Thaw-Induced Land-Cover Change in the Southern Margin of Discontinuous Permafrost, Northeastern British Columbia and Southwestern Northwest Territories

K.M. Haynes, Cold Regions Research Centre, Wilfrid Laurier University, Waterloo, ON, khaynes@wlu.ca

O.A. Carpino, Cold Regions Research Centre, Wilfrid Laurier University, Waterloo, ON

R.F. Connon, Cold Regions Research Centre, Wilfrid Laurier University, Waterloo, ON

É. Devoie, Department of Civil and Environmental Engineering, University of Waterloo, Waterloo, ON

W.L. Quinton, Cold Regions Research Centre, Wilfrid Laurier University, Waterloo, ON

Haynes, K.M., Carpino, O.A., Connon, R.F., Devoie, É. and Quinton, W.L. (2019): Thaw-induced land-cover change in the southern margin of discontinuous permafrost, northeastern British Columbia and southwestern Northwest Territories; *in* Geoscience BC Summary of Activities 2018: Energy and Water, Geoscience BC, Report 2019-2, p. 123–132.

Introduction

The landscape of the sporadic to discontinuous permafrost zone in the southern Taiga Plains ecoregion is undergoing rapid change as a result of accelerating rates of permafrost loss with a warming climate (Baltzer et al., 2014; Lara et al., 2016). Both vertical permafrost thaw with energy transfer from the ground surface and lateral permafrost degradation with advective transfer of energy from adjacent permafrost-free wetlands results in significant losses of permafrost terrain in this region (Rowland et al., 2010; Quinton et al., 2011). With the loss of underlying permafrost bodies, elevated forested peat plateaus subside and become inundated as they transition to treeless wetland features on the landscape (Quinton et al., 2011). Peat plateaus function as runoff generators due to their elevated topographic position and their limited water storage capacity (Wright et al., 2009). Permafrost barriers impede significant subsurface flow and collapse scar bogs, which form on the permafrost terrain, are hydrologically isolated from the basin drainage network and function as water storage features. As permafrost ‘dams’ are lost due to thaw and ground subsidence, formerly isolated bogs become connected to the drainage network through the process of ‘bog capture’ (Connon et al., 2014) facilitating more direct and efficient drainage of the landscape. Thaw-induced landscape changes in the sporadic to discontinuous permafrost zone catalyze significant rerouting of water through the landscape, which may have long-term impacts on water availability in northern communities.

Discharge from discontinuous permafrost basins throughout the Northwest Territories (NWT) has increased significantly over long-term (more than 30 years) records, with considerable increases in flow occurring in the southern NWT (St. Jacques and Sauchyn, 2009). This increase in basin runoff has not been accompanied by an increase in precipitation over this period. The magnitude of such increases cannot solely be accounted for by the water derived from thawing permafrost and therefore is likely due to the expansion in runoff contributing area as previously isolated wetlands are ‘captured’ by the drainage network, activating both surface and subsurface hydrological flowpaths (Connon et al., 2014). The sustainability of the observed increase in basin runoff throughout the sporadic and discontinuous permafrost region is unclear. However, a maximum threshold in the amount of water contributed to runoff will likely be met as all bogs become incrementally connected to the drainage network as permafrost barriers are lost (Haynes et al., 2018). With continued permafrost loss, increased fragmentation and shrinking of peat plateaus are anticipated to occur (Baltzer et al., 2014). As the landscape transition catalyzed by permafrost thaw results in significant loss of forest cover, the progression of such large-scale changes can be monitored with remotely sensed imagery of land cover and coupled with standard climate and environmental variables to provide insight into the controls and conditions associated with the progressive stages of increasing wetland extent at the expense of forest cover (Carpino et al., 2018). A latitudinal gradient in the extent of permafrost loss and the associated pattern of land-cover type spanning the southern Taiga Plains ecoregion can be utilized as a reasonable space-for-time proxy to understand the trajectory of thaw-induced land-cover transition.

The overall objective of this project is to understand the trajectory of sporadic to discontinuous permafrost environments, with continued climatic warming, by examining the landscape changes at 10 subarctic boreal sites along a latitudinal transect spanning from the southern NWT to northeastern British Columbia (BC). This transect was established by the Consortium for Permafrost Ecosystems in

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Transition (CPET) to understand the implications of climate- and industry-induced changes to the landscape on the availability of water resources in the region. An in-depth study of the impacts of permafrost-thaw-induced landscape change on the hydrology of the most northerly site along the transect, the Scotty Creek basin, NWT, is examined to understand the role of wetlands in either storing or conveying water as elevated permafrost plateaus become inundated and are lost over time.

Methods

The north-south CPET transect spans a distance of approximately 200 km at the southern margin of thawing discontinuous to sporadic permafrost, from the southern NWT to northeastern BC (Figure 1). The landscape along this transect is dominated by peatlands with fragmented forested peat plateaus underlain by permafrost interspersed with permafrost-free wetlands including channel fens and bogs. The area underlain by permafrost has decreased significantly along this transect accompanied by an increase in surface water on the landscape, as permafrost terrain transitions to wetland cover with permafrost thaw (Robinson and Moore, 2000; Quinton et al., 2011; Baltzer et al., 2014). Along this transect 10 areas of interest (AOI) characterized by plateau-wetland complexes were selected to examine the rate and pattern of forest cover transition to wetland using remotely sensed imagery over a period of approximately 40 years (Figure 1). These 10 AOI range in latitude from 59.96 to 61.30°N (Figure 1). The trends in forested permafrost plateau loss across these AOI were related to climatic and environmental variables including annual and seasonal temperature and precipitation as well as latitude and degree of plateau fragmentation (perimeter-to-area ratio) for each AOI.

A 15-year examination of water level trends on both peat plateaus and wetland features was conducted in the headwaters of the Scotty Creek basin, NWT (61.30°N, 121.30°W), the most northerly location on the CPET transect. The purpose of this case study was to examine over time the water storage trends of the dominant landscape features characteristic of the plateau-wetland complexes in the discontinuous to sporadic permafrost region. The headwaters area, located in the southern portion of the basin, is entirely composed of peatland land-cover types, including permafrost plateaus, bogs and fens. Water levels were monitored from 2003 to 2017 on a degrading peat plateau, a channel fen, as well as bogs both isolated from and connected to the drainage network. Given the hypothesis that the process of bog capture significantly contributes to basin drainage (Connon et al., 2014), the magnitude of enhanced runoff observed from the Scotty Creek basin since discharge measurements began in 1996 was compared to the overall loss of water storage from wetlands as they became connected to the drainage network over a similar 15-year timeframe. The magnitude of permanent and transient contributions to basin runoff including precipitation-induced changes in runoff from direct precipitation on the channel fen, and the nonprecipitation-induced sources of primary runoff from the plateau flanks, and moisture derived from thawing permafrost were estimated and similarly compared to the observed excess runoff from the basin. The partitioning of runoff contributions in the Scotty

AOI	Unofficial name	Location
A	Scotty Creek, NWT	61.30°N, 121.30°W
B	Deep Lake, NWT	61.19°N, 120.45°W
C	Trout lake, NWT	60.74°N, 121.05°W
D	Trout River tributary, NWT	60.65°N, 120.64°W
E	Paradise river, NWT	60.55°N, 120.81°W
F	Tetcho Lake, NWT	60.42°N, 120.84°W
G	Trainor lake, NWT	60.41°N, 120.41°W
H	Island river, NWT	60.10°N, 120.56°W
I	Hossitl Creek, BC	59.96°N, 120.84°W
J	Calendar Creek, BC	59.97°N, 120.34°W

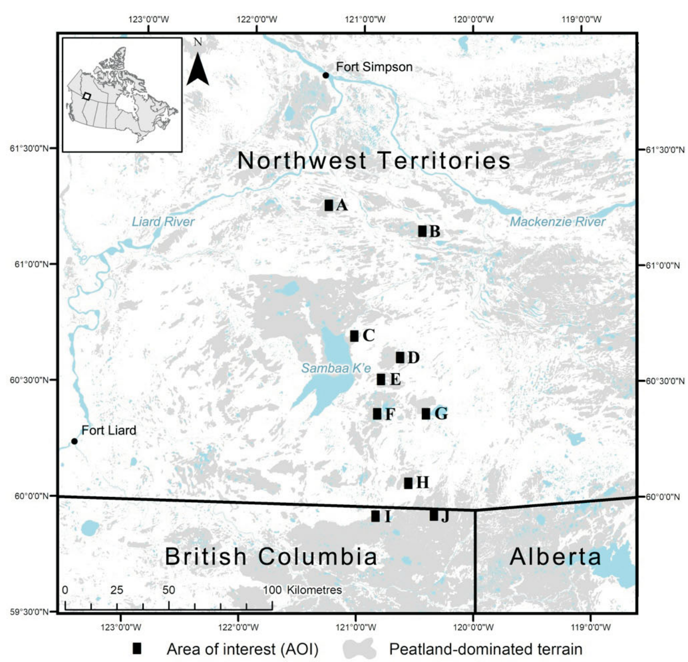


Figure 1. Locations of 10 areas of interest (A–J), northeastern British Columbia and southwestern Northwest Territories. Adapted from Carpino et al. (2018).

Creek basin facilitated the proposal of a new conceptual model detailing the role and timing of wetland water storage as bogs become increasingly connected to the drainage network with permafrost thaw.

Results

Latitudinal Land Cover Transition

All 10 AOI, which span the north-south latitudinal transect, experienced net forest loss over the 40-year period of study, from 1970 to 2010 (Figures 2, 3). This net loss of forest decreased along the latitudinal gradient, with a maximum value of 11.6% at the northerly Scotty Creek, NWT, AOI (61.30°N), and a minimum value of 6.9% at the southerly Hossitl Creek, BC, AOI (59.96°N; Figure 2). At the seven most northerly AOI, the magnitude of net forest loss closely resembled the trend in total forest loss, as rates of forest gain in these locations were negligible (ranging from 0.2 to 1%). In contrast, the two southernmost AOI experienced considerable gross forest gain, on the order of 6 to 10%, over the 40-year period (Figure 2).

Predictors of Landscape Transition

With the examination of correlative relationships between landscape change (using the metrics of net forest loss, forest loss and forest gain at each AOI) and climatic and environmental variables along the transect, several factors emerged as significant indicators of landscape transition. Mean annual air temperature was positively correlated with both forest loss and forest gain over the study period (r = 0.647, r = 0.794, respectively; see Table 1). Seasonal influences of temperature were also observed, with a significant negative correlation between average winter temperature and net forest loss (r = –0.782; Table 1) and a positive correlation between average winter temperature and forest gain (r = 0.745; Table 1) between 1970 and 2010. However, average summer temperature did not exhibit a significant correlation with any of the landscape change metrics (Table 1). On an annual timeframe, average annual precipitation was significantly negatively correlated with net forest loss (r = –0.636) and positively correlated with forest gain (r = 0.661; Table 1). These trends between precipitation and landscape transition are driven by summer precipitation, with a negative correlation between average summer precipitation and net forest loss (r = –0.636) and a positive correlation with forest gain (r = 0.709; Table 1). No significant correlations were observed between average winter precipitation and the metrics of landscape change.

Changes in climatic variables over the 40-year study period from 1970 to 2010, likely resulting from a changing climate, significantly affected net forest loss. Changes in both summer and winter temperatures were positively correlated with net forest loss (r = 0.690, r = 0.691, respectively; see Table 1). Winter precipitation changes over this 40-year period were negatively correlated with net forest loss (r = –0.762; Table 1) and positively correlated with forest gain (r = 0.726; Table 1). However, changes to summer precipitation from 1970 to 2010 did not significantly influence landscape change.

Case Study of Landscape Change: Examining AOI A, Scotty Creek, NWT

Trends in Wetland Water Storage

Over the 15-year period from 2003 to 2017, the water levels in bogs, with varying degrees of connection to the drainage network, declined (Table 2; Figure 4). The magnitude of water drained from connected bogs over this period ranged from 44 to 219 mm (Table 2; Figure 4). The average loss of water previously stored in isolated bogs that are now con-

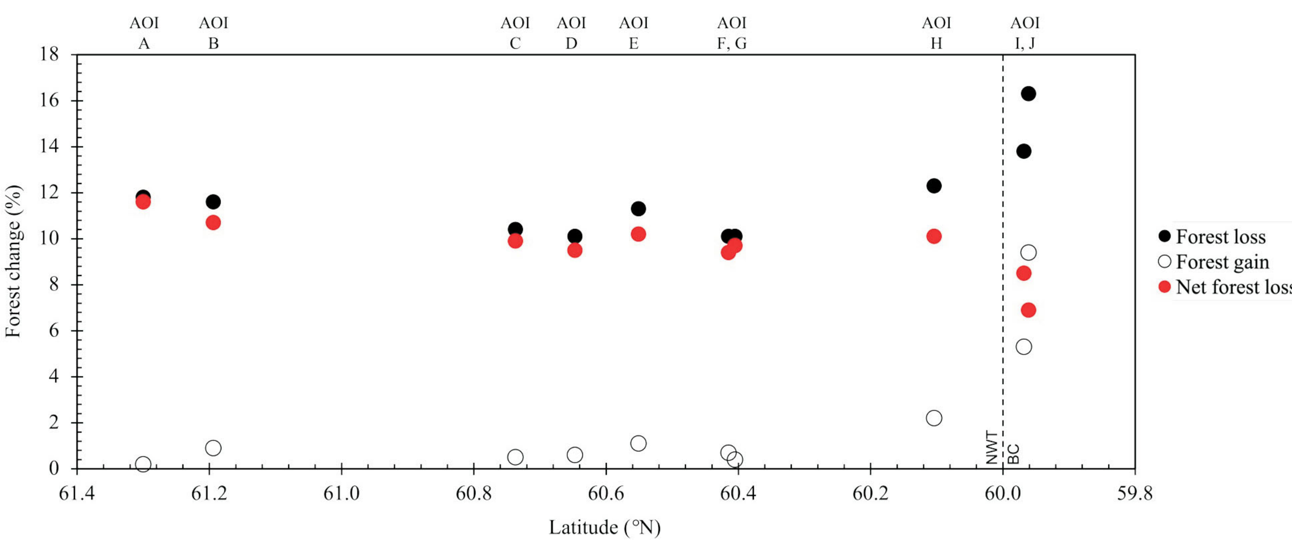


Figure 2. Relationships between net forest loss, forest loss and forest gain with latitude over the 1970 to 2010 study period for the 10 areas of interest (AOI), British Columbia (BC) and Northwest Territories (NWT). Adapted from Carpino et al. (2018).

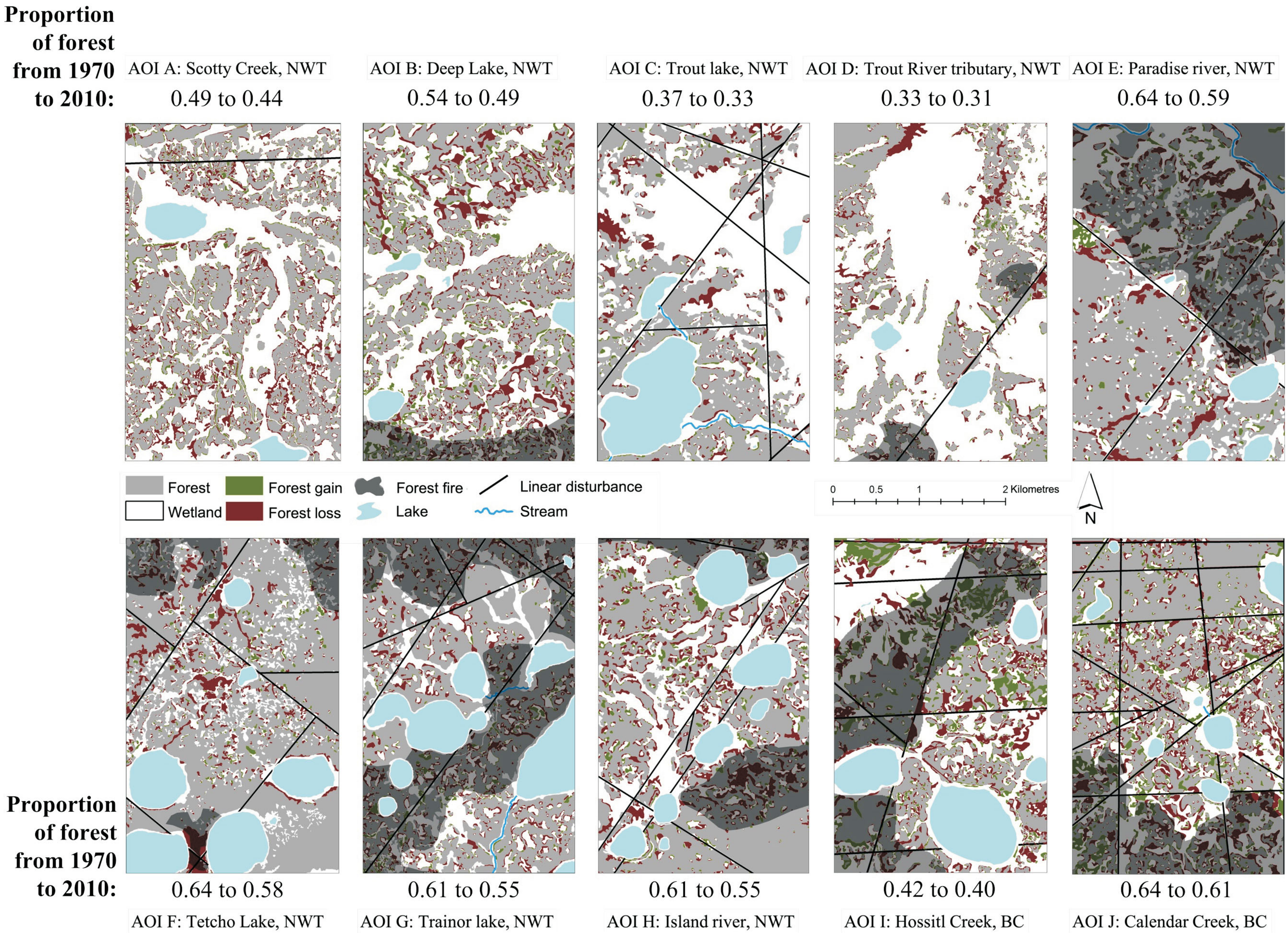


Figure 3. The proportion of land classified as forested, and predictably underlain by permafrost, in 1970 and 2010, for a representative 10 km^2 subset of each of the areas of interest (AOI). Areas of forest loss and gain are presented alongside areas burned by forest fires during this 40-year period and areas of linear disturbance. Adapted from Carpino et al. (2018).

Table 1. Nonparametric correlation associations between net forest loss, forest loss and forest gain with climatic variables including average temperatures (T_{avg}; 1970–2010), and average annual precipitation (P_{avg}) as well as seasonal factors over the study period (1970–2010) including average winter and summer temperatures, average winter and summer precipitation, change in winter and summer temperature (ΔT; 1970–2010) and change in winter and summer precipitation (ΔP; 1970–2010). Significant (p <0.05) correlations have been highlighted by bold text. Adapted from Carpino et al. (2018).

	T_{avg} (1970–2010)	P_{avg} (1970–2010)	T_{avg} winter (1970–2010)	T_{avg} summer (1970–2010)	P_{avg} winter (1970–2010)	P_{avg} summer (1970–2010)	ΔT winter (1970–2010)	ΔT summer (1970–2010)	ΔP winter (1970–2010)	ΔP summer (1970–2010)
Net loss	-0.491	**-0.636**	**-0.782**	0.273	-0.612	**-0.636**	**0.691**	**0.690**	**-0.762**	0.333
Loss	**0.647**	0.313	0.387	0.387	0.362	0.436	-0.313	-0.171	0.401	-0.483
Gain	**0.794**	**0.661**	**0.745**	-0.018	0.612	**0.709**	-0.587	-0.527	**0.726**	-0.602

Table 2. Change in mean water level (mm) from 2003 through to 2017 calculated from best-fit trend for each of the eight long-term monitoring wells within the 0.25 km^2 area of study within the area of interest at Scotty Creek (see Figure 4). The p-values of significant regression trends are in bold. Adapted from Haynes et al. (2018). Abbreviation: CI, confidence interval.

Site		Change in mean water level over record (mm)	Regression p-value
Peat plateau	Plateau interior	-205	0.06
	Plateau edge	-511	**< 0.001**
Fen	Fen	-38	0.50
Isolated bogs	I-bog 1	+38	0.60
Connected bogs	C-bog 1 (fully connected)	-219	**< 0.0001**
	C-bog 2 (fully connected)	-44	0.22
	C-bog 3 (partially connected)	-110	0.06
	C-bog 4 (partially connected)	-164	**0.03**
All connected bogs - areal-weighted mean (n = 4 bogs) ±95% CI	Areal-weighted mean:	-109 ± 15	
	With porosity of 0.85:	-93 ± 13	
	Watershed scale:	**-46 ± 6**	

nected bogs, as a result of permafrost thaw, was determined assuming an average peat porosity of 0.85 (Quinton and Hayashi, 2004) and estimating approximately 50% bog coverage across the entire Scotty Creek basin, given that this value represents the approximate areal coverage of wetland in the headwaters portion of the basin. The mean depth of water storage lost from the connected bogs from 2003 to 2017 was 46 ±6 mm.

In contrast, the water level in the channel fen, which conveys water to the basin outlet, did not significantly change over the 15-year period of study (Figure 4c). Similarly, in a bog isolated from the drainage network, the water level did not significantly change with time. On an actively thawing permafrost peat plateau, the elevation of the perched water table declined significantly, with a decrease of 205 mm occurring at the interior of the plateau from 2003 to 2017 (Figure 4d). Near the edge of the plateau a considerable decline of 511 mm was observed over this period (Figure 4d). The plateau edge well was approximately 20 m from the edge of the plateau at the time of installation, but is now situated only 4 m from the receding plateau edge. The perched water level in the active layer is significantly lowering as the permafrost thaws and the plateau width shrinks. As the plateau degrades and subsides, the water level elevation at the plateau edge approaches that of the adjacent bog and fen as the plateau transitions to wetland.

Partitioning Sources of Excess Runoff

Runoff from the Scotty Creek basin has been steadily increasing since measurements began in 1996. Between 1998 and 2012 excess runoff on the order of approximately 1000 mm was observed beyond that expected based on trends in precipitation and runoff ratios prior to 1996 in neighbouring watersheds, including the Jean Marie watershed (Figure 5). Of this extra cumulative runoff approximately 52% was the result of greater effective precipitation received by the expanding channel fen areas, which is available to be partitioned to runoff. As peat plateaus became increasingly fragmented with permafrost thaw, resulting in greater perimeter-to-area ratios (Baltzer et al., 2014), runoff from the banks of the degrading plateaus (termed ‘primary runoff’; Connon et al., 2014) contributed approximately 27% of the excess observed runoff from 1998 to 2012. Using aerial imagery analysis to determine the rate of permafrost thaw based on landform conversion and an estimate of total ice volume in the basin, the amount of runoff derived directly from the thawing of permafrost accounts for 11% of the extra cumulative runoff. Collectively, these permafrost-thaw-induced changes account for 90% of the excess runoff over the 15-year period of 1998 to 2012. The residual of approximately 109 mm that cannot be accounted for by these precipitation- and nonprecipitation-induced landscape changes is of similar magnitude to the average depth of wetland drainage water from the connected bogs monitored over a similar 15-year period from 2003 to 2017.

Discussion

Permafrost degradation and thaw results in a significant loss of forest cover as peat plateau landforms subside and become inundated by adjacent wetlands (Wright et al., 2009; Baltzer et al., 2014). This transitioning of the land-

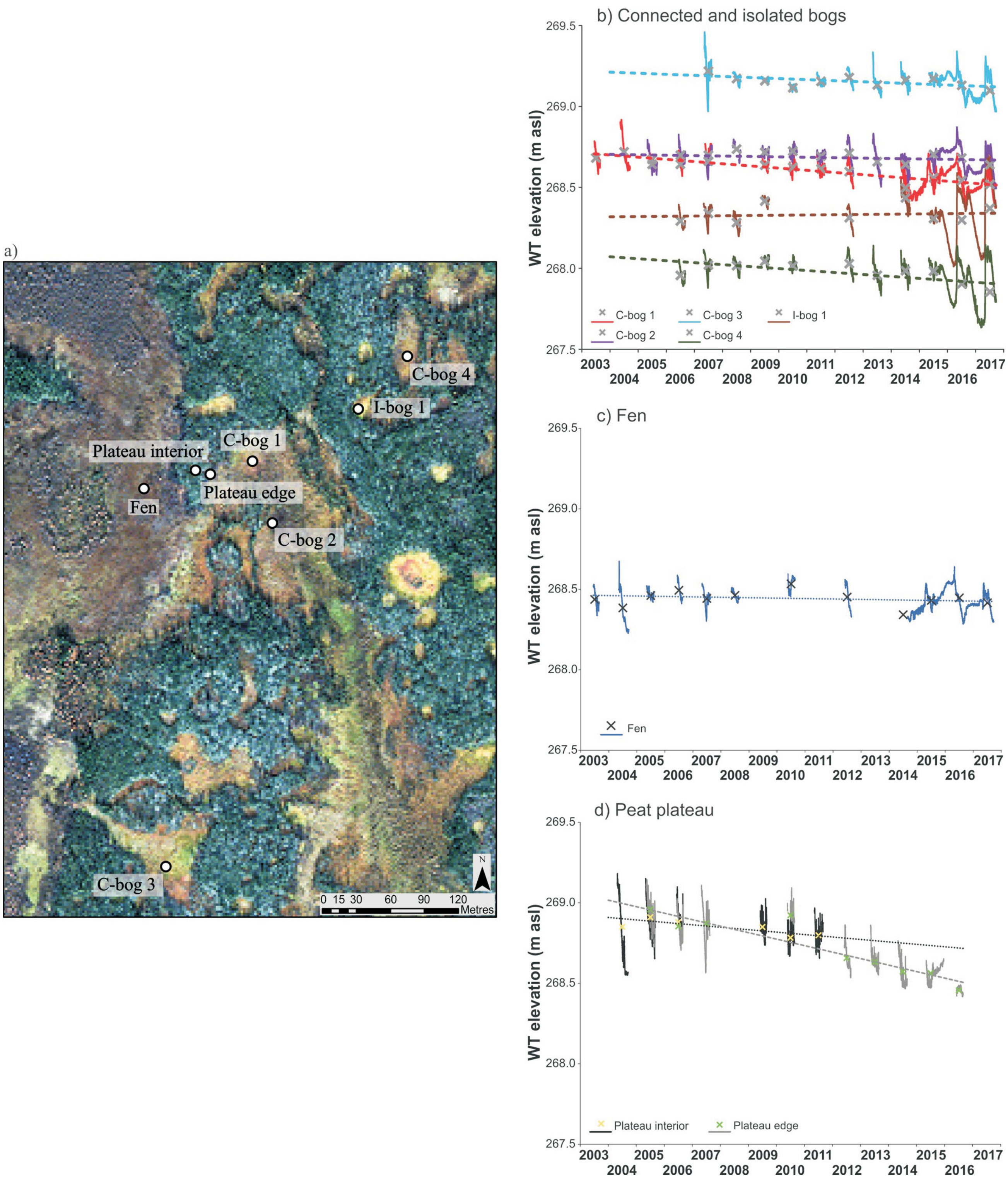


Figure 4. a) A 2010 WorldView-2 image (©DigitalGlobe, Inc. all rights reserved) of the 0.25 km^2 area of study within the Scotty Creek area of interest. White dots represent the locations of wells in each of the monitored connected bogs (C-bog), isolated bog (I-bog), as well as channel fen and peat plateau sites. Water table (WT) elevations (in m asl) from 2003 to 2017 for the **b)** representative connected and isolated bogs, **c)** channel fen, and **d)** peat plateau. In b), c) and d), solid lines are the 30 min water level records, 'x' symbols represent mean annual water level position in each site, and dotted lines represent linear best-fit trends in water level over the period of record. Adapted from Haynes et al. (2018).

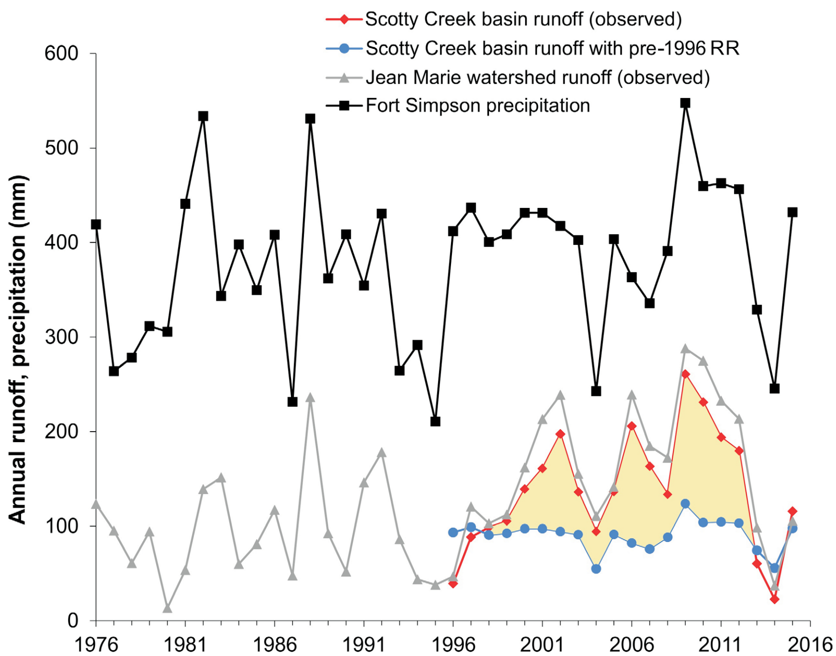


Figure 5. Total annual runoff (mm) measured at the Scotty Creek basin outlet (red line) and total annual precipitation (including both rain and snow; mm) measured at Fort Simpson (black line) from 1976 to 2015. Yellow area denotes extra observed runoff beyond that expected based on the mean of runoff ratios (RR) prior to 1996 and current precipitation patterns at Scotty Creek basin (blue line). Runoff from the neighbouring Jean Marie watershed (grey line), which functions similarly to the Scotty Creek basin, from 1976 to 2015 is plotted to illustrate the observed shift in increased runoff post-1998 to 2012. All runoff amounts totalled over the water year (October 1 to September 30). Adapted from Haynes et al. (2018).

scape to wetland area at the expense of forest cover was observed at all 10 AOI in this study area, which spans the discontinuous to sporadic permafrost regions of northwestern Canada. One main control on permafrost loss, as reflected by decreasing forest cover, is increasing average air temperature resulting in accelerated rates of forest cover loss. Subsidence and inundation of degrading permafrost plateaus (Quinton et al., 2009) and peat overmaturation (Zoltai, 1993; Beilman and Robinson, 2003) are the dominant mechanisms accounting for the dramatic landscape changes observed in these environments as permafrost bodies warm and thaw. The former mechanism occurs at all AOI along the CPET transect, whereas the formation of fissures in desiccating and heavy surface peat deposits as they become disconnected from the underlying water table, an indicator of peat overmaturation, is also observed at the southernmost AOI. However, the significant positive relationship between mean annual air temperature and forest gain along the CPET transect suggests that warming temperatures may also play an important, although contrasting, role in these transitioning regions depending upon the degree of landscape change. The promotion of forest regrowth with increased air temperatures has been attributed directly to enhanced forest productivity (Baltzer et al., 2014). An indirect influence of increasing air temperatures facilitating afforestation likely involves the alteration of the magnitude and routing of hydrological flows across the landscape providing suitable conditions for tree regrowth.

The long-term trends in water levels in representative land-cover types across the Scotty Creek site illustrate the change to the amount of water stored, drained and routed across the transitioning landscape. Significant drainage of previously isolated bog features occurs as they become connected to the drainage network (Figure 4). These connected wetlands lose significant amounts of water to runoff, which was previously impounded by permafrost barriers and stored in the basin. Warming air temperatures result in the thaw and degradation of these permafrost barriers allowing for more efficient and direct routing of water to the drainage network and ultimately exporting it as runoff from the basin. Therefore, permafrost thaw results in drying of wetlands in this region. Enhanced wetland drainage coupled with amplified evapotranspiration as a result of increasing temperatures (Warren et al., 2018) indirectly enhance forest succession and regrowth by providing an optimal environment in terms of hydrology for tree establishment.

Trajectory of Discontinuous to Sporadic Permafrost Landscape

It is likely that the hydrological mechanism responsible for controlling afforestation is favourable moisture conditions with landscape change. The loss of permafrost barriers has resulted in increasing runoff exiting the transitioning Scotty Creek basin (Figure 5). With accelerated permafrost loss in recent decades, elevated runoff beyond that expected given pre-1996 runoff ratios and current trends in precipitation patterns is observed (Figure 5). In addition to the contributions to elevated runoff from the expansion of area contributing to the drainage network as permafrost barriers are lost, increased primary runoff from the banks of increasingly fragmented peat plateaus and direct moisture from permafrost thaw (Connon et al., 2014), draining of wetland features as they become connected to the basin drainage network accounts for approximately 10% of excess runoff.

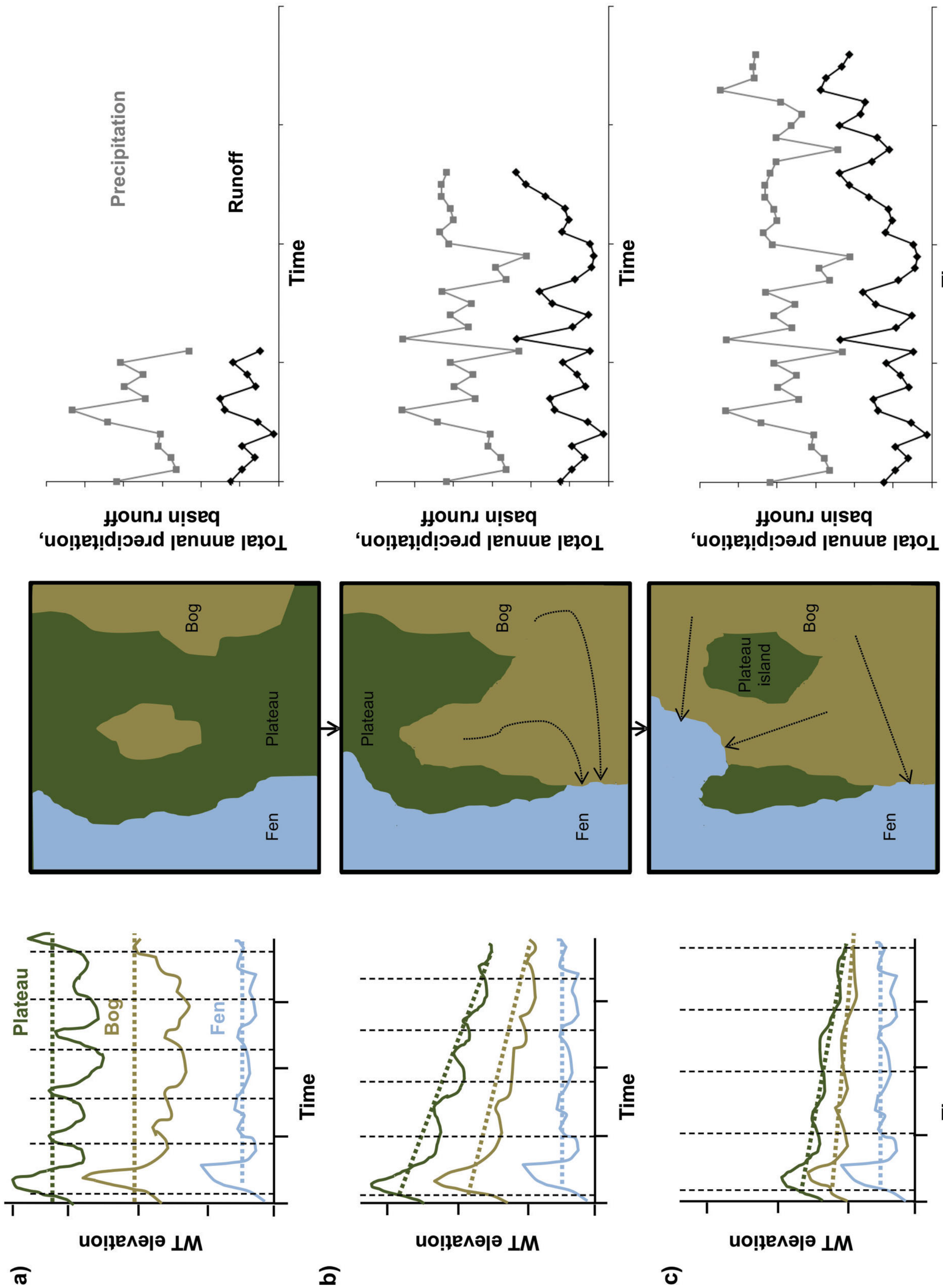
Given the hydrological trends observed at the Scotty Creek site, a conceptual model for the anticipated relationship between water storage on the landscape and associated runoff over time is proposed (Figure 6). As the landscape continues to change with further permafrost thaw, runoff from discontinuous and sporadic permafrost basins is anticipated to increase as wetlands become incrementally connected to the drainage network (Figure 6; Quinton et al., 2009). However, once the maximum contributing area is reached, when all bogs have developed a connection to the drainage network, a threshold of peak potential runoff will be achieved, which is higher than previously observed due to the significant expansion of the runoff contributing area. The observation of afforestation in southern latitude AOI (Figure 2) reinforces the likelihood of continued wetland drainage as connections to the drainage network broaden as permafrost thaw proceeds, leading to drier wetland soils. Under such conditions hydrological connectivity within plateau-wetland complex basins will only be achieved during periods of high moisture supply, activating secondary runoff pathways (Connon et al., 2014). In periods of limited moisture availability, the lack of active runoff pathways will restrict contributions from collapse scar bogs to basin runoff.

Changes in precipitation patterns, including decreases in snowpack depth (Hinzman et al., 2005), earlier spring melt (Intergovernmental Panel on Climate Change, 2007) and increases in the frequency of mid-winter melts resulting from warm periods and rain-on-snow events (Putkonen et al., 2009), all influence permafrost stability. The relationships between winter precipitation and forest loss and gain suggest that decreases in winter precipitation promote the transition from forest to wetland due to permafrost thaw, whereas greater snow accumulation facilitates forest regrowth with reduced saturation following snowmelt. Although tree regrowth is occurring at the southern AOI of the transect, which are at an advanced stage of permafrost degradation and loss, it does not appear to be accompanied by the re-establishment of permafrost likely due to warmer climatic conditions (Robinson and Moore, 2000; Jorgenson et al., 2010).

Conclusions

The latitudinal gradient of the CPET transect illustrates the likely trajectory of permafrost-thaw-induced landscape change. This space-for-time substitution proxy demonstrates that net forest loss decreases with decreasing latitude, whereas forest gain is negligible other than at the most southerly locations. Therefore, considering that this transect represents the likely trajectory of permafrost-thaw-induced landscape change, it may be concluded that the landscape of forested plateaus interspersed with treeless wetlands, as observed in the Scotty Creek basin, is not likely the climax community for this region. As plateau features subside and transition to wetlands as a result of inundation, the water stored in previously isolated bogs is directed to basin runoff. Drying of wetlands through drainage enhances runoff from these environments. This significant change in hydrology facilitates the re-establishment of tree species and, in association with such climatic changes as increasing air temperatures and altered precipitation patterns, promotes afforestation in these landscapes. Further research is required to determine if conditions will be favourable for the return of permafrost beneath the newly established forest cover despite continued climate change–induced warming of air temperatures. Understanding how permafrost-thaw-induced landscape changes in the sporadic to discontinuous permafrost zone affect the hydrology of these environments is important in order to assess the availability and sustainability of freshwater resources for northern communities.

Figure 6. Conceptual model for the transition of the permafrost landscape, from **a)** the initial condition with wetlands isolated from drainage networks with perched, flashy water tables (WT) on permafrost terrain and interannual runoff generation in response to precipitation trends; **b)** to an intermediate condition where, as permafrost barriers are lost and perched plateau water tables subside, bogs drain as a result of the newly formed connections to channel fens, with bog and plateau water levels approaching the level of the drainage channel and runoff begins to increase without a corresponding increase in precipitation; **c)** to an advanced condition where, due to the enhanced runoff contributing area partitioning precipitation to runoff, basin runoff is elevated as compared to preconnected conditions as bog drainage across the basin approaches a diminishing return. Plateau water level responses become increasingly attenuated and follow a similar trend to adjacent wetlands. Dotted lines in the water table plots illustrate the mean water level trend for each of the bog, fen and plateau. Black vertical dashed lines in water table plots denote annual cycles, whereas points in precipitation and runoff plots represent annual totals. Black dotted arrows in the landscape images represent the direction of water flow as areas become connected to the drainage network with permafrost loss. Changes in the runoff and precipitation trends along the three transitional phases are represented by the incremental addition of data for plots a) through to c). Adapted from Haynes et al. (2018).


a)
b)
c)
WT elevation
Plateau
Bog
Fen
Time
Plateau
Bog
Fen
Plateau island
Total annual precipitation, basin runoff
Precipitation
Runoff
Time

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 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 paper benefited from a review by M. English, Wilfrid Laurier University.

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