Long-term climate-influenced land cover change in discontinuous permafrost peatland complexes

Olivia Carpino[1*], Kristine Haynes[1], Ryan Connon[2], James Craig[3], Élise Devoie[3] and William Quinton[1]

[1]*Cold Regions Research Centre, Wilfrid Laurier University, Waterloo, Ontario, N2L 3C5, CANADA*
[2]*Environment and Natural Resources, Government of the Northwest Territories, Yellowknife, Northwest Territories, X1A 2L9, CANADA*
[3]*Department of Civil and Environmental Engineering, University of Waterloo, Waterloo, Ontario, N2L 3G1, CANADA*
**Corresponding author contact information: ocarpino@wlu.ca (519-884-1970)*

Abstract

The discontinuous permafrost zone is undergoing rapid transformation as a result of unprecedented permafrost thaw brought on by circumpolar climate warming. Rapid warming over recent decades has significantly decreased the area underlain by permafrost in peatland complexes. It has catalyzed extensive landscape transitions in the Taiga Plains of northwestern Canada, transforming forest-dominated landscapes to those that are wetland-dominated. However, the advanced stages of this landscape transition, and the hydrological and thermal mechanisms and feedbacks governing these environments, are unclear. This study explores the current trajectory of land cover change across a 300,000 km^2 region of northwestern Canada's discontinuous permafrost zone by presenting a north-south space-for-time substitution that capitalizes on the region's 600 km latitudinal span. We combine extensive geomatics data across the Taiga Plains with ground-based hydrometeorological measurements collected in the Scotty Creek basin, Northwest Territories, Canada, which is located in the medial latitudes of the Taiga Plains and is undergoing rapid landscape change. This data is used to inform a new conceptual framework of landscape evolution that accounts for the observed patterns of permafrost thaw-induced land cover change, and provides a basis for predicting future changes. Permafrost thaw-induced changes in hydrology promote partial drainage and drying of collapse scar wetlands, leading to areas of afforestation forming treed wetlands without underlying permafrost. Across the north-south latitudinal gradient spanning the Taiga Plains, relatively undisturbed forested plateau-wetland complexes dominate the region's higher latitudes, forest-wetland patchworks are most prevalent at the medial latitudes, and forested peatlands are increasingly present across lower latitudes. This trend reflects the progression of wetland transition occurring locally in the plateau-wetland complexes of the Scotty Creek basin and informs our understanding of the anticipated trajectory of change in the discontinuous permafrost zone.

Keywords: discontinuous permafrost zone; Taiga Plains; peatland; climate change; boreal forest; hydrology; energy dynamics

Key Points

1. Conceptual framework developed to understand the trajectory of permafrost thaw-induced land cover change
2. Permafrost thaw-induced land cover change varies latitudinally across the plateau-wetland complexes of the discontinuous permafrost zone
3. Partial wetland drainage triggers ecohydrological and thermal feedbacks that promote reforestation after full permafrost thaw

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1. Introduction

Northwestern Canada is one of the most rapidly warming regions on Earth (Vincent *et al.,* 2015; Box *et al.,* 2019) and it is transitioning to a warmer state at a rate that appears to have no analogue in the historical record (Porter *et al.,* 2019). This transition includes region-wide thaw and disappearance of permafrost at unprecedented rates (Rowland *et al.,* 2010). The Taiga Plains ecoregion of northwestern Canada extends from 55º to 68º N and as such, encompasses the spectrum of permafrost cover, from continuous to sporadic. Permafrost thaw in the Taiga Plains ecoregion is especially pronounced in its lower latitudes where the permafrost is relatively thin and warm, often already at the thaw-point temperature (Biskaborn *et al.,* 2019), indicating a state of disequilibrium with the current climate (Helbig *et al.,* 2016a). For example, Kwong & Gan (1994) repeated the permafrost surveys of Brown (1964) in northern Alberta and the southern Northwest Territories (NWT) and found that the southern limit of permafrost occurrence had migrated northward by about 120 km over a period of 26 years. Beilman & Robinson (2003) estimated that 30-65% of the permafrost has disappeared from the southern Taiga Plains in the preceding 150 years, most of which disappeared in the latter 50 years. The accelerated rates of permafrost warming and thaw observed in recent decades throughout the circumpolar region (Biskaborn *et al.,* 2019), including all of northwestern Canada (Kokelj *et al.,* 2017; Holloway & Lewkowiz 2019), have dramatically transformed land covers in the southern Taiga Plains (Chasmer & Hopkinson, 2017).

Much of the southern Taiga Plains is occupied by peatland-dominated lowlands, a landscape of raised, black spruce (*Picea mariana*) tree-covered peat plateaus overlying thin (<10 m), ice-rich permafrost interspersed with permafrost-free, treeless wetlands. These permafrost-free wetlands are predominantly classified as channel fens and collapse scar wetlands, the latter

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While permafrost (*i.e.* perennially cryotic ground) underlies 16% of the Earth's land surface (Tarnocai 2009), it is estimated that 80% of the world's boreal forest lies within this circumpolar permafrost zone (Helbig et al. 2016a). In the southern extensive discontinuous and sporadic discontinuous permafrost zones in the Taiga Plains ecoregion of northwestern Canada, permafrost is preferentially located in low-lying,

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of which is developed from thermokarst erosion of the plateaus (Robinson & Moore, 2000). Peat plateaus and collapse scar wetlands are typically arranged into distinct "plateau-wetland complexes," which are separated by channel fens. Each of these major land cover types in the lowlands of the southern Taiga Plains, have contrasting hydrological functions (Hayshi *et al.*, 2004) and therefore changes to their relative proportions on the landscape can affect water flux and storage at the basin scale (Quinton *et al.*, 2011). Permafrost thaw underlying plateaus is driven by horizontal conduction and advection from adjacent wetlands, and vertical heat flows from the ground surface (Walvoord & Kurylyk, 2016). As this permafrost thaws, the overlying plateau ground surface subsides and is engulfed by the surrounding wetlands (Beilman *et al.*, 2001; Quinton *et al.*, 2011; Helbig *et al.*, 2016a). As such, permafrost thaw in this environment transforms forests to treeless, permafrost-free wetlands (Robinson & Moore, 2000). In the process, this also changes the hydrological function of the transformed land cover, in part due to a change in surface water-groundwater interactions (McKenzie & Voss 2013). Such a transformation can profoundly affect local drainage processes and pathways (Connon *et al.*, 2014; 2015) with implications to regional hydrology (St. Jacques & Sauchyn, 2009; Korosi *et al.*, 2017; Connon *et al.*, 2018), ecology (Beilman, 2001) biogeochemical processes (Gordon *et al.*, 2016) and carbon cycling (Vonk *et al.*, 2019; Helbig *et al.*, 2016a).

Zoltai (1993) described a perpetual cycle of permafrost development and thaw in which permafrost evolves from perennial ice bulbs that form below *Sphagnum* hummocks in permafrost-free treeless wetlands (*i.e.* collapse scars). Such hummocks expand and coalesce eventually forming tree-covered plateaus. However, over time plateaus experience a disturbance (*e.g.* fire, disease) that initiates the development of collapse scars and as a result, the plateau or portions of it revert to a permafrost-free wetland. In a stable climate, the permafrost and permafrost-free fractions of a landscape are assumed to remain relatively consistent. Zoltai

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Deleted: and degradation, particularly when vegetation is disturbed by anthropogenic (Smith et al. 2008; Smith & Riseborough 2010) or natural (*e.g.* fire) causes (Gibson et al. 2018). Further north, permafrost in the extensive discontinuous zone is warming, but has not been documented to reach the temperatures found further south (Smith et al. 2005). While the northern portion of extensive discontinuous permafrost is not as immediately vulnerable to the thaw and degradation widely documented across the southern discontinuous zones, the conditions that occur there may provide insight into the future conditions of northern environments as pan-Arctic warming continues. ¶
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(1993) estimated that the time required to complete this cycle is approximately 600 years. Treat and Jones (2018) indicated time scales for forest recovery following permafrost thaw in the range of 450 to 1500 years. However, there is growing evidence throughout the southern Taiga Plains that the climate warming of recent decades has disrupted the cycle of permafrost thaw and redevelopment such that the rates of permafrost loss greatly exceed those of permafrost development (*e.g.* Halsey *et al.,* 1995; Robinson & Moore, 2002; Quinton *et al.,* 2011).

The accelerated rates of permafrost thaw and resulting land cover change described above call into question the utility of existing concepts (*e.g.* Zoltai, 1993) as a means to estimate the current trajectory of land cover change since such concepts were developed from analyses of geological sediments (*e.g.* peat cores) which generally lack the resolution needed to identify land cover change sequences over relatively short (*i.e.* decadal) periods. Moreover, it is uncertain whether the current rates of climate warming are represented in the sediment record. As a result, there remains considerable uncertainty on the trajectory of permafrost thaw-induced land cover change in this region, including possible end-members and intermediate stages. Because of the close connection between land cover type and hydrological function in this region, the uncertainty related to possible land cover change trajectories also raises new uncertainties in regards to the region's water resources.

In addition to unprecedented climate warming in the North, accelerated permafrost thaw is also driven by positive feedbacks including increased fragmentation of forested peat plateaus with increasing thaw (Chasmer *et al.,* 2011), a process which increases the length of interface between permafrost and permafrost-free terrain, and therefore also increases the overall flux of energy into the remaining permafrost bodies (Kurylyk *et al.,* 2016). Connon *et al.,* (2018) demonstrated that talik layers situated between the active layer and underlying permafrost are

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widespread in thawing peatland-dominated terrains and their occurrence increases with increasing permafrost thaw. Devoie *et al.,* (2019) demonstrated that once a talik forms, the rate of permafrost thaw can increase 10-fold.

Since the permafrost table beneath peat plateaus rises above the water surface of the adjacent wetlands, plateaus function as "permafrost dams" that prevent wetlands from draining. Permafrost thaw therefore removes this effect and enables previously impounded wetlands to partially drain until the hydraulic gradient driving their partial drainage reaches an equilibrium state (Haynes *et al.,* 2020). The slow release of water from the long-term storage of wetlands no longer impounded by permafrost changes the physical and ecological characteristics and hydrological function of these wetlands (Haynes *et al.,* 2020). Such drainage transforms the uniformly wet *Sphagnum* lawns that characterise impounded wetlands, into hummocky surfaces that provide a wider range of near surface moisture conditions including those sufficiently dry to support the re-growth of trees (Haynes *et al.,* 2020). There is also evidence that when black spruce forest is lost due to permafrost thaw and plateau inundation, forest regeneration does not depend on the regeneration of permafrost (Haynes *et al.,* 2020; Chasmer & Hopkinson 2017). For example, treeless collapse scars have transformed into black spruce forest within two to three decades after the permafrost dams disappear (Haynes *et al.,* 2018).

In addition to the transient drainage process described above that may occur following the removal of the impounding permafrost (Haynes *et al.,* 2018), such removal also increases the hydrological connectivity of basins through the incorporation of wetlands that were previously impounded and therefore hydrologically isolated from the basin drainage network (Connon *et al.,* 2015). This process of "wetland capture" expands the runoff contributing areas of basins, a process that increases their runoff potential. Connon *et al.,* (2018) attributed the trends of

increasing runoff ratio (*i.e.* fraction of basin runoff per unit input of precipitation) in basins throughout the Taiga Plains to this permafrost thaw-induced process of runoff contributing area expansion.

The transition of one type of ground cover to another as a result of permafrost thaw or a subsequent process such as partial wetland drainage and re-establishment of forest also results in a change of surface energy balance (Kurylyk *et al.*, 2016; Devoie *et al.*, 2019). Insight into the nature of such changes can be obtained through comparing the energy regimes of the existing suite of land covers including the end-members of land cover change. For example, the incoming solar radiation measured at a height of 2 m above the ground surface is highest in the treeless wetlands and lowest in areas of peat plateaus with dense forest (Haynes *et al.*, 2019). The average shortwave radiation flux density of treeless wetlands is approximately twice of that measured below dense forest (Haynes *et al.*, 2019). Plateau areas with moderate or sparse tree canopies have incoming solar radiation values intermediate between these two end members (Chasmer *et al.*, 2011). The ground surface albedo varies over the narrow range of 0.15 to 0.19 (Hayashi *et al.*, 2007) among the ground surface types discussed here, the exception being the late snowmelt period while plateau ground surfaces are still snow covered and the treeless wetlands are snow-free (Disher *et al.*, 2021; Connon *et al.*, Submitted).

The nature of changes to a land cover's surface energy balance is governed by the properties of its subsurface, ground surface, and the overlying tree canopy, all of which change as one land cover type transitions to another (Helbig *et al.*, 2016b). The reduction in the areal cover of forested plateaus and concomitant increase in the coverage of treeless wetlands indicates that in the first instance, permafrost thaw increases the incoming shortwave flux to the transformed land cover (Kurylyk *et al.*, 2016; Devoie *et al.*, 2019). Chasmer *et al.*, (2011) found

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that this thaw-induced transition and associated increase of incoming shortwave radiation occurs over several years as tree mortality decreases the density of tree canopies. However, the forests that subsequently re-establish in partially drained wetlands may have an energy balance that shares some characteristics of the forested peat plateaus, where insolation is relatively low, and the low albedo (and therefore high energy adsorption) of trunks, branches and stems result in relatively high long-wave and sensible heat compared to the treeless wetland surfaces (Helbig *et al.*, 2016b).

Unprecedented climate warming and the feedbacks to thaw and land cover change are new factors not accounted for in current theories on permafrost degradation-aggregation cycles based on the analysis of peat cores. As a result, the time scales for land cover transformations derived from such theories cannot account for the current rates and patterns of all thaw-induced land cover change. This study examines peat plateau-wetland complexes along a latitudinal gradient through the Taiga Plains to improve the understanding of permafrost thaw-driven land cover change in this region as well as to advance the ability to predict land cover changes over the coming decades. This overall objective will be accomplished by: (1) delineating the current extent of peatlands and forest distribution along the latitudinal span of discontinuous permafrost; (2) characterising the end-members and intervening stages of land cover transition; (3) providing an interpretation of the hydrological and ground surface energy balance regimes for each stage of land cover transition based on twenty years of field studies at the Scotty Creek Research Station; and (4) presenting a conceptual framework of peatland transition during and following permafrost thaw.

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2. Study Site

2.1 The Taiga Plains Ecozone

Much of northwestern Canada's boreal region is located within the discontinuous permafrost zone, which ranges latitudinally from extensive-discontinuous (50-90% areal permafrost coverage) in the north to sporadic-discontinuous (10-50%) in the south. Within this region, the Taiga Plains ecozone contains a patchwork of mineral and organic terrain. This study examines the peat plateau-collapse scar wetland complexes that dominate the lowlands of this ecoregion (Wright *et al.*, 2009; Helbig *et al.*, 2016a). While air temperature is the predominant control on permafrost, relatively dry peat at the ground surface can allow permafrost to exist where mean annual air temperatures (MAATs) are at or even above 0°C due to thermal insulation (Vitt *et al.*, 1994; Camill & Clark 1998). Permafrost is therefore largely restricted to below peat plateaus since only these features contain unsaturated layers sufficiently developed to insulate permafrost (Zoltai & Tarnocai 1975; Hayashi *et al.*, 2004; Quinton *et al.*, 2009). The areal coverage of permafrost in the discontinuous zone has significantly decreased in recent decades due to increasing MAATs and has resulted in a shift towards more wetland-dominated landscapes (Thie, 1974; Robinson & Moore, 2000; Wright *et al.*, 2009; Quinton *et al.*, 2011; Olefeldt *et al.*, 2016).

The discontinuous permafrost zone of the Taiga Plains ecozone covers 312,000 km^2 and, for the purposes of this study, is divided into the areas of extensive-discontinuous permafrost (151,000 km^2) and sporadic-discontinuous permafrost (161,000 km^2) (Brown *et al.*, 2002; Figure 1). The Taiga Plains, bounded by the Taiga Cordillera to the west and Taiga Shield to the east, has a dry continental climate with short summers and long, cold winters with MAATs ranging from -5.5°C to -1.5°C (Vincent *et al.*, 2012). MAATs have increased across the Taiga Plains

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over the past 50 years (1970 – 2019) (Vincent *et al.*, 2012) in a manner consistent with panarctic warming (Overland *et al.*, 2019). This is largely due to increases in average winter and spring temperatures of approximately 3°C over this period (Vincent *et al.*, 2012). However, there has been no consistent trend in mean annual precipitation over this period in the Taiga Plains (Mekis & Vincent, 2011).

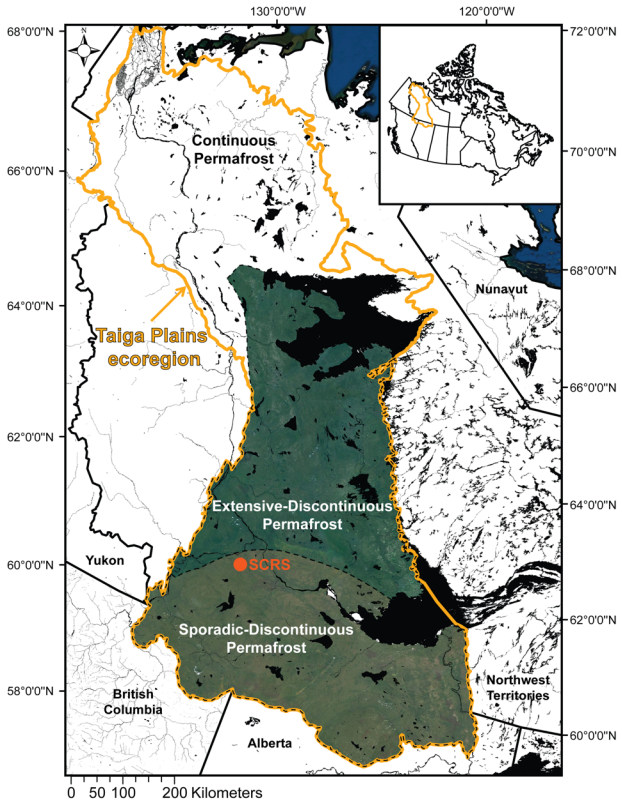

Figure 1: The Taiga Plains ecoregion with the discontinuous permafrost zones (coloured) defining the study region (Brown *et al.*, 2002). The location of Scotty Creek Research Station (SCRS) is also indicated. Contains information licensed under the Open Government Licence – Canada.

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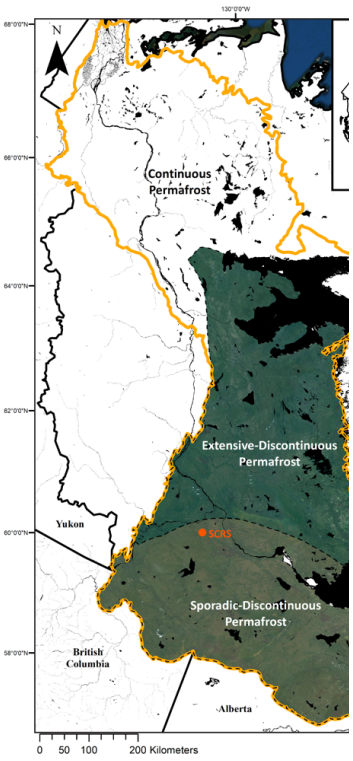

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2.2 Scotty Creek, Northwest Territories

Scotty Creek (61.3°N, 121.3°W) has been the focus of field studies and monitoring since the mid-1990s and as such, the long-term and detailed data archive at Scotty Creek (Haynes *et al.*, 2019) provide a unique opportunity to evaluate land cover changes over a period that coincides with rapid climate warming. Scotty Creek therefore also provides a reference to interpret land cover changes for terrains that are also present throughout the region. Scotty Creek is located approximately 50 km south of Fort Simpson, Northwest Territories (Figure 1) where the MAAT (1970-2015) is -2.6°C and the mean annual precipitation (1970-2015) is 400 mm, of which 150 mm falls as snow (Environment and Climate Change Canada, 2019). Data collected by Environment and Climate Change Canada at the Fort Simpson A climate station show that MAAT has increased by approximately 0.05°C/year since 1950, with warming most pronounced during the winter. Scotty Creek drains a 152 km^2 area dominated by peatlands with peat accumulations ranging between 2 and 8 m overlying a clay and silt rich glacial till (McClymont *et al.*, 2013). The Scotty Creek drainage basin occupies one of many peatland-dominated lowlands of the Taiga Plains, and as such its landscape is dominated by complexes containing tree-covered peat plateaus overlying permafrost alongside treeless and permafrost free collapse scar wetlands. Such plateau-wetland complexes are separated by channel fens that collectively function as the basin drainage network (Hayashi *et al.*, 2004; Quinton *et al.*, 2009). This type of land cover not only dominates the lowlands of the Taiga Plains but is also found extensively throughout northwestern Canada and across the circumpolar subarctic (Olefeldt *et al.*, 2016).

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3. Methods

3.1 Geomatics Methods

To place Scotty Creek into a regional context, geomatics methods were applied to both zones of discontinuous permafrost within the Taiga Plains to quantify the areas occupied by each of the major land covers of all areas identified as peatland-dominated lowland. Multispectral Landsat 8 imagery (30 m resolution; Figure 2a) was acquired across an area of over 300,000 km^2 totalling 70 Landsat scenes. Of these, 59 scenes were used to construct the base of the mosaic and 11 were used as secondary data to patch and minimize cloud cover. The 59 primary scenes were acquired in 2017 and 2018 while the 11 secondary scenes were acquired between 2013 and 2016 as data of suitable quality was unavailable during the preferred time period. Acquiring imagery during the snow-free season was prioritized and as such, all 70 Landsat tiles were acquired in June, July, or August, rendering the coniferous forest cover seasonally comparable and allowing for a more streamlined mosaicking process. A colour infrared mosaic (Landsat 8 bands 5, 4, 3 displayed as R, G, B; Figure 2b) was created across the study region in ArcGIS (ESRI, Redlands, California) using a Lambert Conformal Conic projection. The mosaic dataset was colour balanced and the boundary was amended to the Taiga Plains ecozone including the delineations dividing the sporadic and extensive discontinuous zones (Brown *et al.*, 2002).

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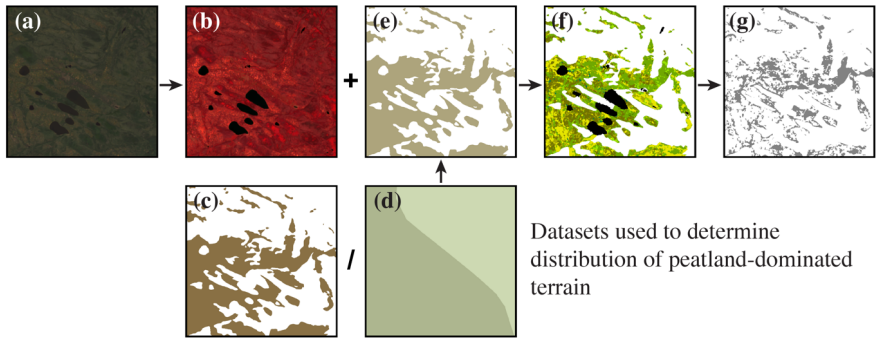

Figure 2: A summary of the regional geomatics methods used over a 2 km x 2 km sample area. Two main workflows are highlighted: the datasets used to map probable peatland-dominated terrain and the methods used to determine fractional forested area within those peatland-dominated areas. (a) Multispectral Landsat 8 imagery; (b) false-colour infrared Landsat 8 imagery; (c) Natural Resources Canada saturated soils dataset; (d) Northern Circumpolar Soil Carbon Database (NCSCD) fractional area of organic soils; (e) probable peatland-dominated terrain; (f) unsupervised classification identifying land covers within peatland-dominated terrain; (g) coniferous forest cover within peatland-dominated terrain.

To determine the current distribution of the peatland-dominated lowlands that contain the same type of terrain as observed at Scotty Creek (*i.e.* plateau-wetland complexes separated by channel fens), two complementary products were used in the ArcGIS suite of programs. First, a Natural Resources Canada saturated soils dataset (Figure 2c; Natural Resources Canada 2017) was selected to isolate areas that were wetland-dominated and likely representative of the plateau-wetland complexes targeted in this study. Next, the Northern Circumpolar Soil Carbon Database (NCSCD) (Figure 2d; Bolin Centre for Climate Research 2013) was selected to determine whether the highlighted wetland-dominated areas are also likely to represent peatland-dominated areas.

The saturated soils dataset is part of a larger digital cartographical project of Natural Resources Canada, CanVec. The CanVec dataset is a vector format dataset, which can be

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downloaded by province/territory or Canada-wide and includes over 60 features organized into 8 themes, including land features. Land features in this dataset, such as the distribution of saturated soils, were originally digitized at a scale of 1:50000 (Natural Resources Canada 2017). The NCSCD is also a polygon database developed by the Bolin Centre for Climate Research through synthesizing data from numerous regional and national soil maps alongside field-data collected across Canada, USA, Russia, and the European Union. The NCSCD includes data on the fractional coverage of different soil types and stored soil organic carbon (Hugelius *et al.,* 2013a; Hugelius *et al.,* 2013b). In the present study, the layer containing information on the fractional coverage of soil types was used. While the original format of the NCSCD is a vector of delineated zones, gridded data is also available at resolutions varying from 0.012° to 1° (Hugelius *et al.,* 2013b). The NCSCD is comprised of a circumarctic dataset as well as country-wide and regional datasets, including one of Canada (Hugelius *et al.,* 2013b).

The NCSCD is a widely used dataset (Olefeldt *et al.,* 2014; Gibson *et al.,* 2018; Stofferahn *et al.,* 2019; etc.) but the zones do not map specific locations of peatland-dominated terrain (Figure 2d). The locations of peatlands is helpful for work in regions such as the Taiga Plains, where the landscape is a patchwork of both organic and mineral terrain. The saturated soils dataset and the NCSCD were then both masked to the Taiga Plains boundaries in ArcGIS, where over 26,000 saturated soil polygons and 572 NCSCD zones were contained within the study region. The saturated soils dataset was mapped to display probable peatland terrain across the study region (Figure 2c). The areas of each saturated soil polygon were calculated alongside the areas for each NCSCD zone using the boundaries in the dataset. As the fractional coverage product from the NCSCD was used in this study, the fractional area of probable peatland terrain within the same NCSCD zone was calculated. The fractional areas of organic soils reported in

the NCSCD were then compared to the fractional areas of probable peatland terrain from the saturated soils dataset within the same NCSCD zone boundary (Figure 2e).

The Landsat mosaic dataset (Figure 2b) was then combined with the resultant product displaying peatland terrain (Figure 2e). An unsupervised land cover classification was subsequently completed on the Landsat mosaic across the areas identified by the saturated soils and NCSCD datasets to identify and classify the land covers within these peat plateau-wetland complexes (Figure 2f). The first iteration of the unsupervised classification (Iso Cluster classification approach) targeted 50-75 classes (72 created). The original 72 classes were then aggregated into 12 final classes within the peatland terrain outlined across the Taiga Plains study region. The final 12 aggregated classes include: coniferous (dense and sparse), mixed (dense and sparse), and broad leaf forests stands (dense and sparse), collapse scar, fen, open water, bare ground, cloud, and cloud shadow.

Forested peatlands are particularly indicative of landscape change in this region (Quinton *et al.*, 2010; Baltzer *et al.*, 2014; Chasmer & Hopkinson 2017) and as such, identifying the forested areas within the already identified peatland-dominated terrain was the focus of the Landsat classification. Specifically, the proportion of coniferous forested area within the total peatland area was quantified across the region's latitudinal span (Figure 2g). Fractional coniferous forested area was selected rather than total forested area to account for the observed spatial differences in peatland distribution across the Taiga Plains. For each degree of latitude, a bin was created for fractional forested area and the median was calculated alongside upper (*i.e.* 75th percentile) and lower (*i.e.* 25th percentile) quartiles. This data was plotted as a function of latitude across the Taiga Plains ecozone. This generated a dataset of forest cover across the

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peatland-dominated regions of interest that was subsequently complemented by field data collected in the Scotty Creek basin to guide the proposed conceptual framework.

3.2 Scotty Creek Imagery

To help capture examples of the stages of the transitioning landscape, imagery was collected using a Remotely Piloted Aircraft System (RPAS) across the Scotty Creek basin to represent how each of these illustrated trajectory stages manifests on the landscape in a peat plateau and collapse scar wetland-dominated environment. The RPAS imagery (0.5 m resolution) was collected in the summer of 2018 using an eBee Plus equipped with a senseFly SODA 3D mapping camera and all image processing was completed in Pix4DMapper.

Imagery for Scotty Creek, including aerial photographs from 1947, 1970, and 1977, IKONOS satellite imagery from 2000, and Worldview satellite imagery from 2010 and 2018 were used to quantify the area occupied by peat plateaus, collapse scar wetlands and channel fens in each of these years. The aerial photographs (0.5-1.2 m resolution) and IKONOS imagery (4 m resolution) were previously classified and the results were presented in Quinton *et al.,* (2011). Carpino *et al.,* (2018) completed the land cover classifications for the 2010 Worldview imagery and Disher (2020) classified the 2018 Worldview imagery. Collectively, these images document the land cover change at the Scotty Creek basin over the period 1947 to 2018.

3.3 Hydrological Data

A comprehensive archive of hydrometeorological measurements was used in this study to examine the temporal variation in hydrological characteristics as land cover transition from one stage to another. The form and hydrological function of the major land cover types of permafrost plateau, collapse scar, and channel fen are well understood from numerous studies at Scotty Creek since the 1990s (Quinton *et al.,* 2019). Field studies and monitoring at Scotty Creek over

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<#>Intensive field studies first began at Scotty Creek in the 1990s with he goal of better understanding northern peatland landscapes (Quinton :t al. 2019). A comprehensive archive of ground-based energy and vater measurements was used in this study to examine the temporal ariation in landscape characteristics at Scotty Creek. These neasurements helped to inform a conceptual model that imultaneously describe both the evolution of peat plateau-collapse car wetland complexes subject to a warming climate and also the andscape transition from north-to-south across the latitudinal and limatic gradient of this study. With each transitional stage of ermafrost thaw-induced landcover change occurring in localized areas hroughout the Scotty Creek basin and its location near the mid-latitude f the discontinuous permafrost zone, the conceptual model developed sing SCRS data also intends to act as a microcosm of the broader andscape change occurring across the Taiga Plains. ¶
<#>Field research at Scotty Creek has improved the nderstanding of plateau-wetland complexes that not only lominate the headwaters of the Scotty Creek watershed but also nuch of the Taiga Plains ecoregion (Quinton et al.

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Table 1: Annual precipitation (2008-2019), runoff (1996-2017), evapotranspiration (2013-2016), and residual storage values are presented (mm year^{-1}) for two distinct transitional landscape stages at Scotty Creek: a landscape dominated by forest and a patchwork landscape of near-equal forest and treeless wetland landcovers. Both of these landscapes represent transitional stages that Scotty Creek has ... [15]

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this period have also provided firsthand accounts of how permafrost thaw changes land covers (Quinton *et al.*, 2019). In the present study, we examined how runoff, evapotranspiration, and water storage are affected as land cover changes. In addition, we examined the precipitation data collected from 2008 to 2019 (Geonor, Model T200B) in relation to the three hydrological components listed above to gain insights into how changes in land cover affect the water balance for each stage in the land cover transition. These stages will be presented in detail in section 4.2. The Geonor precipitation data include both rain and snow measurements logged at 30 minute intervals (Table 1). Monitoring of discharge from Scotty Creek by the Water Survey of Canada began in 1996. For this study, annual basin runoff (mm $year^{-1}$) between 1996 and 2015 was calculated and used in the basin runoff component of the conceptual framework (Table 1) (Connon *et al.,* 2014; Haynes *et al.,* 2018). Given that this period of discharge monitoring coincided with a period of considerable climate warming and documented land cover change at Scotty Creek, the trend in calculated runoff over the period of record reflects a shift from a permafrost plateau-dominated landscape to one increasingly influenced by hydrologically-connected wetlands. Therefore, the temporal trend of runoff from the Scotty Creek basin is driven by permafrost thaw-induced land cover change (Connon *et al.,* 2014; Haynes *et al.,* 2018).

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Table 1: Annual precipitation (2008-2019), basin runoff (1996-2015; Connon *et al.,* 2014; Haynes *et al.,* 2018), evapotranspiration (2013-2016; Warren *et al.,* 2018), and residual storage values are presented (mm year^{-1}) for two distinct transitional landscape stages at Scotty Creek: a landscape dominated by forest and a patchwork landscape of near-equal forest and treeless wetland land covers.

	FOREST > WETLAND	FOREST ≈ WETLAND
PRECIPITATION	493	493
RUNOFF	149	215
EVAPOTRANSPIRATION	206	255
RESIDUAL STORAGE	138	23

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Recent work by Warren *et al.,* (2018) examined evapotranspiration (ET) for forests, wetlands, and the integrated landscape within the Scotty Creek watershed between 2013 and 2016. Daily ET values (mm day^{-1}) reported by Warren *et al.,* (2018) were converted to annual ET (mm year^{-1}) for the purpose of the conceptual framework water balance in the present work (Table 1). The different land covers monitored by Warren *et al.,* (2018) are representative of the land cover end-members identified in our conceptual framework. Therefore, the annual ET values based on the data collected by Warren *et al.,* (2018) for the black spruce forests, open collapse scar wetlands and the integrated landscape were associated with the appropriate stage along our proposed trajectory of change. Stages of the trajectory for which representative measurements were not collected are interpolated between the land cover end-members for which ET was measured.

Given the insignificant changes in annual precipitation over the period of measurement (Connon *et al.,* 2014; Haynes *et al.,* 2018), annual storage was calculated as the residual of annual precipitation inputs, and annual evapotranspiration and runoff outputs for the conceptual framework water balance (Table 1).

3.4 Radiation Fluxes

Four meteorological stations at Scotty Creek were selected for use in this study (Figure 3). This included a station installed in a collapse scar wetland in 2004 (hereafter "wetland station") followed by a second station on a densely forested peat plateau in 2007 (hereafter "dense forest station"). The radiation flux data from these two stations are representative of the collapse scar wetland and permafrost plateau land cover types, respectively. Two additional stations located on forested plateaus were also used to represent tree canopy densities different from that of the dense forest station. These stations were installed on a sparsely forested peat plateau in 2015 (hereafter "sparse forest station") and a forested plateau with a canopy of intermediate density between that of the dense and sparse stations in 2014 (hereafter "intermediate forest station"). All radiation measurements were made below the tree canopy at a height of 2 m above the ground surface. Four component radiation data were collected at the dense forest, sparse forest, and wetland meteorological stations, while only shortwave radiation was collected at the intermediate forest station. The reader is directed to Haynes *et al.,* (2019) for full descriptions of the radiation instrumentation within the Scotty Creek basin. Radiation was measured every minute, and averaged and recorded every 30 minutes from which daily (24 hourly) averages were computed. The daily averages were then used to compute annual average radiation for each station. While these computations defined some of the variability of radiation fluxes among land cover types, they do not account for flux variations over short temporal and spatial scales (Webster *et al.,* 2016). To address these, the daily average four component radiation data from each station were compared on a monthly time step. The monthly averages were calculated and compared across the land covers represented by each of the four meteorological stations using a one-way analysis of variance (ANOVA) with Tukey post-hoc test

(α = 0.05), thereby testing the effect of land cover on monthly shortwave and longwave incoming and outgoing radiation.

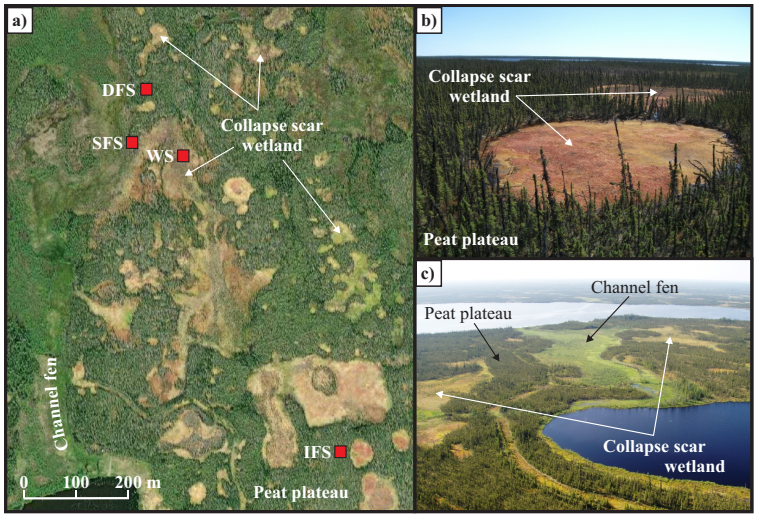

Figure 3: Worldview 2 satellite image (a) and oblique aerial photographs (b, c) over Scotty Creek, Northwest Territories. The satellite image also shows the locations of the Dense Forest Station (DFS), Sparse Forest Station (SFS), Wetland Station (WS) and Intermediate Forest Station (IFS) micrometeorological stations. The oblique aerial photographs show the land cover types that dominate lowlands with discontinuous permafrost in the Taiga Plains including peat plateau (permafrost), collapse scar wetland, and channel fen.

4. Results and Discussion

4.1 Peatland and Forest Occurrence

The type of peatland-dominated terrain composed of peat plateau-wetland complexes separated by channel fens as described for Scotty Creek, occupy approximately 35% of the discontinuous permafrost zones of the Taiga Plains (Figure 4a). Large peatland clusters are located in lowland areas with high histel or histosol soil percentages. In the extensive-discontinuous permafrost zone, peatlands are clustered to the west near to the Mackenzie River,

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and are largely absent from the eastern portion of the study area in the region bounded by Great Bear Lake to the north and the Taiga Shield to the east. In the sporadic-discontinuous zone however, the peatland clusters are more longitudinally dispersed.

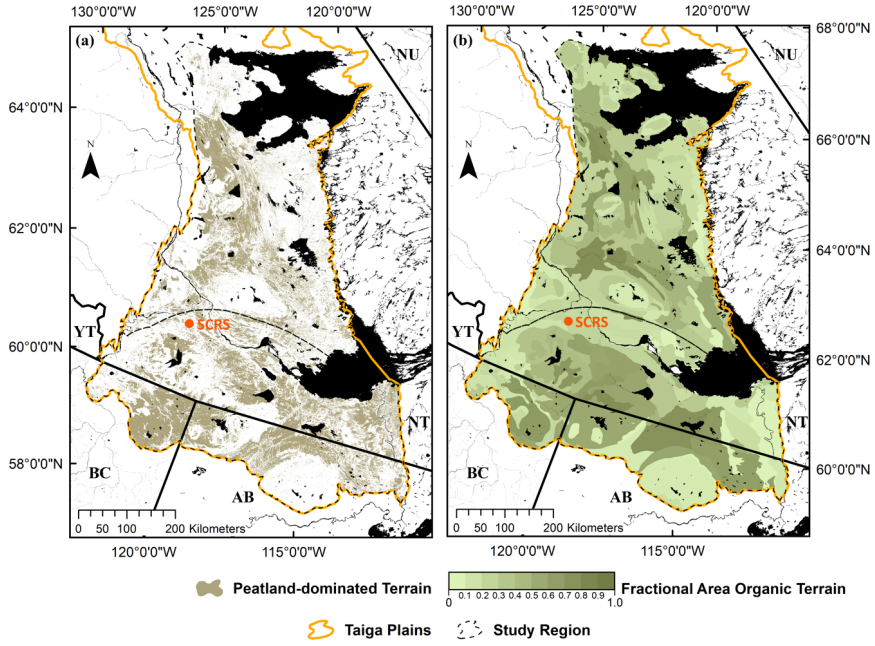

Figure 4: Predicted distribution of peatland-dominated terrain in the discontinuous permafrost zone of the Taiga Plains (a). Peatland-dominated terrain was mapped using a saturated soils dataset (Natural Resources Canada 2017) (a) and compared to the NCSCD (Bolin Centre for Climate Research 2013) (b). Contains information licensed under the Open Government Licence – Canada.

Comparing the fractional areas of probable peatland terrain from the saturated soils dataset to the NCSCD showed the saturated soils dataset was more likely to overstate the distribution of probable peatland terrain compared to the NCSCD maps. Approximately 20% of the fractional areas were exact matches between the two datasets, 20% were lower in the

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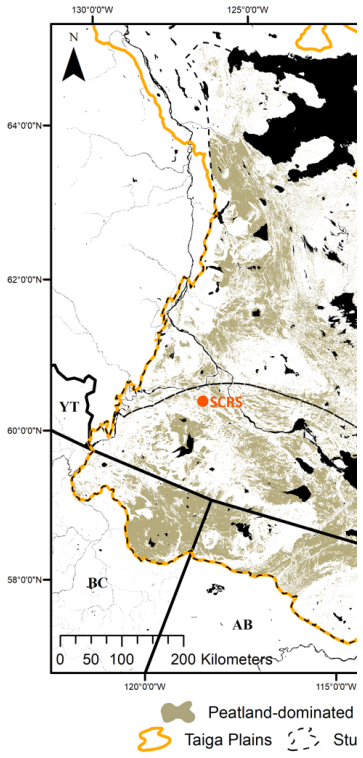

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saturated soils dataset, and 60% were higher in the saturated soils dataset. However, despite these disagreements, 79% of the fractional areas determined using the saturated soils dataset were within 15% of the fractional areas in the NCSCD. This suggests that using the Natural Resources Canada saturated soils dataset may be an appropriate method of mapping probable peatland terrain in the Taiga Plains on a finer scale (Figure 4a) compared to the broad zones presented by the NCSCD (Figure 4b). Only 11 of the 572 NCSCD zones (~2%) had disagreements over 25% when comparing the fractional areas between both datasets. The majority of these zones of disagreement were located along the Slave River, in the far southeast of the Taiga Plains study region.

A latitudinal trend in land cover percentage was found for the mapped peatland-dominated terrain (Figure 5). Along the boundary between the extensive-discontinuous and sporadic-discontinuous permafrost zones near the centre of the study region, collapse scar wetland features are most prevalent. Median fractional forest cover in peatlands (*i.e.* peat plateaus or treed wetlands) reaches its minimum value of 33% within the 61º N bin, near the latitude of Scotty Creek. The proportion of forested peatlands remains relatively low throughout the transitional zone between sporadic and extensive discontinuous permafrost (approximately 61º to 62º N) where the median forest cover does not exceed 34%. The widespread occurrence of collapse scars suggest that permafrost thaw and the resulting processes of ground surface subsidence and inundation are particularly active in this zone compared to the extensive discontinuous permafrost zone to the north and the sporadic discontinuous permafrost zone to the south, where the fractional forested areas are higher.

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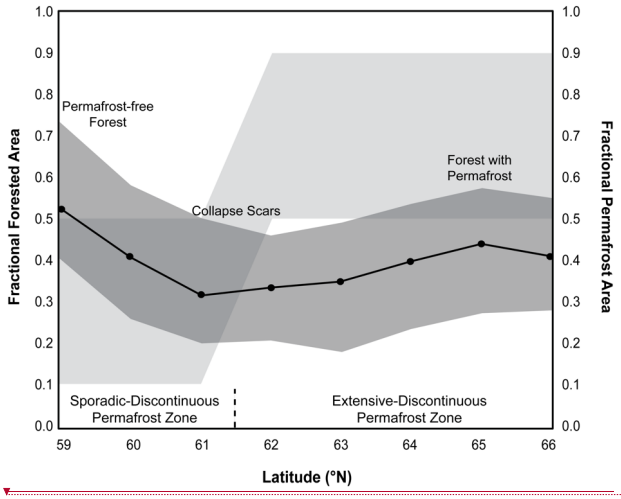
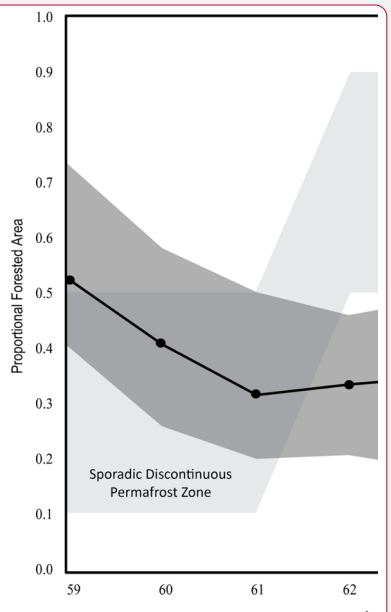


Figure 5: Median forested peatland area expressed as a fraction of the total peatland area and plotted as a function of latitude. The dark grey area represents the range in the proportion of the landscape occupied by forested peatland (i.e. fractional forested area) between the 25th percentile and 75th percentile. The lighter grey area indicates the range in the proportion of landscape underlain by permafrost (i.e. fractional permafrost area) as indicated by Brown *et al.*, (2002).

The median proportion of forested peatlands in the extensive-discontinuous zone (63º to 66º N) ranges from approximately 35 to 45%, indicating that permafrost thaw is less prevalent over the landscape than in the transition zone immediately to the south. However, the median fractional forested area is at its greatest (52%) south of the transition in the sporadic-discontinuous zone (59º to 60º N), where about half of the peatland area is forest covered. Expansion of forest cover in this zone, especially in the areas of north-eastern British Columbia and north-western Alberta, has been reported by others (*e.g.* Zoltai 1993, Carpino *et al.*, 2018). A pattern of forest expansion over permafrost-free terrain is consistent with the observation of a northward-moving southern limit of permafrost reported by Kwong and Gan (1994) and with the process of tree re-establishment following permafrost thaw-induced partial drainage of wetlands described by Haynes *et al.*, (2020).



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4.2 Conceptual Framework of Land Cover Change

From the remote sensing and field-based hydrological studies at Scotty Creek since the mid-1990s, key insights into incremental land cover changes initiated by permafrost thaw have emerged. Using this knowledge as a foundation, the present study examines both the hydrological and radiation regimes of each incremental stage and the land cover changes over the larger region in which permafrost thaw is known to be widely occurring and within which the southern edge of permafrost is migrating northward (Kwong & Gan, 1994). From this approach, a new conceptual framework is presented (Figure 6), which describes permafrost thaw-induced land cover change in the peatland-dominated regions of the discontinuous permafrost zone. The land cover change occurring simultaneously (to varying degrees) at Scotty Creek and latitudinally across the wider Taiga Plains region can be categorized into seven distinct land cover stages, the first and last of which are forest cover, with the difference being that the former overlies permafrost and the latter does not. The stages are as follows: (I) Forested permafrost plateaus; (II) Forested permafrost plateaus with small, isolated collapse scars; (III) Forested permafrost plateaus with larger, interconnected wetlands; (IV) Wetland complexes with small plateau islands; (V) Wetland complexes with hummock development and tree establishment; (VI) Hummock growth with forest establishment; and (VII) Forested peatlands (Figure 6). In the following sections, the biophysical, hydrological and radiation regimes of each of these stages are presented and discussed, drawing on several investigations in the region.

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Plateau-Wetland Complex Landscape Trajectory¶
The evolution of peat plateau-collapse scar wetland complexes over time can be represented by seven phases

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Deleted: Afforested wetlands (Figure 4). A sequence of hydrological processes and energetic mechanisms occurs to initiate landscape change and drive the landscape along the proposed spectrum of transition. As permafrost thaw commences, a landscape dominated by forested plateaus and underlain by permafrost (Figure 4I) transitions to one with small, suprapermafrost taliks (Connon et al. 2018) and isolated collapse scar bogs begin to emerge (Figure 4II; Quinton et al. 2011). As permafrost thaw and talik development continues, the previously isolated collapse scars expand (Figure 4III; Devoie et al. 2019) and become interconnected with surrounding wetlands (Connon et al. 2015). As permafrost thaw continues, wetlands proliferate and become increasingly connected, creating a landscape dominated by widespread wetland complexes with only isolated plateau islands (Figure 4IV; Baltzer et al.

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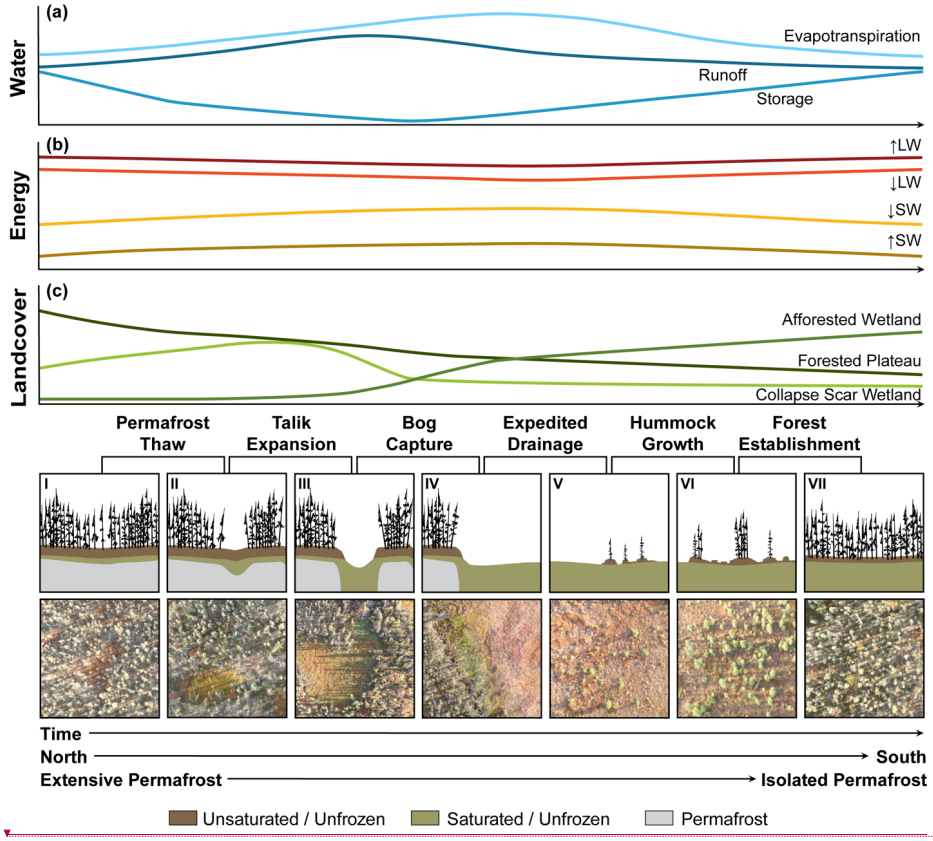

Figure 6: (Bottom) Proposed conceptual framework of landscape trajectory including a space-for-time substitution for changes to both permafrost and land cover. Conceptual diagrams are presented to illustrate landscape change with the support of RPAS imagery collected in the Scotty Creek basin. The conceptual framework is presented alongside the processes that initiate the trajectory's progression. (a) Relative changes to local water balances of measured Scotty Creek basin runoff, evapotranspiration and residual storage with unchanging precipitation are summarized and presented over the trajectory of landscape change based on the proportion of forested vs. wetland area. (b) Relative changes to local energy balances are presented using data collected from sub-canopy meteorological stations installed at Scotty Creek. (c) Changes to relative land cover proportions are presented using historical aerial photographs and recent acquisitions of satellite imagery over the Scotty Creek basin.

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4.2.1 Biophysical Characteristics

The present study found that the early land cover stages presented in Figure 6 are more prevalent at the higher latitudes of the study region and the later stages at the lower latitudes. Considering that permafrost thaw is more advanced in the lower latitudes and that the southern limit of permafrost is advancing northward (Kwong & Gan, 1994), it is reasonable to expect that the more advanced stages presently characterising the lower latitudes will, in the future, characterise the higher latitudes, assuming a continuation of climate warming induced permafrost thaw. Approaching a change in latitude through the study region as analogous to a change in land cover stage, or more specifically, to a change in time, is supported by studies that examined land cover change over the last half-century at Scotty Creek (Chasmer & Hopkinson, 2017; Quinton *et al.*, 2019) and along a north to south transect extending from Scotty Creek to northeastern British Columbia (Carpino *et al.*, 2018).

The Scotty Creek basin, located near the northern limit of sporadic discontinuous permafrost (Figure 1) is characterised mainly by stages III and IV. However, examples of all seven stages can be found in local areas at Scotty Creek. For this reason, the long term monitoring and research programs at Scotty Creek involving each of these land cover types contributes detailed information on their form and functioning, and on their transition from one to another. For example, permafrost thaw changes a landscape dominated by forested plateaus (Figure 6I) to one with small, suprapermafrost taliks (Connon *et al.*, 2018) and isolated collapse scars (Figure 6II; Quinton *et al.*, 2011). Continued thaw expands isolated collapse scars (Figure 6III; Devoie *et al.*, 2019) enabling them to coalesce to form interconnected wetlands (Connon *et al.*, 2015), a process that then leads to a landscape of expansive wetlands dotted with isolated plateau "islands" (Figure 6IV; Baltzer *et al.*, 2014; Chasmer & Hopkinson 2017). Since the process of wetland expansion removes peat plateaus, a land cover type that impounds wetlands

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This transition not only represents the dominant trajectory of change observed over recent decades in the Scotty Creek basin (Quinton 2019), but also corresponds with the north-south climatic transition of peatland-dominated plateau-wetland complexes spanning northwestern Canada's zone of discontinuous permafrost. This spans the extensive permafrost found beneath treed peat plateaus in the north, to patchwork or even wetland-dominated landscapes at more moderate latitudes, and finally to more widespread permafrost-free environments at the southern extent of the Taiga Plains. Each of these stages, and the transitional steps between them, can also be observed at smaller scales at local sites including Scotty Creek, which is located on the boundary between the sporadic-discontinuous and extensive-discontinuous zones. The Scotty Creek Research station is in phase III-IV, with localized conditions that correspond to the range of other phases. This exemplifies the concurrent nature of the phases along the spectrum of landscape transition.

Landcover Trajectory

Changes to the relative proportions of the three main landcovers represented across the trajectory (Figure 4c) (forest plateau, collapse scar wetland, and afforested wetland) have been observed at the landscape-scale with remotely-sensed imagery. At Scotty Creek, the early portions of the trajectory (*i.e.* stages I, II) represent the changes observed between 1947 and 2000 as the landscape transitioned from predominantly forested and underlain by permafrost to one defined by a forest-wetland patchwork and degrading permafrost bodies (Quinton et al. 2010). This ~ 50 year period shows a change in proportional landcover as forested areas move from covering approximately 70% of Scotty Creek to approximately 50% (Quinton et al. 2010; Baltzer et al. 2014). This forest loss directly corresponds with wetland expansion at the expense of permafrost as treeless wetland features (both collapse scar bogs and channel fens) shift from approximately 30% of the landcover to approximately 50% over the same time period (Quinton et al. 2010). As of 2018, the headwaters of the Scotty Creek basin were comprised of approximately 40% forested permafrost plateau, 45% treeless wetland (13% collapse scar wetland and 32% channel fen), and 13% afforested wetland (Disher 2020). These results indicate that the proportional area of peat plateau, and thus permafrost terrain, has continued to decline since previous analyses (Quinton et al. 2010; Baltzer et al. 2014; Connon et al. 2014; Carpino et al. 2018). While permafrost thaw-induced forest loss continues rapidly at Scotty Creek, forest re-establishment is also occurring in the form of afforested wetlands (Disher 2020). As such, these results are also indicative of the fact that the transition from one stage of the trajectory to the next is not instantaneous and can occur to varying degrees within a local site such as Scotty Creek.

Between 1970 and 2010 the

and obstructs drainage (Connon *et al.,* 2014), this process enables the landscape drain more efficiently (Haynes *et al.,* 2018). As wetlands drain, hummock micro-topography develops in their relatively drier interiors (Figure 6V; Haynes *et al.,* 2020), which allows black spruce to colonise the wetlands on the relatively dry hummock surfaces (Figure 6VI; Iversen *et al.,* 2018; Dymond *et al.,* 2019). Continued drainage and drying of wetlands enables the expansion of their hummocky terrain and therefore of their tree cover (Eppinga *et al.,* 2007; Iversen *et al.,* 2018) until the landscape returns to a more continuous forest cover (Figure 6VII; Carpino *et al.,* 2018). However, the forest cover in this final stage is permafrost-free and for that reason, the conceptual framework presented in Figure 6 stands in contrast to those presented by Zoltai (1993) and Camill (1999) in which the re-emergence of a forest cover relies on the re-emergence of the underlying permafrost. According to Zoltai (1993), forest re-emerges because permafrost displaces the overlying ground surface upward, resulting in the development of an unsaturated layer suitable for tree establishment. By contrast, the tree establishment described in Figure 6 results not from the re-emergence of permafrost, but from its continued thaw over the landscape, a process that dewaters wetlands (Connon *et al.,* 2014; Haynes *et al.,* 2018) to the extent suitable for tree establishment (Haynes *et al.,* 2020).

The land cover transition depicted in Figure 6 involving wetland drainage and forest re-establishment occurs in less than half a century as indicated by analysis of historical imagery for Scotty Creek. By contrast, the process of forest re-growth enabled by the re-establishment of permafrost occurs over a much longer time frame of several centuries (Zoltai, 1993; Treat and Jones, 2018). At Scotty Creek, the early stages of Figure 6 (*i.e.* stages I, II) represent the changes observed between 1947 and 2000 over which time the tree-covered area decreased from approximately 70% to approximately 50% (Quinton *et al.,* 2011). The fraction of forested land above permafrost-free terrain cover is unknown for this period but assumed to be negligible

based on land cover descriptions for this region (*e.g.* NWWG, 1988; Zoltai 1993; Robinson & Moore, 2000). This period therefore generated a concomitant rise in the cover of wetlands over the landscape (*i.e.* 30 to 50%) since permafrost thaw transitions the tree covered plateaus to collapse scars and channel fens, as confirmed by analysis of archived imagery (Chasmer *et al.*, 2010). By 2018, tree-covered peat plateaus decreased to 40%, and treeless wetlands occupied 45% of the land cover (13% collapse scars and 32% channel fens) (Disher 2020). These studies indicate that permafrost thaw and the resulting processes have both removed forest as a result of thaw-induced subsidence and inundation of plateau surfaces, and more recently, enabled forest re-establishment in the form of treed wetlands (Haynes *et al.*, 2020; Disher *et al.*, 2021). However, the dominant land cover transition at Scotty Creek is still from forest (peat plateau) to wetland as a result of permafrost thaw, resulting in a net forest loss, a process that will continue until the later stages of Figure 6 are reached (*i.e.* stages VI, VII), at which point there will be a net forest gain.

The sequence of land cover stages following permafrost thaw observed at Scotty Creek and depicted in Figure 6 is supported by vegetation successional changes described in the literature for wetlands as they age. For example, aquatic *Sphagnum* species, notably *S. riparium*, are the first to occupy the inundated margins between thawing permafrost plateaus and developing collapse scars (Garon-Labrecque *et al.*, 2015; Pelletier *et al.*, 2017). Such recent areas of collapse are easily identified on high-resolution RPAS imagery by the distinct bright green colour of *S. riparium* (Figure 6II, III, IV; Gibson *et al.*, 2018; Haynes *et al.*, 2020). These wetland-plateau edges may also be identified by bare peat or moats of water (Zoltai 1993). As collapse scars expand, lawn species, such as *S. angustifolium,* and hummock species, such as *S. fuscum*, emerge, particularly in the drier interior of wetlands (Zoltai 1993; Camill 1999; Pelletier *et al.*, 2017). Hummock species, mainly *S. fuscum*, first emerge near the centre of collapse scars,

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and expand outward over time (Camill 1999; Loisel & Yu 2013). Much like *S. riparium*, *S. fuscum* is also easily identified in high-resolution imagery, where *S. fuscum* is distinguished by its russet colour (Figure 6V) (Haynes *et al.*, 2020). As the density of the *S. fuscum* hummocks increases, imagery and ground-based observations indicate the presence of young black spruce trees (Liefers & Rothwell 1987; Haynes *et al.*, 2020), first on isolated hummocks (Figure 6VI) but eventually as widespread afforestation (Figure 6VII; Camill 2000; Ketteridge *et al.*, 2013).

4.2.2 Radiation Flux Characteristics

The Scotty Creek basin is a microcosm of its larger regional setting since it contains each of the land cover stages of the conceptual framework in Figure 6. As such, the micro-meteorological measurements made at Scotty Creek for different land cover types provide insight into how energy regimes change as one land cover stage transitions to the next. Both incoming and outgoing shortwave radiation peak at the middle stages (IV, V), where treeless collapse scars predominate. Annual incoming and outgoing shortwave radiation is lowest at the dense forest station, which represents the initial stage (I). Likewise, incoming and outgoing annual longwave radiation are greatest in the early (I, II) and late stages (VI, VII) and lowest in the wetland-dominated middle stages (IV, V).

Statistically significant differences were found between stations for incoming (Figure 7a) and outgoing (Figure 7b) shortwave and incoming longwave radiation (Figure 7c), while there was no statistical differences between stations for outgoing longwave (Figure 7d). However, Tukey post-hoc tests revealed variability between the two shortwave components in terms of which groups showed these significant differences. As the four meteorological stations fall along a gradient of forest density from treeless wetland to a densely forested plateau, no significant differences in incoming shortwave radiation were ever found between stations only one rank

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apart on that gradient. As such, measurements indicate average monthly incoming shortwave radiation is significantly greater at the wetland compared to both the intermediate forest ($p \leq 0.05$) and the dense forest ($p \leq 0.05$), while no significant difference exists between wetland and the sparse forest. However, the dense forest receives significantly less incoming shortwave radiation than both the wetland ($p \leq 0.05$) and the sparse forest ($p \leq 0.05$), but this station is not significantly different from the intermediate forest.

No significant differences in outgoing shortwave radiation exist between any of the forested plateau stations but all are significantly different from the wetland. Specifically, outgoing shortwave radiation recorded at the wetland station is significantly greater than the sparse forest ($p \leq 0.05$), intermediate forest ($p \leq 0.05$), and dense forest stations ($p \leq 0.05$). The differences between the wetland station and the forested plateau stations are also increasingly significant with increasing tree density. There was a statistically significant difference between the three stations (intermediate forest omitted due to lack of measurements) for incoming longwave radiation, while no statistically significant differences were observed in the outgoing longwave radiation component. The only significant difference in incoming longwave was observed between the wetland and dense forest ($p \leq 0.05$). No significant differences exist between the sparse forest and the wetland or dense forest.

The comparison among the plateau stations of contrasting tree canopy densities provides insight into the permafrost thaw-induced progression of radiation regimes as plateaus transition to wetlands, a process involving the gradual thinning and eventual loss of the tree canopy. Wright *et al.*, (2009) demonstrated that small-scale changes to the tree canopy density can increase insolation to the ground in localized areas leading to thaw depressions in the active layer and water flows toward such depressions from their surroundings. Such areas of preferential

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thaw therefore develop elevated soil moisture contents, and since soil thermal conductivity increases with its moisture content, the preferential thaw process is reinforced. This is suggested as the mechanism driving the transition from stage I to II in the trajectory (Quinton *et al.*, 2019). This feedback is present in the initial stages of the trajectory, and is often associated with talik formation and expansion into collapse scars due to localized permafrost loss (Chasmer & Hopkinson 2017; Connon *et al.*, 2018). Such thaw can extend to the base of the active layer in which case further thaw results in permafrost loss, ground surface subsidence, waterlogging of the ground surface, local tree mortality, and therefore further thinning of the overlying tree canopy and consequently more insolation at the ground surface. These processes and feedback mechanisms are critical in the generation of collapse scars in stage III.

Differing ground surface properties, particularly albedo, can amplify the differences in incoming shortwave radiation among the land covers. However, the difference in mean albedo during the snow-free season (May-September) below the plateau canopies is less than 5% and displays a small increasing gradient as the canopy becomes more dense (sparse: 0.111, intermediate: 0.127, dense: 0.147). The mean wetland albedo (0.145) during the snow-free season is also similar to the plateau surfaces and most closely resembles the surface albedo of the dense plateau. The greatest contrast in albedo occurs during the period of several weeks while snow still covers the plateaus but is absent on the adjacent wetlands (Connon *et al., Submitted*). This contrast in albedo is also evident in Figure 7b, which shows that following winter, outgoing shortwave radiation from the wetland increases before the forested stations. Helbig *et al.*, (2016b) attributed their observed increase in landscape albedo in this late winter/spring period to the permafrost thaw-induced conversion of forest (lower albedo) to wetland (higher albedo), and suggested that this could lead to a regional cooling effect during this time of the year. However, that study implicitly assumed that the wetlands were a final land cover stage rather than an

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incremental step toward the re-establishment of forest as depicted in the conceptual framework presented in Figure 6.

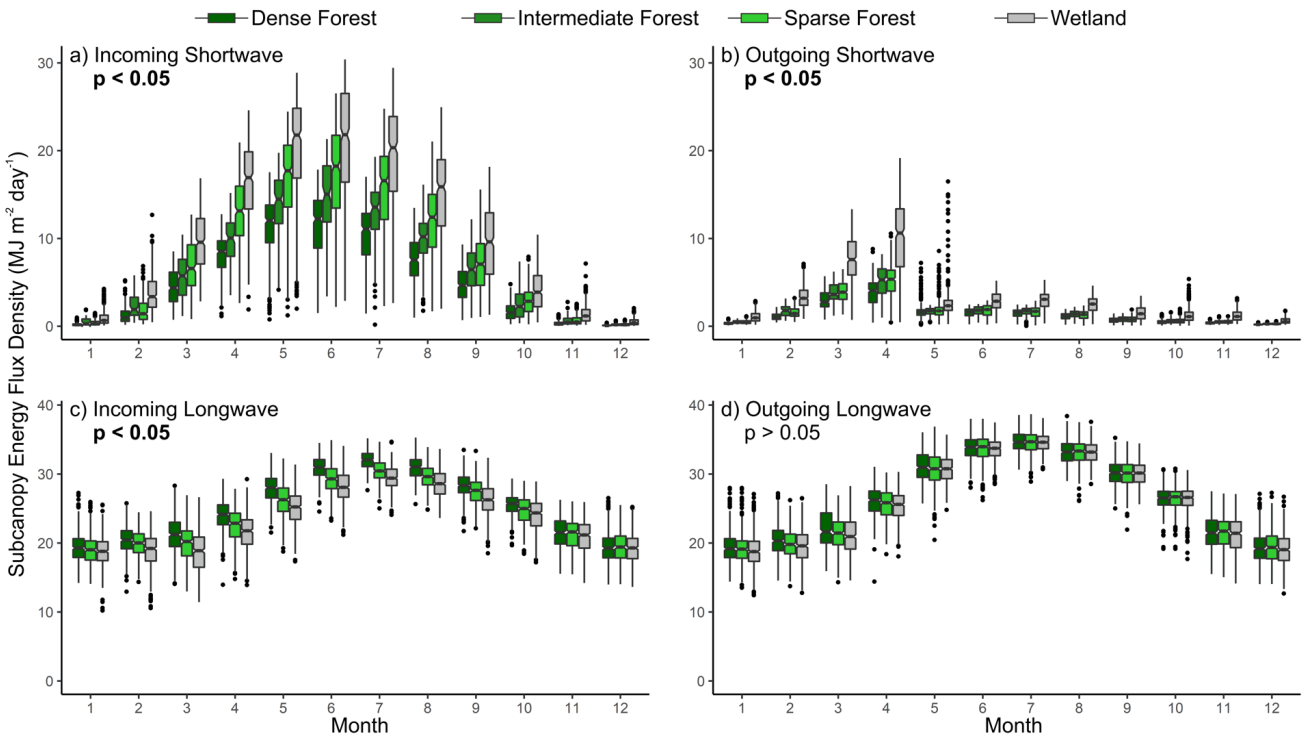

Figure 7: Sub-canopy daily total (MJ/m^2/day) incoming shortwave (a), outgoing shortwave (b), incoming longwave (c), and outgoing longwave (d) at the four meteorological stations. Each station represents a distinct land cover: dense forest (2007-2019), intermediate forest (2014-2019), sparse forest (2015-2018), and treeless wetland (2004-2019). The boxes represent the 25th and 75th percentile, while the whiskers represent the range of the data. The notches on each box indicate the confidence interval (a = 0.05) around the mean while the statistical differences between meteorological stations have been presented in the upper left of each plot as determined by one-way ANOVA. Significant *p* values have been highlighted with bold text.

4.2.3 Hydrological Characteristics

As the land covers presented in the conceptual framework transition from one to the next, hydrological processes also change (Figure 6a). In the early stages (I, II), a relatively large proportion of hydrological inputs from the atmosphere are stored in collapse scars due to their impoundment by the permafrost on their margins (Connon *et al.*, 2014). Evapotranspiration from the landscape is relatively low given the high proportion of forest and relatively low transpiration by the black spruce that dominates the plateau canopies (Warren *et al.*, 2018). In the early land cover stages (I, II) when forests predominate, understorey vegetation provide the pathway for evapotranspiration (Chasmer *et al.*, 2011). The incremental change in land covers presented in Figure 6 involves biophysical changes that affect the partitioning of precipitation into storage or runoff. By stage III to IV, wetlands are interconnected and rapidly expanding, the storage of water on the landscape reaches its minimum level while runoff from the landscape is maximized (Figure 6a). This increased runoff is enabled by the removal of permafrost barriers (Haynes *et al.*, 2018) and areal expansion of runoff contributing areas resulting in greater hydrological connectivity and therefore drainage of the landscape (Connon *et al.*, 2014). These observations coincide with a period of steady, unchanging annual precipitation; therefore precipitation does not account for elevated basin runoff (Connon *et al.*, 2014). A decrease in landscape drainage then follows in the subsequent stages as the transient runoff contributions from "captured" collapse scars diminishes as the importance of evapotranspiration increases as the wetlands become the predominant land cover (IV, V). The increase in evapotranspiration is due to increases in evaporation from areas occupied by standing water and saturated or near-saturated wetland vegetation, including *Sphagnum* mosses, with losses due to transpiration driven by shrub vegetation (Warren *et al.*, 2018). In the advanced stages (VI, VII) evapotranspiration would decrease as a result of the drier wetland surfaces as hummock microtopography replaces

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At peatland-dominated sites such as Scotty Creek, changes to energy can act as a driver of permafrost thaw-induced landcover change and are also closely coupled to changes in water and runoff regimes. Therefore, as the trajectory progresses through the proposed stages, the relative influence of the processes governing the hydrology of the landscape changes dynamically (Figure 4a). The early stages (I, II) of the proposed successional trajectory are dominated by hydrologically isolated wetlands, where storage is maximized and outflow from the basin is limited to primary runoff from plateau features into nearby fens (Connon et al. 2014; Quinton et al. 2003). Water arriving directly into one of the isolated, but rapidly expanding collapse scar wetlands will be stored as there is no direct flow path to the channel fen (Quinton et al. 2019). The contributions of evapotranspiration during the forest-dominated stages are similarly minor due to the limited transpirative ability of black spruce on organic soils (Warren et al. 2018). Even when forest is the predominant landcover, understory vegetation is the principal contributor to evapotranspiration (Chasmer et al.

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As the environment becomes more wetland dominated, runoff and storage diverge. By stage III, where

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saturated *Sphagnum* lawns. The treed (afforested) wetlands (VII) have not been studied to the same degree as peat plateaus or collapse scar wetlands (Haynes *et al.*, 2020; Disher *et al.*, 2021) and therefore ground based hydrological data specific to these features are lacking.

5. Conclusions

The discontinuous permafrost zone of the Taiga Plains exemplifies a landscape in transition. Coupling a broad-scale mapping initiative with the detail of site-specific data collected in the Scotty Creek basin demonstrates a permafrost thaw-induced land cover transition. This transition is incremental and involves distinct land cover stages. The first and last of these is a continuous forest cover, although in the first stage the forest is underlain by permafrost while in the last stage it is not. Unlike traditional concepts of land cover change in peatland dominated regions of discontinuous permafrost in which forest re-establishment occurs over centuries and is constrained by the rate of permafrost re-development, the concept presented here described forest re-establishment within decades and resulting from continued permafrost thaw, a process which allows wetlands to de-water sufficiently for tree growth. Each land cover stage has characteristic biophysical, hydrological and micro-meteorological features.

The proposed conceptual framework of landscape evolution describes the transitions occurring across the Taiga Plains in peat plateau-collapse scar wetland complexes like Scotty Creek. This study also identifies the applicability of this conceptual framework across a large region of the Canadian north. We establish the likely pattern of change across these peat plateau-collapse scar wetland complexes and project their future trajectory by combining long-term field observations with analyses of contemporary and historical imagery. It is proposed that, while permafrost thaw-induced land cover changes have previously been dominated by a transition from forest to wetland, this transition is not permanent and forested land covers are likely to

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Deleted: in comparison to better-documented landforms even at sites such as Scotty Creek where intensive field studies are ongoing. Further examination is warranted into the hydrology and energy dynamics at these sites, particularly if afforestation represents an end-stage in the trajectory of peat plateau-collapse scar wetland complexes. The impacts of increasingly widespread afforested wetlands on basin runoff should be investigated as well as further work to confirm whether evapotranspiration for this landcover is intermediary much like soil moisture appears to be (Haynes et al. under review). Furthermore, the persistence and permanence of afforested wetland landcovers has not been documented. Exploring canopy or stand properties such as age, health, and productivity across these features may provide insight and assist in further defining the role of afforested wetlands in the trajectory of plateau-wetland complexes

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Deleted: at the SCRS emphasizes the close dependence of landcover on climate by way of local energy and water budgets. Small changes to climate or tree cover can initiate permafrost thaw and trigger a series of positive feedbacks related to energy, water and vegetation communities, leading directly to changes across the landscape. The proposed conceptual model of landscape evolution summarized in Figure 4

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return over time, although unlikely to be underlain by permafrost. This research improves the understanding of how peat plateau-collapse scar wetland complexes in the Taiga Plains may be impacted by ongoing permafrost thaw and these results may also be of relevance to other peatland-rich permafrost environments across the circumpolar north.

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6. Acknowledgements

We gratefully acknowledge the support of the Dehcho First Nations, in particular, the Liidlii Kue First Nation and Jean Marie River First Nation. We also thank these communities for their long-standing support of the Scotty Creek Research Station. This work was funded by ArcticNet through their support of the Dehcho Collaborative on Permafrost (DCoP), and by the Natural Sciences and Engineering Research Council of Canada (NSERC). We also acknowledge the Canada Foundation for Innovation (CFI) for providing funding for infrastructure critical to this study.

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7. Data Availability

The radiation flux data used in this paper are catalogued for open access in the Wilfrid Laurier University (WLU) Data Repository at https://doi.org/10.5683/SP2/JTIQDO.

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8. Author Contributions

All authors contributed to the development of the research question and the methodological approach used in this study. OC and RC performed the analyses. OC, KH, and WQ wrote the manuscript with input and editorial contributions from RC, JC, and ÉD.

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9. Competing Interests

The authors declare that they have no conflict of interest.

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