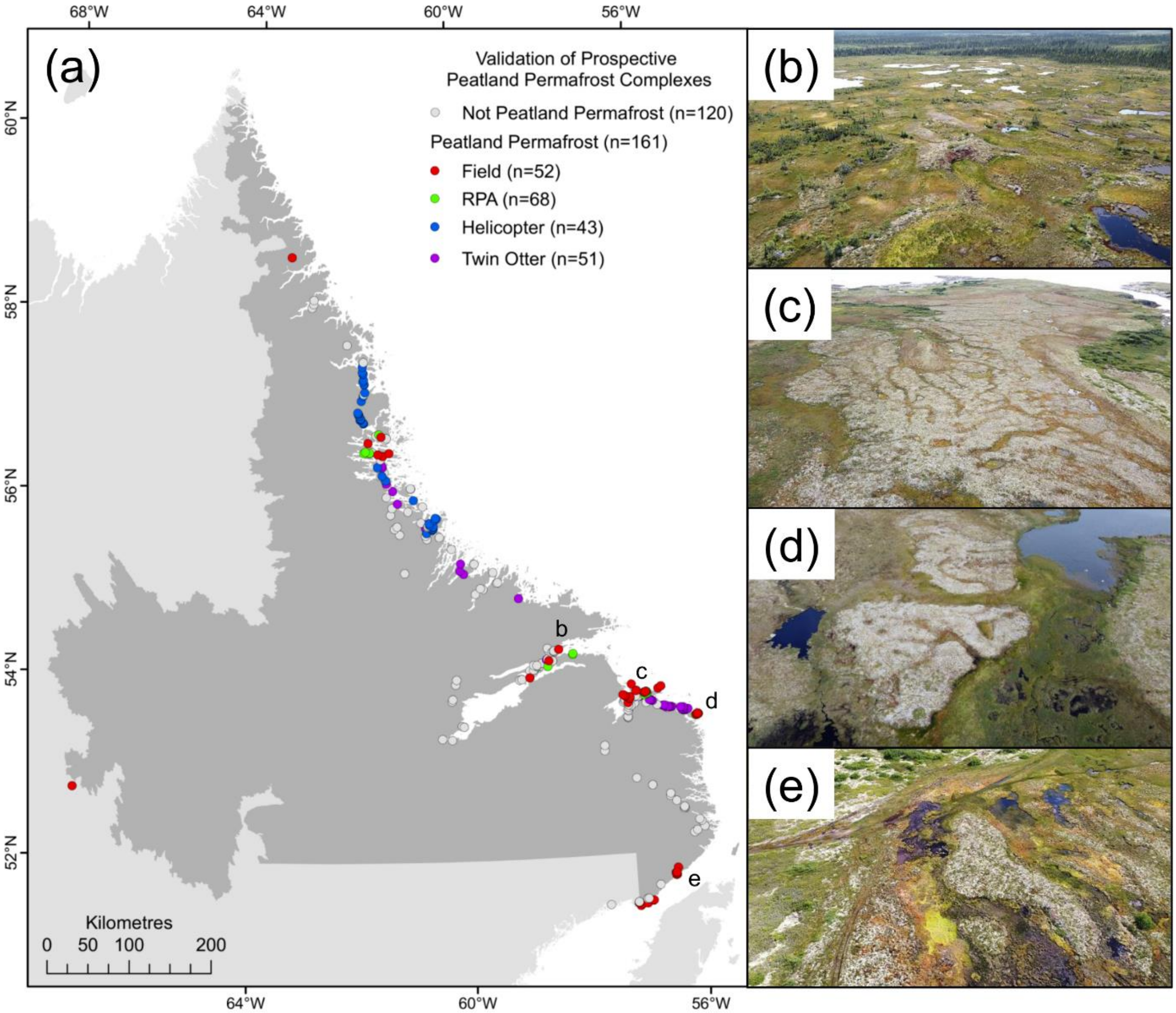

Figure 2. (a) Locations of validated peatland permafrost complexes in coastal Labrador from field-based activities and imagery acquisition using RPA, helicopter, and Twin Otter from 2013 to 2021; Example of peatland complexes containing palsas and/or peat plateaux near (b) Rigolet, (c) Cartwright, (d) Black Tickle-Domino, and (e) Red Bay.

4.3 Peatland permafrost complex inventory

A total of 1023 out of 1885 WOIs were classified as likely containing peatland permafrost landforms, with an additional 192 wetland complexes classified as possibly containing peatland permafrost landforms (Figure 3). The largest clusters of likely and possible peatland permafrost complexes were located along the coastline between Makkovik (55.0° N) and Black Tickle (53.5° N) (Figure 3; Figure 4A). Of the 1023 likely peatland permafrost complexes, 1022 were at low elevations (mean elevation of 30 m a.s.l.) (Figure 4C) within 41 km of the coastline (mean distance from coastline of 4.2 km)

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(Figure 3; Figure 4B), and one was located in alpine tundra, near the Labrador-Quebec interior border (Brown, 1979). The 1022 coastal complexes that were likely to contain peatland permafrost were distributed along the coastline from 51.4° N near Blanc-Sablon to 58.6° N in the Torngat Mountains National Park (Figure 3; Figure 4A), with most complexes located in southeastern Labrador (mean latitude of 54.1° N) (Supplement Sect. S4). Comparison against gridded climate products showed that the MAAT of peatland permafrost complexes ranged from -7.5 °C to +1.2 °C, with corresponding ranges for FDDs of 1126 degree days to 3466 degree days and TDDs of 736 degree days to 1704 degree days (Figure 4D-F). Despite the wide range in MAAT, the majority of the coastal likely peatland permafrost complexes (87%) were found in locations with MAATs between -2 °C and 1 °C (Figure 4D).

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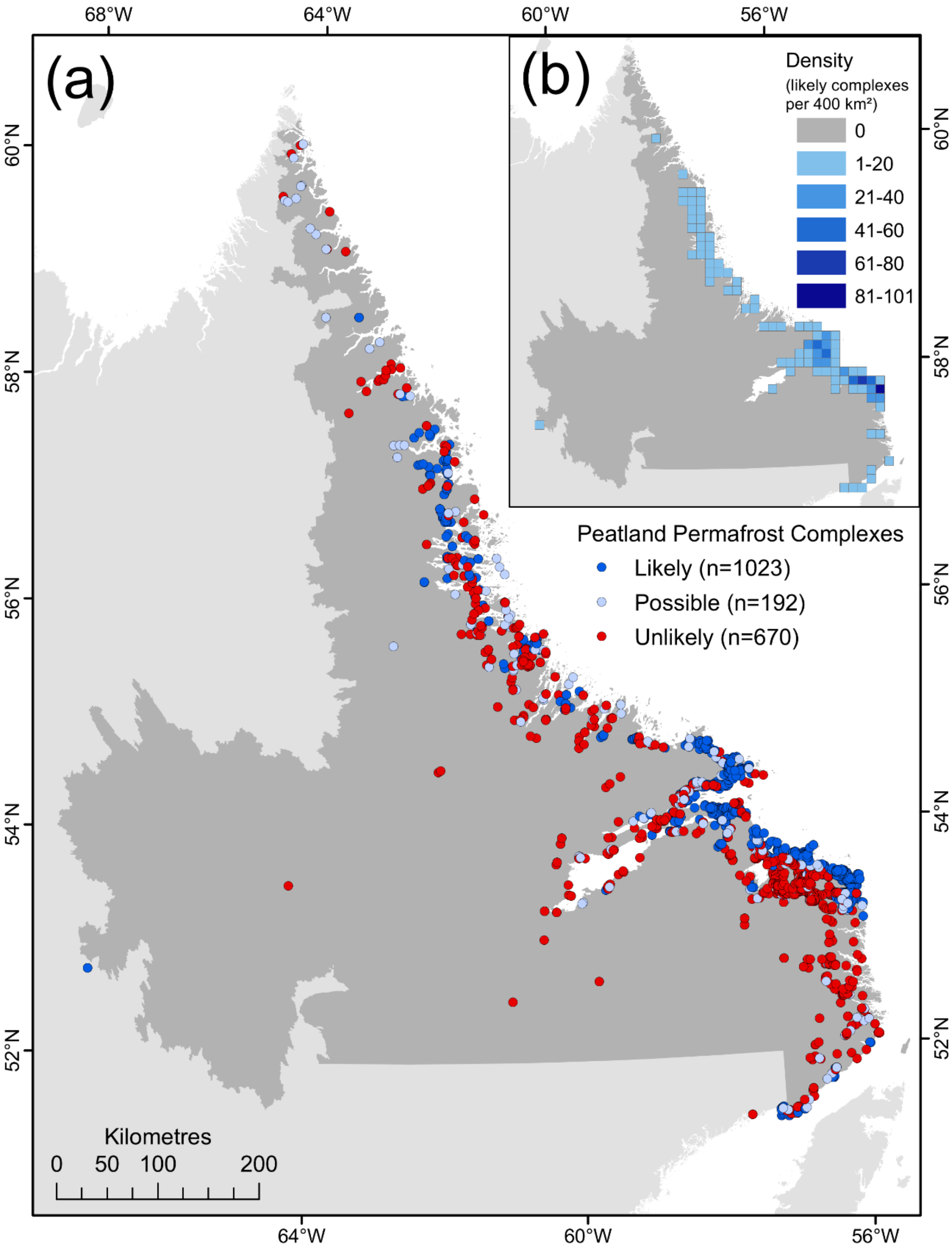

Figure 3. (a) Spatial distribution of inventoried peatland complexes (n=1885) classified as likely containing peatland permafrost landforms (n=1023), possibly containing peatland permafrost landforms (n=192), and unlikely to contain peatland permafrost landforms (n=670); (b) Number of wetlands of interest that are likely to contain peatland permafrost landforms within 20 by 20 km (400 km²) grid cells.

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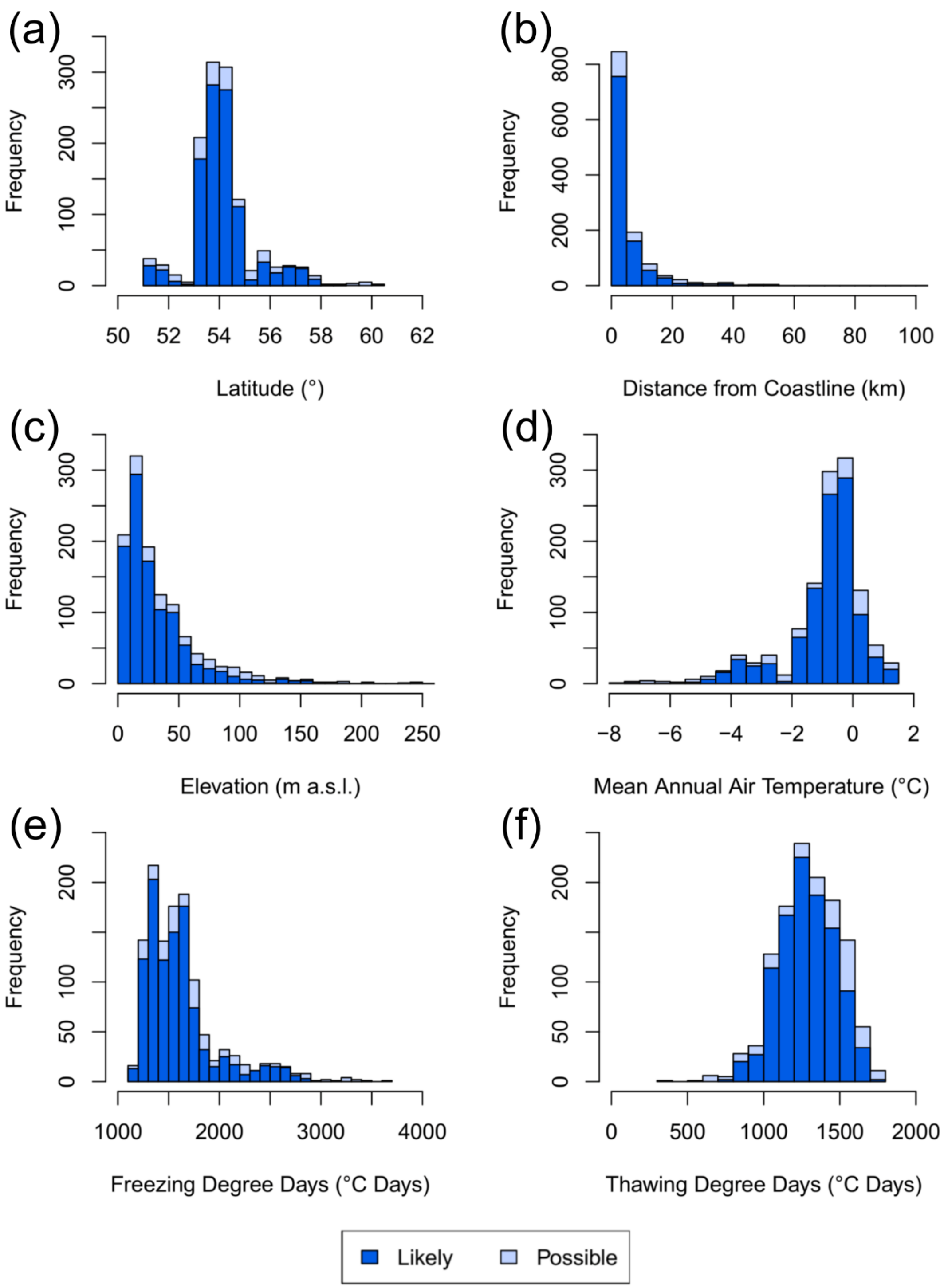

Figure 4. Distribution of wetland complexes likely or possibly containing peatland permafrost landforms by (a) latitude; (b) distance from the coastline; (c) elevation; and (d) mean annual air temperature; (e) mean annual freezing degree days; and (f) mean annual thawing degree days for the 1981 to 2010 climate normal.

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ANOVA and *post hoc* Tukey's HSD tests revealed that the mean distance from coastline, elevation, MAAT, FDD, and TDD were statistically different between the likely, possibly, and unlikely peatland permafrost complexes at the 95 % confidence level. When compared with the complexes that likely contained peatland permafrost, the 192 complexes that possibly contained peatland permafrost were similarly distributed all along the coastline but were skewed further north (mean latitude of 54.5° N) and extended as far as 60.2° N (Supplement Sect. S4). These less certain features were at greater distances from the coastline (mean distance from coast of 11.7 km) and at higher elevations (mean elevation of 68 m a.s.l.). The 670 complexes that were unlikely to contain peatland permafrost were well distributed between 51.4° N and 60.2° N (Figure 3) but were located further from the coastline (mean distance from coastline of 18.9 km), at higher elevations (mean elevation of 79 m a.s.l.), and at warmer MAATs (mean MAAT of -0.6 °C) than the complexes that likely or possibly contained peatland permafrost (Supplement Sect. S4).

5 Discussion

5.1 Distribution of peatland permafrost in Labrador

In this study, we demonstrated that peatland permafrost complexes in Labrador and portions of Quebec are concentrated in lowlands within 40 km of the Labrador Sea or Gulf of St. Lawrence coastline. A geographic gradient is especially apparent between Rigolet (54.2° N) and Black Tickle (53.5° N), where peatland permafrost complexes are abundant along the coast but generally absent farther inland. The higher density of peatland permafrost complexes along the coast could be linked to climatic factors like persistent fog and cloud cover leading to less incoming solar radiation (Way et al., 2018) or thinner and denser snowpacks (Seppälä, 1994; Vallée and Payette, 2007) in the wind-exposed barrens along the coast (Way et al., 2018). In Labrador, peatland permafrost was identified for a range of MAATs from -7.5 °C to +1.2 °C. This compares favourably with a previous study from the region, where palsas and peat plateaux were identified in five locations in southeastern Labrador with corresponding MAATs of up to +1.0 °C (Way et al., 2018). By contrast, the distribution of MAATs in peatland permafrost locations in Labrador is warmer than the upper MAAT thresholds of +0.4 °C and +0.2 °C that have been modelled for northern Finland, Norway, and Sweden (Parviainen and Luoto, 2007) and for the rest of Canada and Alaska (Fewster et al., 2020), respectively. Our results suggest that the upper MAAT threshold of +0.2 °C that is estimated for North America (Fewster et al., 2020) is too low for Labrador, due to the relict nature (Dionne, 1984) and predicted resilience (Way et al., 2018) of many peatland permafrost landforms. The large thermal offset that is typical of peatland permafrost (Burn and Smith, 1988; Williams and Smith, 1989) is expected to promote continued landform persistence under the context of a warming climate, leading to exceedance of existing MAAT-based thresholds.

As peatland permafrost landforms form from the epigenetic development of segregated ice, it would be expected that the regional distribution of fine-grained sediments and local depositional history would also play an important role in the landscape suitability of these complexes (O'Neill et al., 2019). We identified the largest clusters of peatland permafrost complexes in locations where post-glacial marine invasions had occurred, such as along the lowland-dominated coastline between Makkovik (55.0° N) and Black Tickle (53.5° N), where frost-susceptible, glaciomarine surficial materials are widespread (Fulton, 1989, 1995; Hagedorn, in press; Occhietti et al., 2011). Fewer peatland permafrost complexes were mapped between Makkovik (55.0° N) and Hopedale (55.5° N), where the elevated topography resulted in limited marine invasions and post-glacial marine deposition along the coast (Hagedorn, in press; Occhietti et al., 2011).

5.2 Implications for peatland permafrost and permafrost distribution in northeastern Canada

Comparisons between our inventory results and several recent national to global wetland, peatland (Supplement Sect. S5), and peatland permafrost distribution products (e.g., Fewster et al., 2020; Hugelius et al., 2020; Olefeldt et al., 2021) (Figure 5) provide compelling evidence that peatland permafrost along the Labrador coast has been poorly represented by existing datasets. Although these products can have inconsistencies with one another (Figure 5A-C), they do consistently model more abundant peatland permafrost in the continental interior and little to no peatland permafrost along much of the Labrador Sea and Gulf of St. Lawrence coastline. Model predictions showing more peatland permafrost in the interior compared to along the coast could reflect inaccurate assumptions on the climate limits of permafrost or may be due to a lack of field data from other northern coastal peatland permafrost environments (Borge et al., 2017). Inclusion of physiographic variables, like soil conditions and frost-susceptibility, and more detailed glacial depositional information is likely necessary for an improved representation of peatland permafrost in northern coastal regions. Recent work by O'Neill et al. (2019), for example, has demonstrated that segregated ice can be more reliably modelled along sections of the Labrador Sea coastline (Figure 5D) by incorporating paleogeographic variables like vegetation cover, surficial geology, and glacial lake and marine limits.

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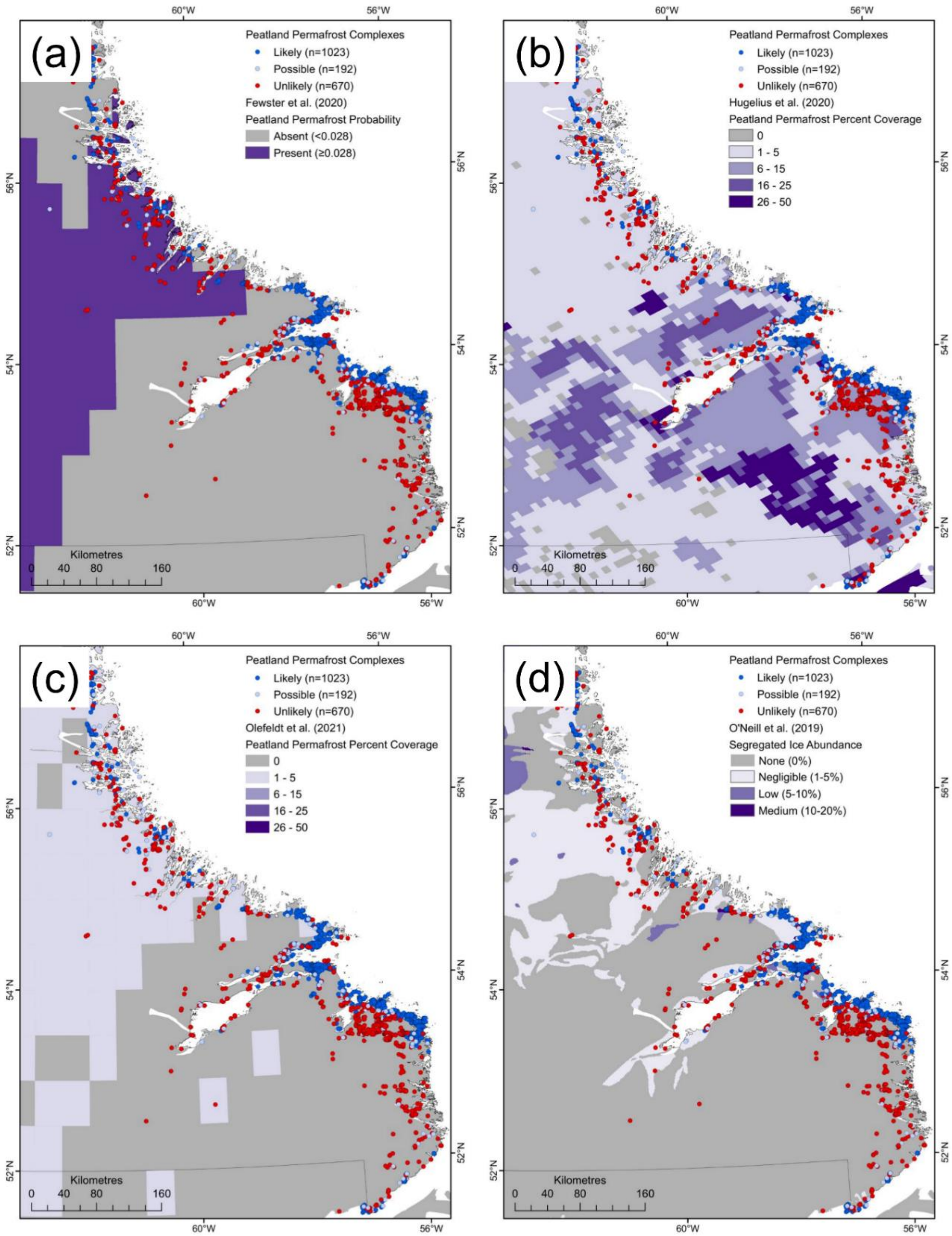

Figure 5. Comparison of inventoried peatland permafrost complexes with peatland permafrost presence and percent coverage as modelled by (a) Fewster et al. (2020); (b) Hugelius et al. (2020); and (c) Olefeldt et al. (2021) and with segregated ice content as modelled by (d) O'Neill et al. (2019).

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The results of our inventory also suggest that amendments to existing permafrost distribution maps may be required for coastal Labrador. For example, the highest density of peatland permafrost complexes along the Labrador Sea and Gulf of St. Lawrence coastline was found near the community of Black Tickle (53.5° N) (Figure 3B), which is currently classified in the isolated patches of permafrost zone on the Permafrost Map of Canada (Heginbottom et al., 1995) and the no permafrost zone on the 2000-2016 Northern Hemisphere Permafrost Map (Obu et al., 2019) (Supplement Sect. S6). The identification of large swaths of likely peatland permafrost complexes between Cartwright (53.7° N) and Black Tickle (53.5° N) suggest that the Permafrost Map of Canada's limit for the sporadic discontinuous zone along the Labrador coast could reasonably be extended south by ~110 km from its current position of ~53.7° N to ~53.1° N. This southerly extension of the sporadic discontinuous permafrost zone has previously been suggested by Allard and Seguin (1987) and Payette (2001), based on regional vegetation and geomorphology (Payette, 1983). Clusters of likely peatland permafrost complexes were also identified near the communities of Red Bay (Supplement Sect. S7) and Blanc-Sablon, which are respectively classified in the isolated patches and no permafrost zones on the Permafrost Map of Canada (Heginbottom et al., 1995) and in the no permafrost zone on the 2000-2016 Northern Hemisphere Permafrost Map (Obu et al., 2019) (Supplement Sect. S6). An extension of the southern limit of the Permafrost Map of Canada's isolated patches of permafrost zone by 15 km to include Blanc-Sablon may better reflect regional permafrost conditions, as permafrost has been previously detected in both mineral soils in the community and in surrounding peatlands (Dionne, 1984).

5.3 Challenges and limitations of point-based inventorying of peatland permafrost complexes in coastal Labrador

Differences in peatland permafrost landform size, shape, and vegetation coverage across a large, heterogeneous study area like Labrador (Beer et al., 2021) can lead to difficulties in feature mapping and identification, especially when performed by a single mapper. The inclusion of multiple mappers in the inventorying process facilitated the development of a large initial database that reduced the potential for omission of prospective WOIs. The consensus-based review process that followed was designed to minimize the inclusion of false positives in the final dataset of 1023 likely peatland permafrost complexes, but this conservative approach may have resulted in the exclusion of some complexes. The most challenging aspect of the inventorying process was interpreting WOIs containing small landforms in relatively isolated wetlands, while in the case of more obvious features, there were at times difficulties in determining distinct wetland boundaries. At the northern end of the study area, where other types of periglacial landforms become more common, misclassification of palsas and peat plateaux for other elevated landforms (i.e., lithalsas) may have contributed to the designation of a higher number of possible peatland permafrost complexes in certain subregions.

While grid-based approaches (Ramsdale et al., 2017) have been applied in peatland permafrost mapping studies in the Northwest Territories (Gibson et al., 2020, 2021) and parts of Norway (Borge et al., 2017), the point-based nature of our study allowed for the incorporation of dedicated, co-located field- and imagery-based validation information. Despite the high agreement during the review stage, reclassification of 34 WOIs following integration of field- and imagery-based validation

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information highlights the importance of ground-truthing in remote sensing- or modelling-based periglacial landform inventories. Owing to a lack of prior field-based assessments of permafrost conditions in Labrador, it was difficult to independently validate our peatland permafrost inventory results. However, a detailed aerial photograph- and field-based Ecological Land Classification (ELC) survey undertaken in the late 1970s did cover a subset of our study area in southeastern Labrador (Environment Canada, 1999). The ELC identified a total wetland area of 666 km² that contained peatland permafrost landforms (Figure 6). Mappers successfully identified likely peatland permafrost complexes in 21 out of the 24 ELC wetland polygons that were identified as containing palsas. Re-examination of the three remaining polygons revealed the presence of wetland complexes with irregular ponding patterns indicative of thermokarst development and elevated landforms that, due to their small size, would require in situ field visits for validation. Overall, the results of our inventory are in good agreement with previous overlapping field investigations and inventorying efforts from the ELC.

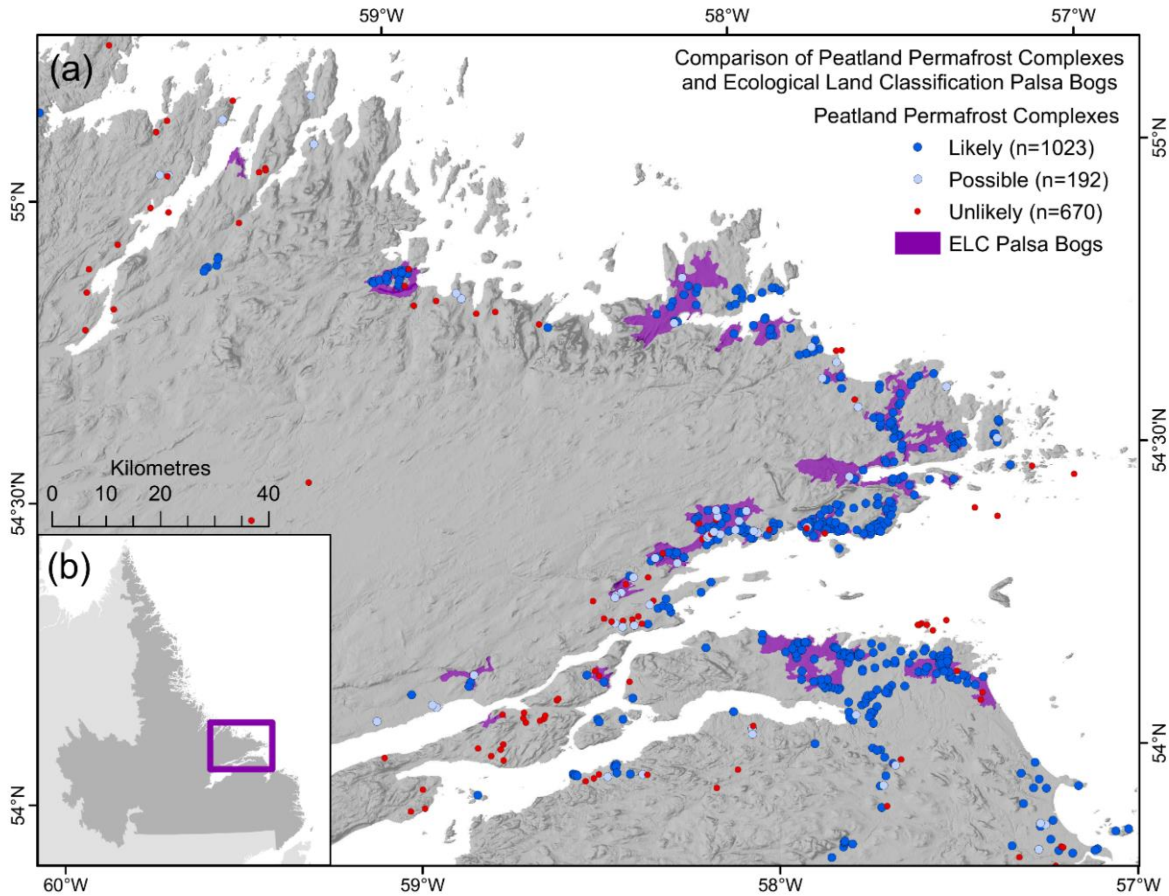

Figure 6. (a) Comparison of inventoried peatland permafrost complexes with palsa bog regions identified in the Ecological Land Classification (ELC) survey (Environment Canada, 1999); (b) Location of ELC palsa bogs in relation to Labrador.

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6 Conclusion

This study provides the first detailed inventory of peatland permafrost landforms along the understudied Labrador Sea and Gulf of St. Lawrence coastline. Using high-resolution satellite imagery and extensive field- and imagery-based validation efforts, we applied a multi-stage, consensus-based inventorying approach to identify a total of 1885 wetlands of interest, 1023 of which were classified as likely to contain peatland permafrost landforms. Likely peatland permafrost complexes were primarily found in coastal, lowland locations spanning from 51.4° N to 58.6° N, with the largest clusters occurring just south of the limit of sporadic discontinuous permafrost in northeastern Canada (Heginbottom et al., 1995).

Comparisons between our inventory results and existing wetland, peatland, and peatland permafrost distribution products reveal major discrepancies in prior estimates of peatland permafrost in Labrador with implications for ground ice content (O'Neill et al., 2019), thermokarst potential (Olefeldt et al., 2016), and carbon content (Hugelius et al., 2014). Our results highlight the importance of field-based validation for periglacial landform mapping and modelling, particularly when mapping small, dynamic features like palsas and peat plateaux, and of considering physiography and geomorphology in accurate representations of peatland permafrost in larger scale spatial products. This study provides an important baseline for future peatland permafrost mapping and modelling efforts along the Labrador Sea coastline and will support local to regional infrastructure and climate change adaptation strategy development. The significant underestimation of peatland permafrost along the Labrador Sea and Gulf of St. Lawrence coastline identified in this study should inform future regional to global permafrost, peatland permafrost, and carbon content mapping efforts for Labrador and other northern coastal locations.

Data availability. Likely and possible peatland permafrost locations from the coastal Labrador peatland permafrost complex inventory are available for download from Nordicana D (Wang et al., 2022).

Author contribution. YW and RW designed the study and drafted the manuscript. YW led the raw data collection and the data analysis. RW contributed to raw data collection and data analysis and was the PI for the NSERC Discovery Grant supporting peatland permafrost research activities in Labrador. JB contributed to raw data collection and data analysis. AF and RT contributed to raw data collection. MP coordinated the collection of helicopter video footage. JB, AF, RT, and MP reviewed and contributed edits to the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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