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Final Report for Consortium for Permafrost Ecosystems in Transition (CPET)

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SUMMARY

Climate warming in the southern Taiga Plains ecoregion of northwestern Canada has led to unprecedented rates of permafrost thaw and a myriad of land-cover changes with uncertain impacts on hydrology. As a result there is growing uncertainty in regards to the future availability of water resources in this region. This report synthesises key findings of *CPET*'s hydrology field studies and remote sensing analyses of land-cover change in the southern Taiga Plains to improve the understanding of the trajectory of land-cover change in this region and how such change can be expected to influence water flow and storage processes.

KEYWORDS

Permafrost thaw; landcover change; peatlands; Boreal; hydrology.

1. INTRODUCTION

Northwestern Canada is one of the most rapidly warming regions on Earth, and permafrost thaw is one of the most important and dramatic manifestations of warming in this region. Permafrost thaw has wide ranging environmental impacts that include rapid changes in geomorphology (*e.g.* Jorgenson *et al*., 2013); browning of the forest (Michaelian *et al*., 2011); frequency and severity of wild fires (Flannigan *et al*., 2009); soil drainage (Jorgenson *et al*., 2013) flow path lengths and transit times (Jones & Rinehart, 2010); biogeochemical fluxes (Gordon *et al*., 2016), thermakarst lake storage (Korosi *et al*., 2017), groundwater fluxes (Bense *et al*., 2009), and other impacts. Thaw is particularly pronounced in the southern margin of discontinuous permafrost (Kwong & Gan, 1994), where permafrost is thermally insulated by an organic cover of dry peat, allowing it to persist even where mean annual air temperatures are positive (Smith & Riseboroug, 2002). Such "ecosystem-protected permafrost" (Shur & Jorgenson, 2007) is particularly susceptible to thaw since it is already at the melting point temperature, and its discontinuous nature enables energy to enter individual permafrost bodies not only vertically from the ground surface (as for continuous permafrost), but also laterally from adjacent permafrost-free terrain. Furthermore, because such bodies are relatively thin (<10 m), permafrost thaw in this southern margin often quickly leads to local disappearance of permafrost (Beilman & Robinson, 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, a situation made worse by uncertain environmental feedbacks on the rates and patterns of such thaw.

Despite the large number of studies documenting the environmental impacts of permafrost thaw, there remains little consensus on the trajectory of the thaw-induced land-cover change in the southern Taiga Plains. Since hydrological functions vary among land-covers, a change in their relative proportion influences the water balance of drainage basins. To properly manage the water resources of the southern Taiga Plains, decision makers in both government and industry and in

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local communities require an understanding of 1) the hydrological differences among the major land-cover types, and 2) how permafrost thaw is changing the relative proportions of these land-covers. An understanding of these two factors will allow new insights into the trajectory of land-cover change and its implications on regional water resources. By synthesising recent hydrological field and remote sensing studies, this paper provides key insights into the trajectory of land-cover change in the southern Taiga Plains, and how this may affect water resources.

2. METHODS AND SITE DESCRIPTION

This study is focussed on the southern Taiga Plains ecoregion in northwestern Canada (Figure 1a), and draws mainly from studies conducted at Scotty Creek (61°18' N, 121°18' W), a 152 km^2 drainage basin 50 km south of Fort Simpson, Northwest Territories (NWT) (Figure 1b). Scotty Creek basin is underlain by discontinuous permafrost (Hegginbottom & Radburn, 1992) and is covered by peatland complexes typical of the 'continental high boreal' wetland region (NWWG, 1988). The peat thickness at Scotty Creek 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 & 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 and 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 (MSC, 2013). Snowmelt usually commences in early to mid-April and continues throughout most of the month, so that by May, only small amounts of snow

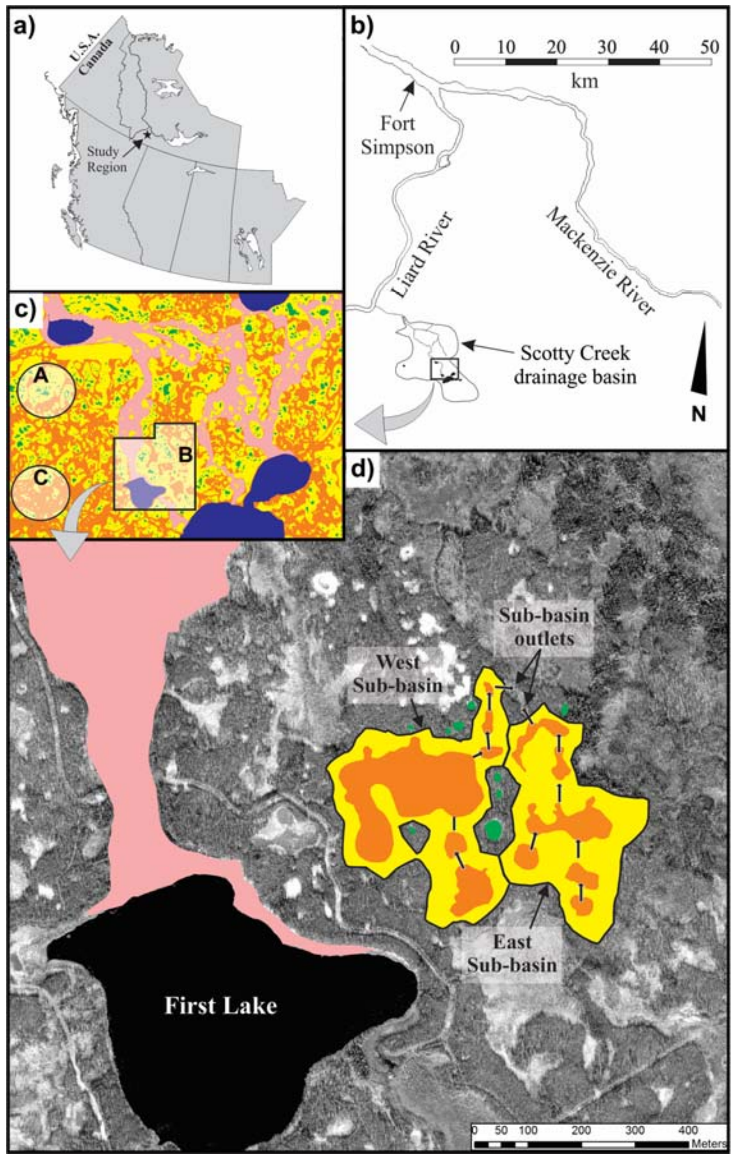

Figure 1: a) study region and b) Scotty Creek; c) peat plateaus (yellow), isolated (green) and connected (orange) bogs, channel fens (pink); d) enlargement of "B" showing cascade bogs.

remain (Hamlin *et al.*, 1998). This paper draws on numerous published and unpublished studies involving both hydrometric field observations and aerial/satellite image analysis. Collectively these studies were used to inform conceptualisations of coupled land-cover and hydrological change presented herein.

3. RESULTS AND DISCUSSION:

Ice-rich permafrost in the form of tree-covered peat plateaus dominates much of the fringe zone, where plateaus rise 1 to 2 m above the surrounding wetland terrain of flat bogs and channel fens. Figure 1c shows a classified Ikonos image acquired in 2000, of a 22 km^2 subarea within the Scotty Creek basin where permafrost plateaus occupy the largest (43%) portion of the subarea, followed by expansive bogs that are hydrologically connected to channel fens (23%), channel fens (21%), lakes (9%) and isolated flat bogs, also known as collapse scar bogs (4%). Unlike the expansive bogs, the isolated bogs are surrounded by raised permafrost and as such are unable to exchange surface or near-surface flows with the fens. The contrasting biophysical properties of these peatland types, gives each a specific role in the water cycle (Quinton *et al*., 2003). The plateaus function primarily as runoff generators, given their relatively high topographic position and limited capacity to store water. 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 (during periods of hydrological connection) expansive bogs, is conveyed laterally along their broad (~50-100 m), hydraulically rough channels to streams and rivers (Quinton *et al*., 2003).

Permafrost thaw increases the cover of the bogs and fens at the expense of the forested peat plateaus. Using tree-cover as a proxy for the presence of permafrost, the area underlain by permafrost at Scotty Creek 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 that estimated for the larger southern Taiga Plains region, where 30%-65% of the permafrost has degraded over the last 100-150 years (Beilman & Robinson, 2003). The above mentioned percentages of Figure 1c occupied by each cover type should be assumed to be in transition.

Recent hydrological field studies at Scotty Creek (Connon *et al*., 2014) provides valuable insights into the nature of this transition and how it affects water flow and storage processes. They described ephemeral flow from bogs that were previously assumed to be hydrologically isolated. Specifically, during periods of high moisture supply, water was found to cascade bog-to-bog and then into 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 (Figure 2) show the amount of water that would otherwise have remained on the plateau in the absence of the bog-to-bog drainage process. 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.

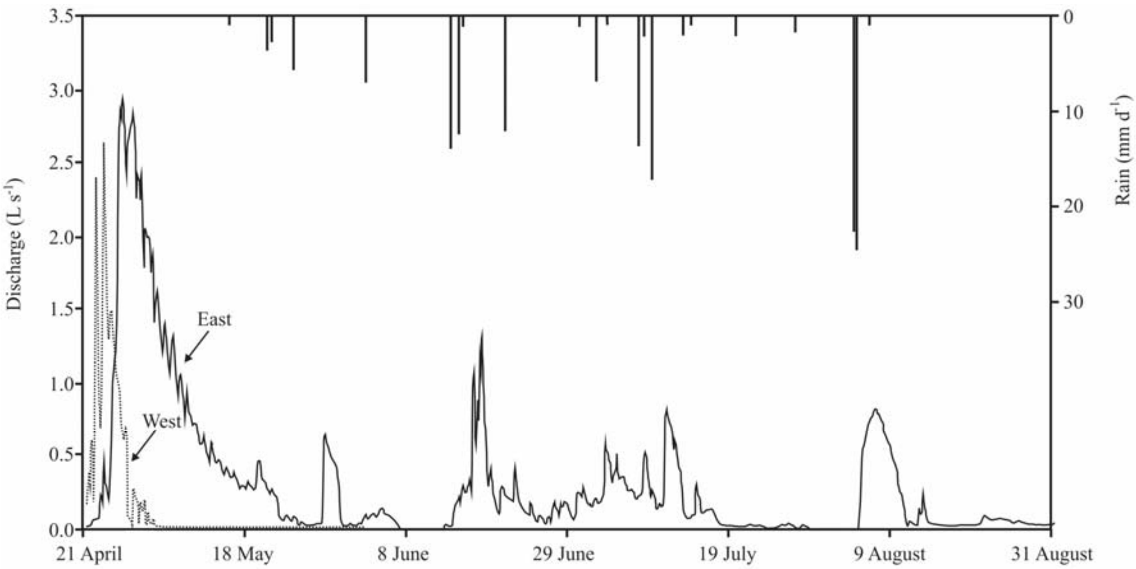

Figure 2: Runoff hydrographs measured at outlets of East and West bog cascades for 2014.

Connon *et al*. (2015) compared historical images of Scotty Creek, and showed that numerous bogs that were isolated from the basin drainage network in 1970 (Figure 3a) had become connected to it by 2010 (Figure 3b). This 'bog capture' process increases basin runoff by increasing the basin's runoff contributing area (Connon *et al*., 2014). Therefore, in addition to initiating or at least enhancing bog-to-bog drainage cascades, permafrost thaw also transforms hydrologically-isolated bogs into 'open' bogs by removing the permafrost that once separated such a bog from the a near-by channel fen. This land-cover transformation is important hydrologically because it adds 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 merge into other bogs, a process that increases both the bog and slope drainage contributions to fens.

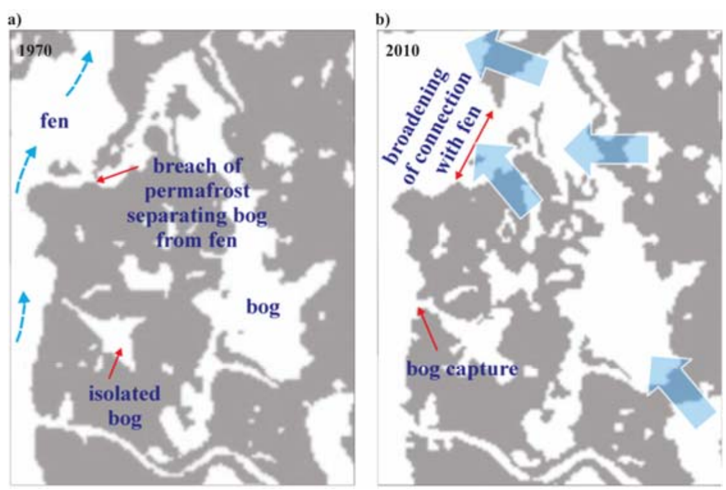

Figure 3: Classified images for a 1 km^2 area in the Scotty Creek catchment showing the change in permafrost coverage (grey) between 1970 (a) and 2010 (b). The large arrows in (b) signify subsurface flow through taliks to the basin drainage network of channel fens.

Figure 4a depicts an example of the bog capture process as it evolved between 2006 and 2015, based on detailed ground surface elevation and permafrost table depth surveys. As the permafrost table lowered between these two years, the plateau surface subsided and was flooded by the adjacent bog or fen, a process leading to loss of forest and expansion of the wetlands. By 2015, the permafrost table was below the elevation of the water tables of the bog and fen, and as a result, the permafrost body no longer obstructed subsurface flow from the bog, through the plateau, to the fen (Figure 4b). Furthermore, by 2015, a talik (*i.e.* perennially unfrozen layer) had formed which enabled the plateau to conduct subsurface flow throughout the year from the bog, down-gradient to the fen. Subsurface flow through the talik (Figure 3b) augments the surface and near surface flows into channel fens.

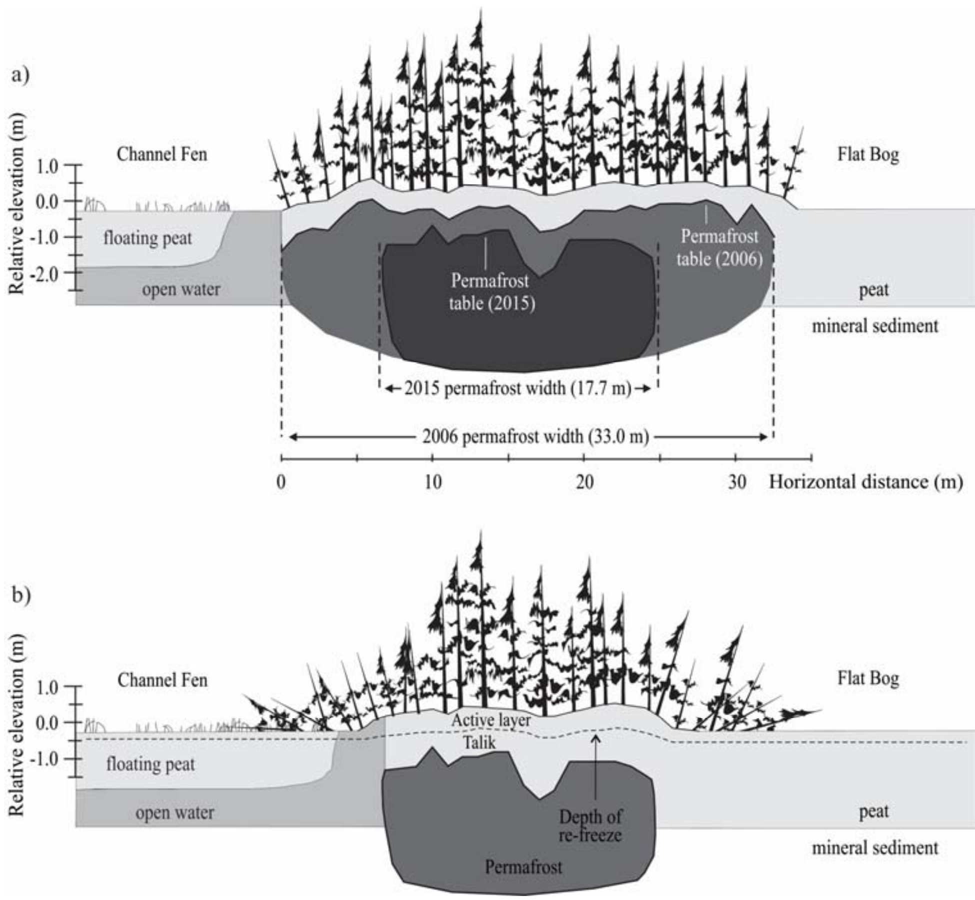

Figure 4: Cross section of a peat plateau at Scotty Creek based on measurements of supra-permafrost thickness and ground surface elevation at 1 m intervals showing the difference in depth and lateral extent of the permafrost table between 2006 and 2015 (a) and the development of a talik in 2015 (b).

There are strong indications that permafrost thaw and the resulting land-cover changes have affected basin water balances, as suggested by rising river flows throughout the border region (St. Louis & Sauchyn, 2009). Most notably, the total annual runoff from all gauged rivers in the lower Liard River valley of the NWT has steadily risen since the mid-1990s (Connon *et al*., 2014). The current understanding of water flow and storage processes in wetland dominated, discontinuous permafrost terrains, and how climate warming and the resulting ecological changes affects these processes, cannot explain this rise in flows, nor is it sufficient to predict future flows. Rising flows from subarctic rivers are often attributed to 'reactivation' of groundwater systems (*e.g.* St. Louis & Sauchyn, 2009), but the very low hydraulic conductivity of the glacial sediments below the peat, precludes appreciable groundwater input. Permafrost thaw-induced changes to basin flow and storage processes offers a more plausible explanation for rising river flows in this region (Connon *et al*., 2015).

Field observations and image analyses (Baltzer *et al*., 2014) suggest that plateaus contain two distinct runoff source areas separated by a break in slope approximately 10 m inland from the fen-plateau edge (Figure 5). Primary runoff drains from the sloped edges of plateaus directly into the basin drainage network (*i.e.* a channel fen). Field measurements suggest that the entire primary area supplies runoff to the fen throughout the thaw season. Secondary runoff drains into the interior of the plateau toward the topographic low often occupied by a bog. If the receiving bog is hydrologically isolated, the runoff it received will remain in storage, evaporate or recharge the underlying aquifer. If the receiving bog is part of a bog cascade, and if its storage capacity is exceeded, then the secondary runoff it receives will be routed toward the channel fen via the down slope bog or bogs. Secondary runoff is therefore, neither direct nor continuous. The rate of secondary runoff 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 "bog-sheds" is maximised. As the active layer thaws and drains, the contributing area shrinks and secondary runoff decreases. Large rain events can temporarily reverse this decrease.

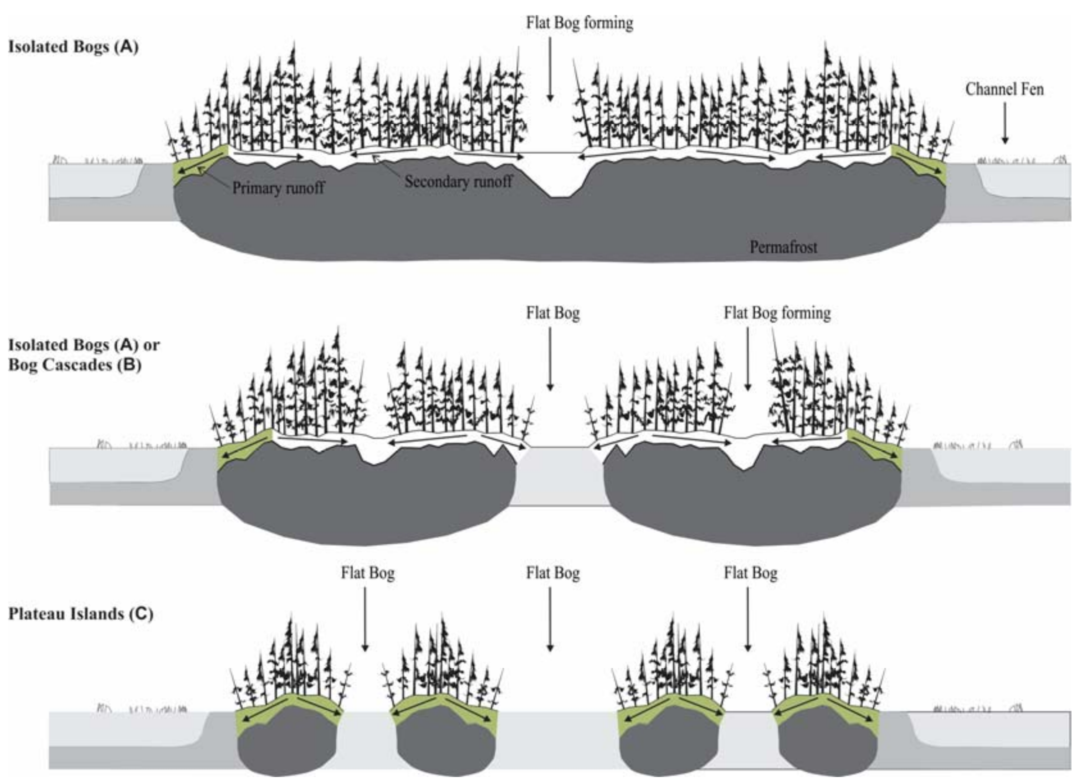

Figure 5: Conceptualisation of permafrost thaw induced land-cover transformation in the wetland-dominated zone of discontinuous permafrost typical of the southern Taiga Plains. Green areas represent the areas producing primary runoff.

Over a period of decades, the plateaus conducting primary and secondary runoff transform as a result of permafrost thaw (Figure 5). Three general stages can be seen from Figure 1c. In chronological sequence, the area indicated by "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. "B" represents an intermediate stage of permafrost thaw where primary runoff is augmented by secondary runoff from the ephemeral bog cascades. 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 the previous stage (Figure 6). Because B is transitional between A and C, some bogs are hydrologically connected (via surface or near surface flow and/or talik flow), while other bogs remain hydrologically isolated. "C" represents an advanced stage, where the shrinking peat plateaus occur as islands within an expansive bog complex. Interestingly, this stage is a near mirror image of "A" where it is the bogs that occur within an extensive plateau complex. By stage "C", plateau diameters are on the order of a few tens of metres and as such contain no secondary runoff and no interior bogs.

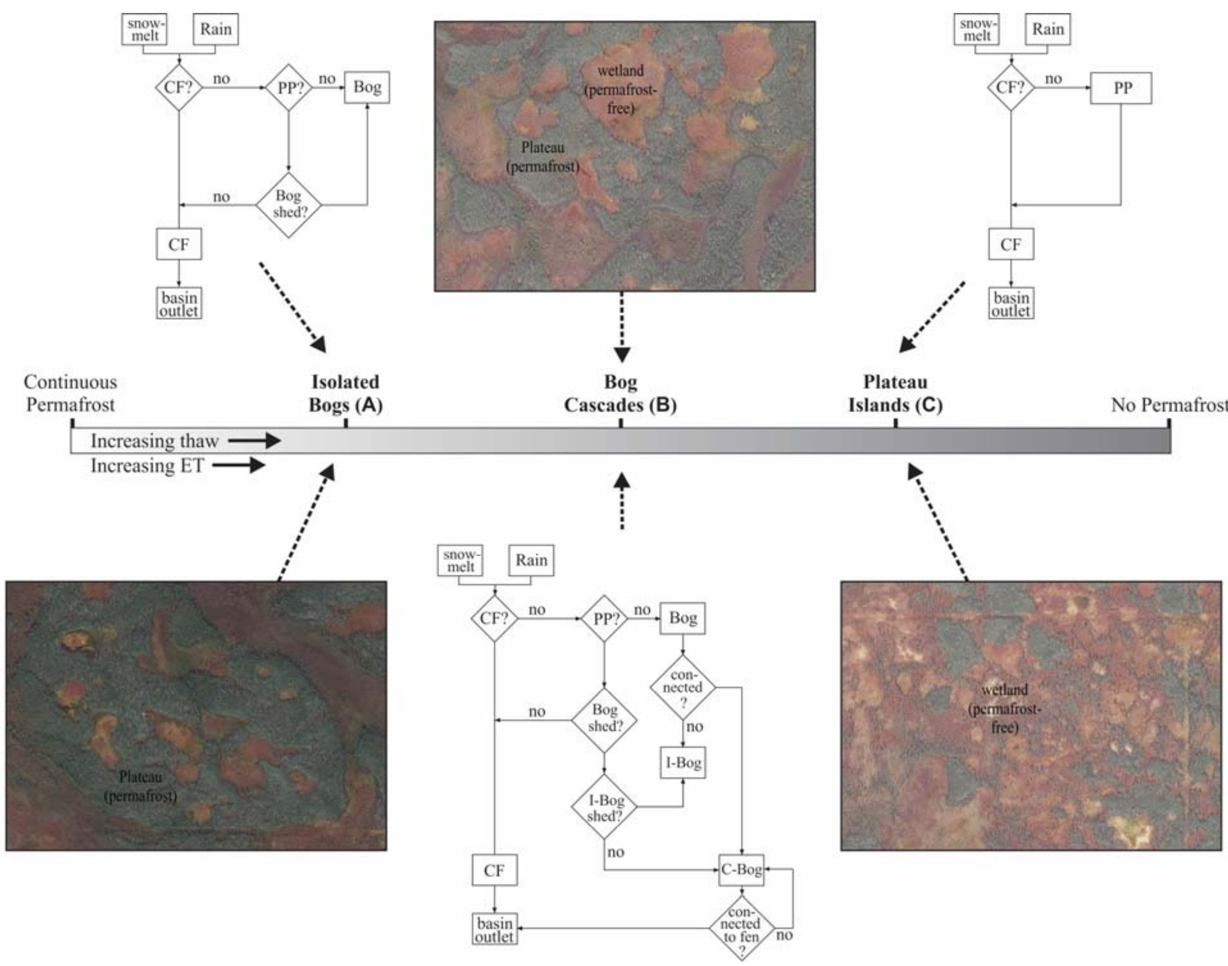

Figure 6: The transformation of peat plateau runoff generation processes with increasing thaw from left to right. PP = peat plateau, CF = channel fen, I = isolated, C = connected.

As the land-cover transitions from the isolated bog (A) to the plateau islands (C) stages, the way in which peat plateaus generate runoff changes dramatically, with direct consequences on their runoff pattern and rate (Figure 6). For each stage, water (snowmelt or rainfall) arriving in the channel fen is conducted directly to the basin outlet. Likewise, water arriving on a plateau but not within a bog catchment (*i.e.* bogshed) is routed directly to the adjacent fen. Water arriving directly into bogs or their bogsheds is prevented from reaching channel fens in stage A, but can reach the latter in stage B depending upon the degree of hydrological connectivity in the bog cascades. Activation of secondary runoff therefore increases the amount of runoff between stages A to B. Primary runoff may also increase between these two stages since the fragmentation of plateaus increase can increase the length of the overall plateau-fen edge. Water arriving onto plateaus in stage C is neither stored nor routed as secondary runoff through bog cascades and as such this stage provides the most direct runoff response. However, stage C has the lowest plateau runoff since it is capable only of generating primary runoff, and this runoff is generated from the relatively small total surface area of the remaining plateaus.

4. SUMMARY & FUTURE DIRECTIONS

Studies at Scotty Creek have recently expanded to include remote sensing and ground-based observations along a ~200 km transect that extends from Scotty Creek southward to the NWT-British Columbia border. By substituting space for time, the land-cover characteristics near the southern end of this transect suggests that the trajectory of Scotty Creek is towards increasing fragmentation and eventual disappearance of peat plateaus. Less clear is the trajectory of the intervening wetland (*i.e.* bog and fen) terrains. The transect studies suggests that a concomitant expansion of the wetland area with the shrinkage and loss of peat plateaus would initially produce a wetter land-cover characterised 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. However, recent studies in the Scotty Creek region (*e.g.* Helbig *et al.*, 2016) indicate increased basin average evapotranspiration (ET) 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-British Columbia border. In that region, the permafrost-free terrain is sufficiently dry to enable the regrowth of forest covers that 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, the proportion of the latter occurring in the form of snow, the number of multi-day events and other precipitation distribution characteristics, and the timing of snowmelt.

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