Toward Understanding the Trajectory of Hydrological Change in the Southern Taiga Plains, Northeastern British Columbia and Southwestern Northwest Territories

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Quinton, W.L., Berg, A.A., Carpino, O., Connon, R.F., Craig, J.R., Devoie, E. and Johnson, E. (2018): Toward understanding the trajectory of hydrological change in the southern Taiga Plains, northeastern British Columbia and southwestern Northwest Territories; *in* Geoscience BC Summary of Activities 2017: Energy, Geoscience BC, Report 2018-4, p. 77–86.

Introduction

Climate warming–induced permafrost thaw is particularly pronounced in the southern Taiga Plains ecoregion, where permafrost is thermally insulated by an organic cover of dry peat, allowing it to persist in areas where the mean annual air temperature is positive (Smith and Riseborough, 2002). The permafrost of this region has already warmed to the melting point temperature, and its discontinuous nature enables energy to enter individual permafrost bodies not only vertically from the ground surface, but also laterally from adjacent permafrost-free terrain. Because such bodies are relatively thin (<10 m), permafrost thaw in this region often results in a local disappearance of permafrost (Beilman and Robinson, 2003). Although the southern Taiga Plains region contains mineral uplands that support forest covers, this region is dominated by peatlands in the form of peat plateaus, channel fens, isolated bogs (often called collapse scars) and expansive bogs (often called poor fens). Unlike the expansive bogs, the isolated bogs are surrounded by raised permafrost and as such are hydrologically isolated from the channel fens with respect to surface or near-surface flows. The plateaus function primarily as runoff generators, given their relatively high topographic position and limited capacity to store water. Unlike the peat plateaus, which are underlain by permafrost and support a forest cover, the bogs and fens are without trees and are permafrost-free. The isolated bogs, being internally drained, are predominantly areas of water storage. The expansive bogs exchange surface and near-surface flows with channel fens during periods of high moisture supply, but otherwise predominantly store the water they receive. Water draining into channel fens from the surrounding plateaus and expansive bogs (during periods of hydrological connection) is conveyed laterally along their broad (~50–100 m), hydraulically rough channels to streams and rivers (Quinton et al., 2003).

Permafrost thaw leads to ground surface subsidence, which transforms landscapes and ecosystems and ultimately affects the distribution and routing of water. As such, permafrost thaw is confounding the prediction of hydrological responses. Streamflow has increased throughout this region since the mid-1990s despite there being no significant change in precipitation (St. Jacques and Sauchyn, 2009). Connon et al. (2015) offered a plausible explanation of how permafrost-thaw–induced land-cover change in this region can increase streamflow by increasing the proportion of the land cover contributing runoff to the stream. However, there is little consensus on the trajectory of the thaw-induced land-cover change in the southern Taiga Plains, and as a result, the water futures of this region are unclear. To properly manage the water resources of this region, decision makers require an understanding of how permafrost thaw is changing the relative proportions of the major land covers. This will allow new insights into the trajectory of land-cover change and its implications on regional water resources.

The Consortium for Permafrost Ecosystems in Transition (CPET) was formed in 2015 among academic researchers, industry partners, and community and government groups to address the aforementioned issues being faced by the northeastern British Columbia–southwestern Northwest

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Territories (NBC–NWT) border region (Figure 1a). The long-term goal of CPET is to produce key insights into the trajectory of land-cover change in the southern Taiga Plains, and how this may affect water resources. This paper provides a synthesis of CPET progress to date based on a combination of published and unpublished materials.

Study Sites

The CPET is focused on a ~200 km north-south transect traversing the southern margin of thawing discontinuous to sporadic permafrost in the southern Taiga Plains (Figure 1b). Field studies are concentrated at the northern (Scotty Creek, NWT) and southern (Suhm Creek, BC) end members of this transect. Between the end-member sites, twelve areas of interest (AOI), each with a footprint of 36 km^2 (432 km^2 total area), were established to examine the temporal (1970 to present) and spatial (within and between AOIs) variations of permafrost-thaw–induced land-cover change (Quinton et al., 2017). The focus of this report, however, is on the Scotty Creek basin (61°17'N, 121°17'W), which drains a 152 km^2 area dominated by peat plateau–bog complexes and channel fens (Figure 1b). Scotty Creek basin is underlain by discontinuous permafrost (Hegginbottom and Radburn, 1992) and is covered by peatland complexes typical of the ‘continental high boreal’ wetland region (National Wetlands Working Group, 1988). The peat thickness at Scotty Creek basin ranges between 2 and 8 m (McClymont et al., 2013), below which lies a thick clay/silt-clay glacial till deposit of low permeability (Aylesworth and Kettles, 2000). Most of the Scotty Creek basin is a heterogeneous mosaic of forested peat plateaus underlain by permafrost, and treeless permafrost-free wetlands (Figure 1c), typical of the southern fringe of discontinuous permafrost (Helbig et al., 2016). The 1981–2010 climate normals indicate that Fort Simpson, to the north, has a dry continental climate with short dry summers and long cold winters. Fort Simpson has an average annual air temperature of –2.8°C and receives 388 mm of precipitation annually, of which 38% is snow (Environment Canada, 2017). Snowmelt usually commences in early to mid-April and continues throughout most of the month, so that by May, only small amounts of snow remain (Hamlin et al., 1998).

Results

Figure 1c shows a classified Ikonos image, acquired in 2000, of a 22 km^2 subarea within the Scotty Creek basin in which permafrost plateaus occupy the greatest (43%) area, followed by expansive bogs that are hydrologically connected to channel fens (23%), channel fens (21%), lakes (9%) and isolated flat bogs (4%). Since permafrost thaw increases the cover of the bogs and fens at the expense of the forested peat plateaus, tree cover can be used as a proxy for the presence of permafrost. The area underlain by permafrost at Scotty Creek basin decreased from 70% in 1947 to 43% in 2008 (Quinton et al., 2011), with degradation rates increasing in recent decades (Baltzer et al., 2014). This rate is consistent with estimates for the larger southern Taiga Plains region, where 30–65% of the permafrost has degraded over the last 100–150 years (Beilman and Robinson, 2003).

Recent hydrological field studies at Scotty Creek basin (Connon et al., 2014) provide valuable insights into how the land cover is changing and how such changes affect water flux and storage of water. It was shown that permafrost thaw had formed ephemeral flow connections between bogs that were assumed to be hydrologically isolated. Specifically, during periods of high moisture supply, water was found to cascade from bog to bog before reaching channel fens. It was also found that the ephemeral channels connecting the bogs were areas of preferential permafrost thaw. Two bog cascades, one draining the West sub-basin and the other draining the East sub-basin, are identified in Figure 1d. The hydrographs of the two sub-basins show the amount of water that would otherwise have remained on the plateau in the absence of the bog-to-bog drainage process (Figure 2). The annual drainage from the slightly smaller East sub-basin is substantially larger since its bogs are smaller and therefore more readily filled (Connon et al., 2015), a condition that must be reached before bog-to-bog flow can commence.

Connon et al. (2015) compared historical images of the Scotty Creek catchment, and showed that numerous bogs that were once hydrologically isolated from channel fens (e.g., Figure 3a) had over a period of a few decades become hydrologically connected to them (e.g., Figure 3b). This ‘bog capture’ process increases the runoff contributing area and therefore the amount of runoff produced by the basin (Connon et al., 2014). Permafrost thaw transforms hydrologically isolated bogs into ‘open’ bogs by removing the permafrost that once separated such a bog from the basin drainage network of channel fens. This land-cover transformation is important hydrologically because it adds two forms of runoff to the basin drainage network: 1) runoff arising from direct precipitation falling onto the captured bog (i.e., bog drainage), and 2) runoff from the captured bog’s watershed (i.e., slope drainage). As captured bogs expand due to permafrost thaw at their margins, they coalesce with other bogs, a process that increases both the bog and slope drainage contributions to the basin drainage network.

Figure 4a shows an example of bog capture between 2006 and 2015 at Scotty Creek basin, as recorded by detailed ground surface elevation and permafrost table depth surveys. As the permafrost table lowered between 2006 and 2015, the plateau ground surface lowered and was flooded, a process resulting in the simultaneous loss of forest and expansion of wetlands. By 2015, the permafrost table was below the elevation of the water tables of the adjacent

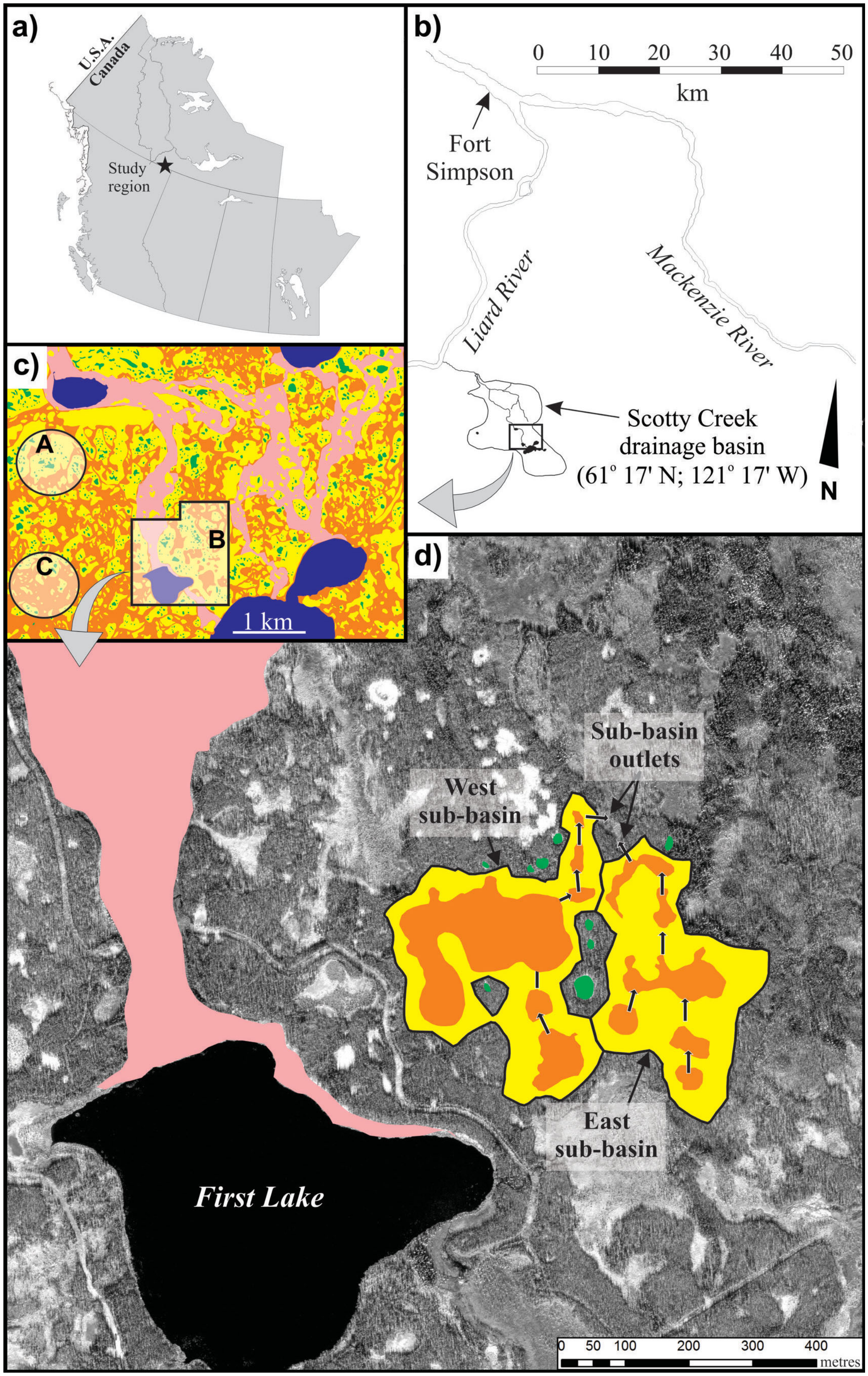

Figure 1. Location of **a)** study region and **b)** Scotty Creek drainage basin. Ikonos image (©DigitalGlobe, Inc.) of **c)** peat plateaus (yellow), isolated bogs (green), connected bogs (orange) and channel fens (pink) in the part of Scotty Creek drainage basin outlined in b); and **d)** enlarged area B, outlined in c), showing cascade bogs. Areas identified by A, B and C are defined in the 'Results' section. Small arrows in East sub-basin and West sub-basin indicate flow direction.

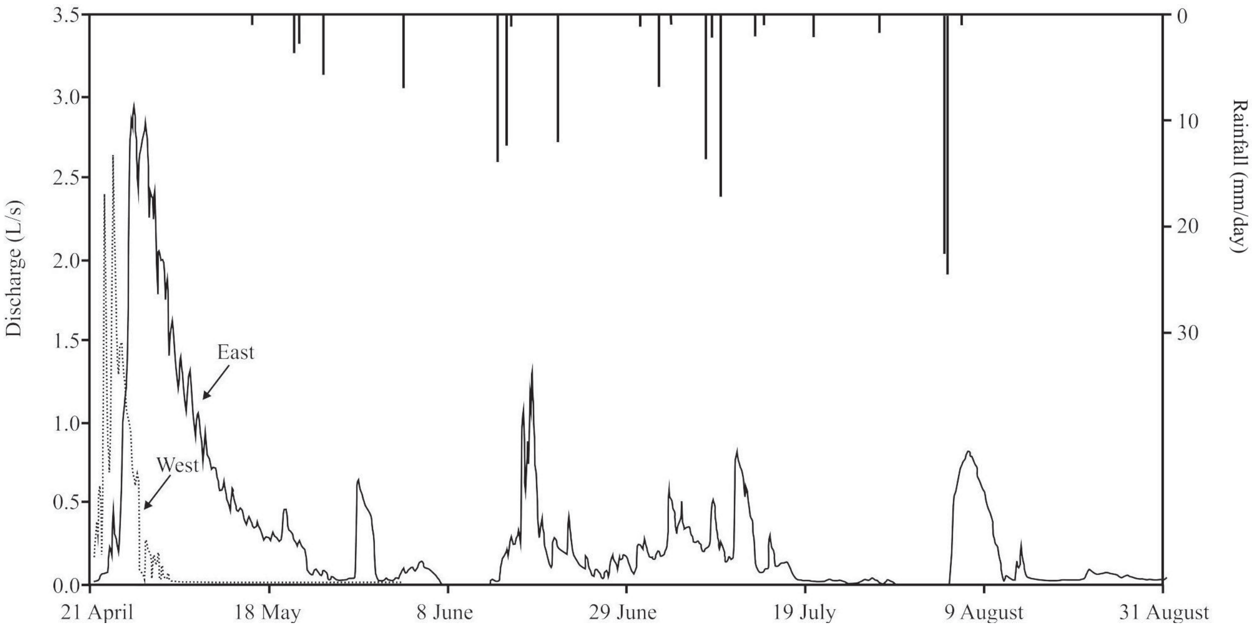

Figure 2. Runoff hydrographs measured at outlets of East sub-basin and West sub-basin bog cascades for 2014.

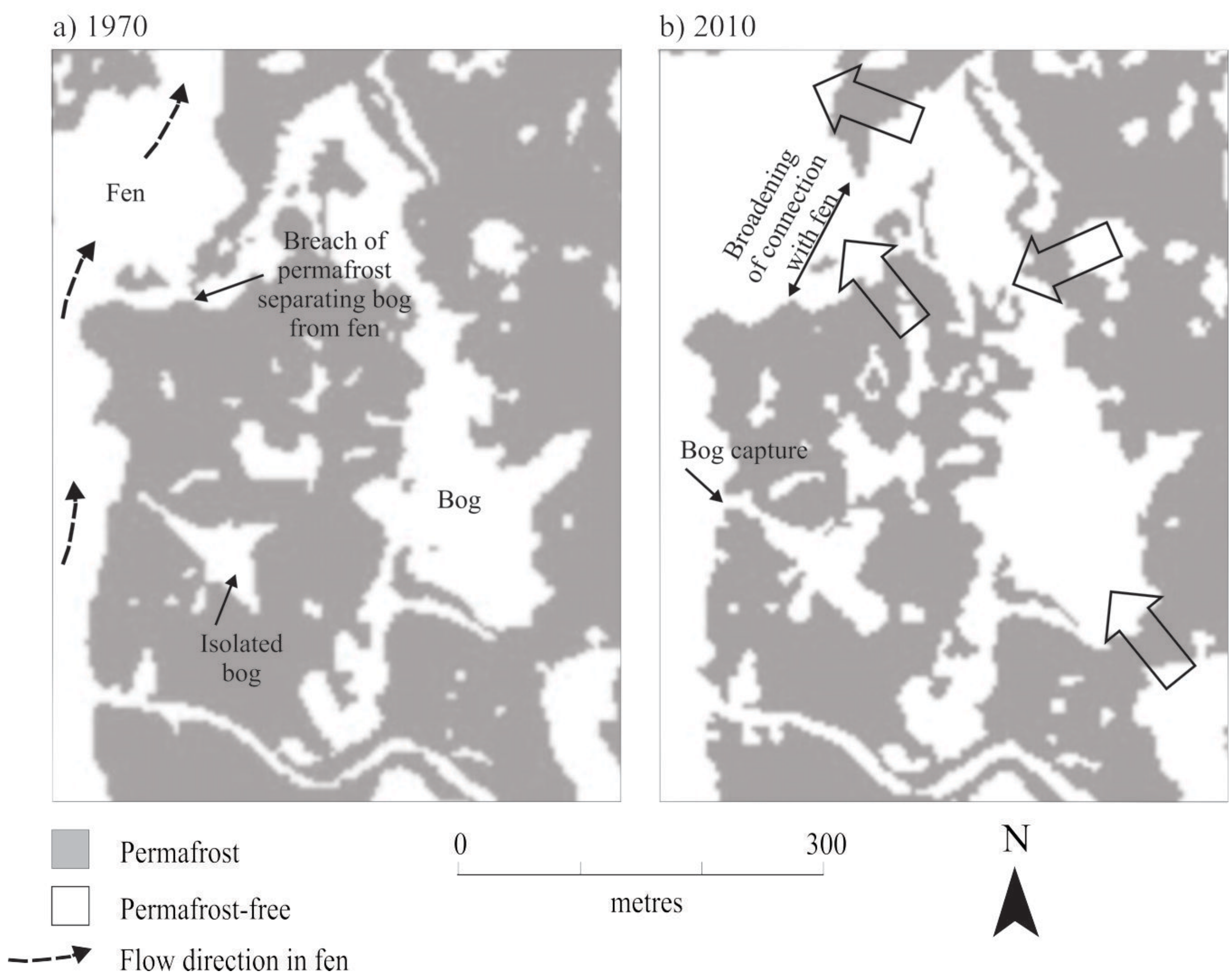

Figure 3. Classified images for a 1 km^2 area in the Scotty Creek catchment showing the change in permafrost coverage (grey) between **a)** 1970 and **b)** 2010. The large arrows in b) signify subsurface flow through taliks to the basin drainage network of channel fens. Centre of images is approximately latitude 61°18'39"N, longitude 121°18'18"W.

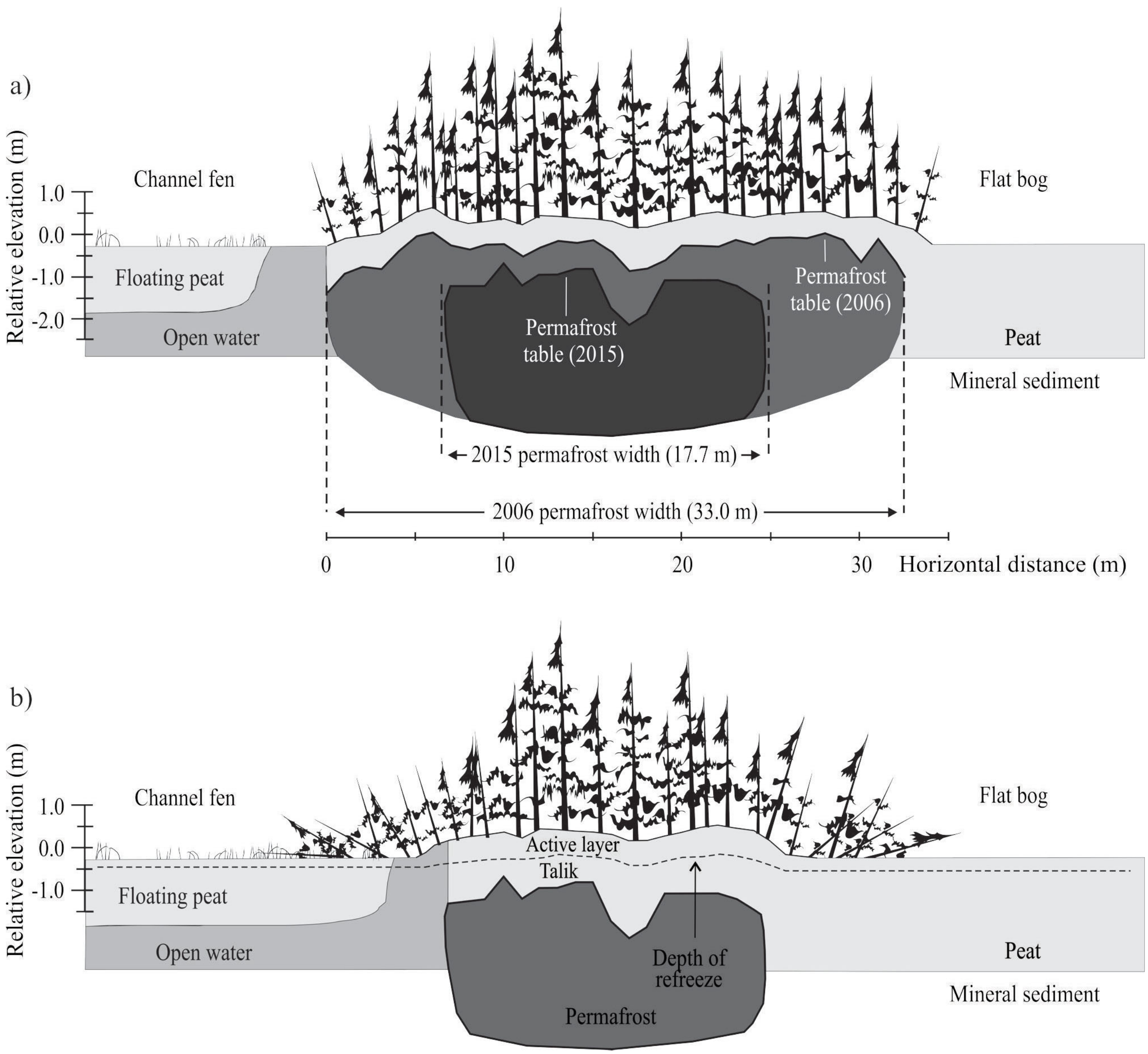

Figure 4. Cross-section of a peat plateau at Scotty Creek basin based on measurements of supra-permafrost thickness and ground surface elevation at 1 m intervals showing the difference in depth and lateral extent of the permafrost table between **a)** 2006 and 2015 and **b)** the development of a talik in 2015.

wetlands, and as a result, the permafrost body no longer prevented subsurface flow from one side of the plateau to the other (Figure 4b). By 2015, a talik (i.e., perennially unfrozen layer) had formed and enabled the plateau to conduct subsurface flow throughout the year from the bog to the fen. Subsurface flow through the talik (Figure 3b) augments the surface and near-surface flows into channel fens from the expansive bogs.

The total annual runoff from Scotty Creek and the other gauged rivers of the lower Liard River valley has steadily risen since the mid-1990s (Connon et al., 2014). The present understanding of water flow and storage processes in the southern Taiga Plains, and how climate warming and the resulting ecological changes affect these processes, cannot account for this rise, nor can it be used to predict future flows with confidence. The very low hydraulic conductivity of the glacial sediments below the peat precludes reactivation of groundwater systems as a cause of the rising flows from subarctic rivers. A more plausible explanation is the permafrost-thaw–induced expansion of runoff source areas as described by Connon et al. (2015). Field observations and image analyses (Baltzer et al., 2014) suggest that plateaus contain primary and secondary runoff source areas separated by a break in slope approximately 10 m inland from the fen-plateau edge (Figure 5).

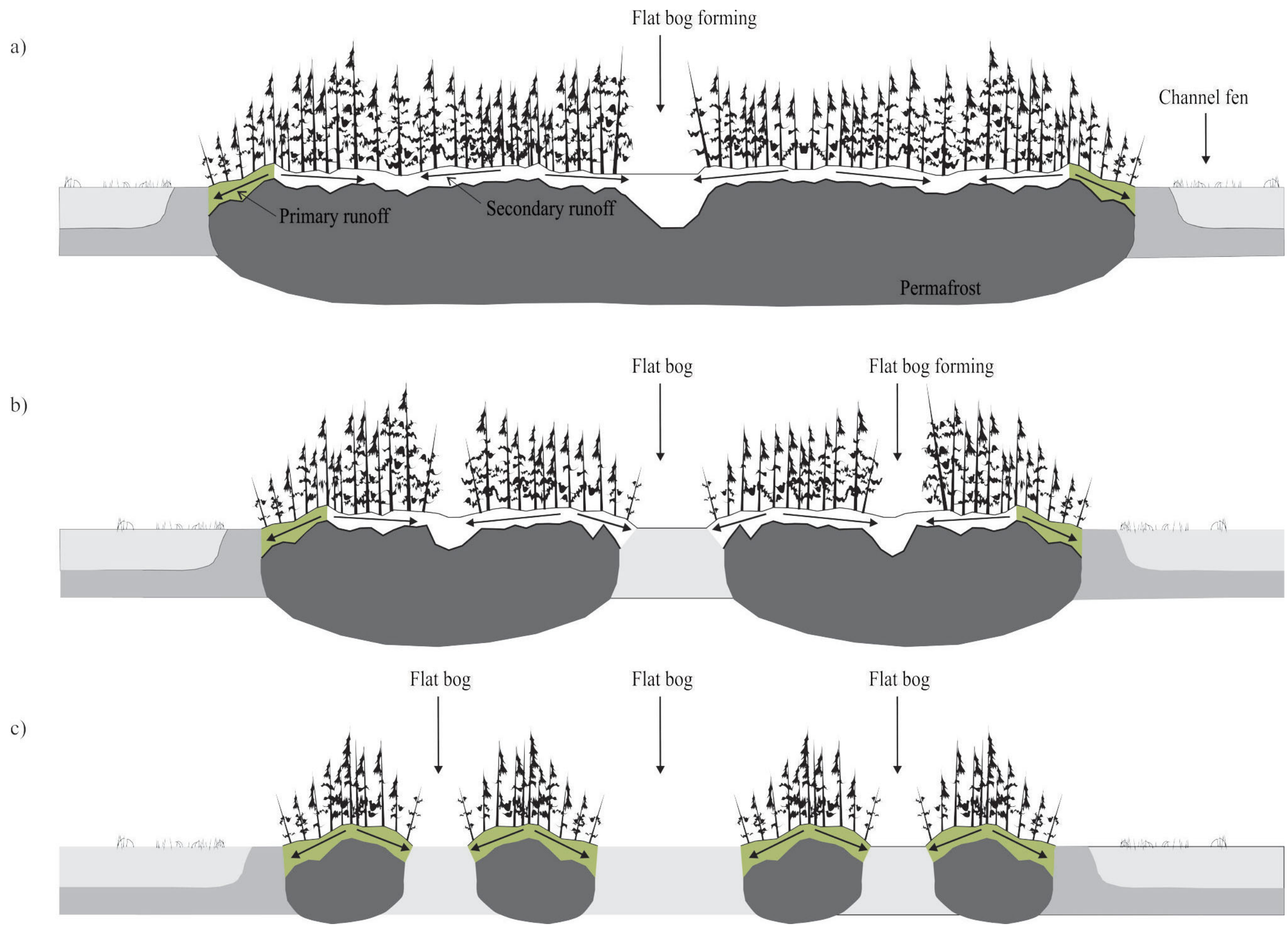

Figure 5. Conceptualization of permafrost-thaw–induced land-cover transformation in the wetland-dominated zone of discontinuous permafrost typical of the southern Taiga Plains: **a)** early stage (isolated bogs), **b)** transitional stage (isolated bogs or bog cascades) and **c)** advanced stage (plateau islands). Green areas represent the areas producing primary runoff. Examples of the early, transitional and advanced stages are identified by A, B and C in Figure 1c.

Primary runoff drains from the sloped edges of plateaus directly into the basin drainage network. Field measurements indicate that the entire primary runoff area supplies runoff to the fen throughout the thaw season. Secondary runoff drains into the interior of the plateau toward the topographic low, which is often occupied by bog within the plateau. If such a bog is hydrologically isolated, the runoff it received will remain in storage, evaporate or recharge the underlying aquifer. However, if it is part of a cascade, and if its storage capacity is exceeded, then the secondary runoff it receives will be conveyed toward the channel fen via the downslope bog or bogs. Secondary runoff is therefore, neither direct nor continuous. Its rate is greatest during periods of high moisture supply and minimal ground thaw, when the hydrological connection among the bogs of a cascade, and between individual bogs and their contributing 'bogsheds' is maximized. As the active layer thaws and drains, the contributing area for secondary runoff diminishes in size and secondary runoff therefore decreases or stops, leaving primary runoff as the predominant runoff process. However, secondary runoff can resume in response to large rain events.

Over decades of permafrost thaw, a plateau transforms through three general stages (Figure 5). Examples of each can be observed at Scotty Creek basin. For example, land cover 'A' represents an early stage of permafrost thaw where bogs are mostly hydrologically isolated, and as such, drainage into the fen is supplied only by primary runoff from the margins of the plateaus (Figure 5a). Land cover 'B' indicates a transitional stage of permafrost thaw where primary runoff is augmented by secondary runoff from bog cascades (Figures 1d, 5b). The activation of secondary runoff arises from the greater hydrological connectivity of land cover B than A. As a result, a greater proportion of the snowmelt and rainfall arriving on land cover B is converted to runoff than in land cover A (Figure 6). Land cover 'C' represents an advanced stage, where the shrinking peat plateaus occur as islands within an expansive bog (Figure 5c). By this stage, plateau diameters are on the order of a few

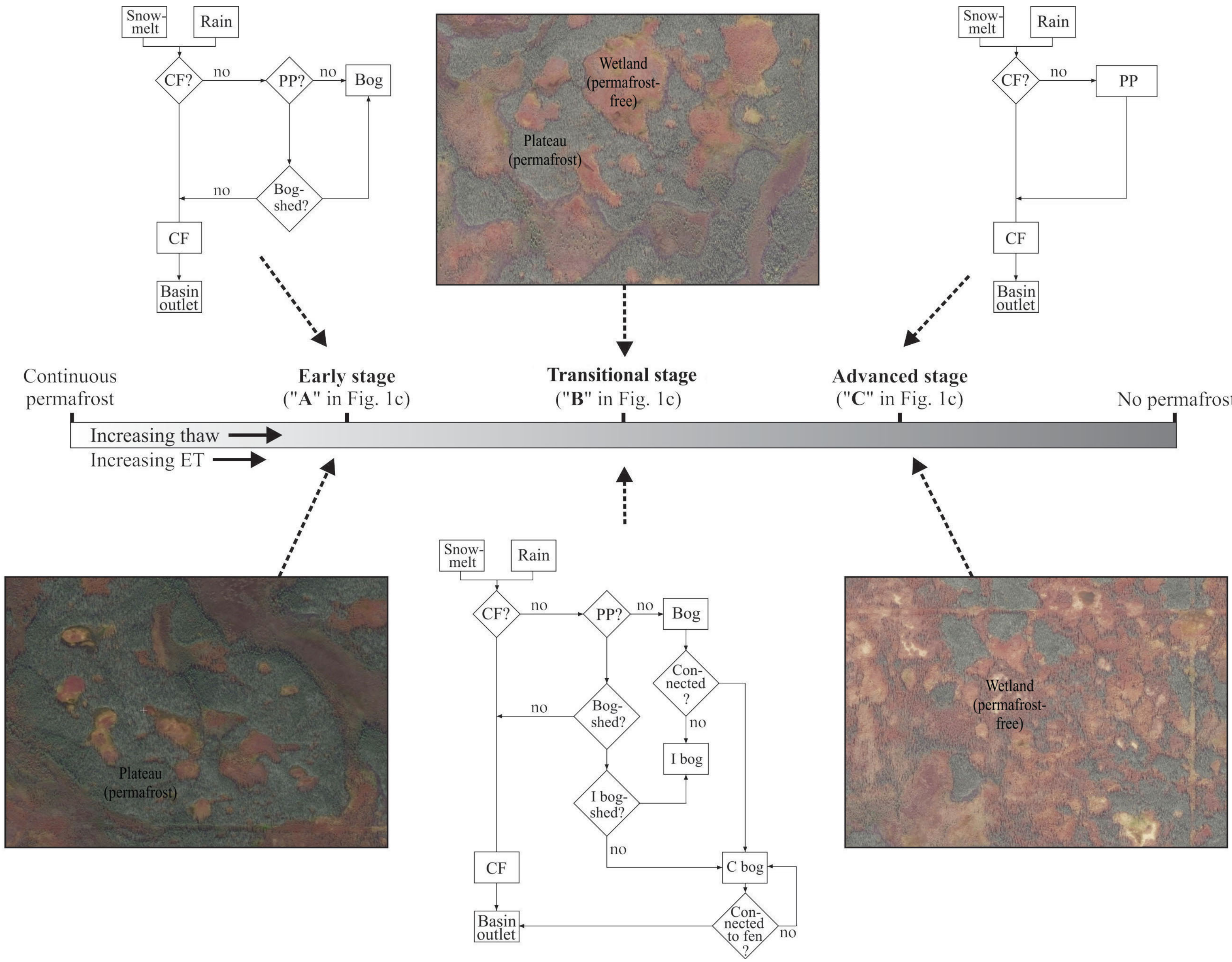

Figure 6. The transformation of runoff generation processes in peat plateaus with increasing thaw (and evapotranspiration) from left to right (image source NASA, 2017). Abbreviations: C, connected; CF, channel fen; ET, evapotranspiration; I, isolated; PP, peat plateau.

tens of metres and as such contain no secondary runoff and no interior bogs. Because land cover B is transitional between A and C, some bogs are hydrologically connected, whereas others remain hydrologically isolated.

As the land-cover transitions through the three stages, the way that peat plateaus generate runoff changes dramatically, with direct consequences on their runoff pattern and rate (Figure 6). Water arriving at the channel fen in each stage, is conveyed to the basin outlet. Water arriving in a primary-runoff–producing area of a plateau is routed directly to the adjacent fen. Water arriving directly into bogs or their bogsheds is prevented from reaching channel fens in the early stage, but can reach the fen in the transitional stage, if the bog is part of a cascade and is hydrologically connected to the downstream bog or bogs. Activation of secondary runoff therefore increases the amount of runoff between the early and transitional stages. Primary runoff may also increase between these two stages since the fragmentation of plateaus can increase the length of the overall plateau-fen edge. Water arriving onto plateaus in the advanced stage is neither stored nor routed as secondary runoff through bog cascades. As such, the advanced stage produces the greatest runoff per unit area of plateau surface, but given the relatively small total surface area of the remaining plateaus, the total plateau runoff is lowest in this stage.

Synthesis

By substituting space for time, the land-cover characteristics near the southern end of the north-south transect suggest that the trajectory of land cover change at Scotty Creek basin is toward increasing fragmentation and eventual disappearance of peat plateaus. Less clear is the trajectory of the intervening wetlands. The transect studies suggest that a concomitant expansion of the wetland area with the shrinkage and loss of peat plateaus would initially produce a wetter land cover characterized by expansive wetland with little forest cover. Although the hydrological connectivity of this stage would be high, the reduction of the plateau area reduces the impact of their relatively rapid flowpaths, and as a result, such a land cover may produce less runoff than presently observed at Scotty Creek basin. However, recent studies in the Scotty Creek region (e.g., Helbig et al., 2016) indicate increased average basin evapotranspiration as the relative coverage of wetland terrain increases (Figure 6). The transect studies also suggest that this initial wet stage is superseded by a drier land cover of the type presently observed near the NWT–BC border. In that region, the permafrost-free terrain is sufficiently dry to enable the regrowth of forest covers, which include black spruce (without permafrost) and a greater proportion of deciduous species. Although this synthesis provides some insights into the trajectory of land-cover and hydrological change in the southern Taiga Plains, there remain several significant unknowns. For example, the time scale over which the land-cover transitions will occur is not well understood. There is also a dearth of knowledge on how possible ecological and/or hydrological feedback mechanisms may affect trajectories of land-cover change. There is also little understanding of how such trajectories may change in response to changes in precipitation regimes, such as total annual precipitation (a proportion of which occurs in the form of snow), the number of multiday events and other precipitation distribution characteristics, and the timing of snowmelt.

Acknowledgments

Consortium for Permafrost Ecosystems in Transition is funded by a Natural Sciences and Engineering Research Council of Canada Collaborative Research and Development grant with partner contributions from Nexen, Petroleum Technology Alliance of Canada, Geoscience BC and BC Oil and Gas Research and Innovation Society. The authors gratefully acknowledge the support of Fort Nelson First Nation, Liidlii Kue First Nation, Jean Marie River First Nation, Government of the Northwest Territories and Government of British Columbia. This article benefited from a review by M. English at Wilfrid Laurier University.

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