Annual reporting for GNWT Environmental Studies Research Fund – 2022/23

Title: Assessing terrain sensitivity to permafrost thaw and fire to understand and predict boreal caribou habitat and forage quality in the Sahtú

Investigators: Drs. Jennifer Baltzer (jbaltzer@wlu.ca) and Merritt Turetsky (merritt.turetsky@colorado.edu)
Collaborators: Drs. Steve Kokelj, Sharon Smith, Andrew Spring, Eliot McIntire, Steve Cumming, Heidi Swanson, Catherine Dieleman

Project Description: The proposed research will address how fire and permafrost conditions interact to determine caribou habitat responses to climate change and human activity in the Sahtú, a resource-rich region poised for substantial oil and gas development. Using a combination of field measurements and remotely sensed land cover change, we will improve predictions about the sensitivity of permafrost to fire and human activity in the Sahtú and how this relates to caribou forage availability and quality and caribou habitat use. This will be accomplished by quantifying key metrics of land cover change, terrain stability, and vegetation across a range of permafrost conditions and disturbance gradients.

Research team:

Name	Position	Funding
Carolyn Gibson	PhD – completed	NSERC
Kirsten Bill	PhD – withdrawn	ESRF
Katerina Coveny	MSc	Global Water Futures – Northern Water Futures
Evan Schjins	MSc	University of Guelph
Emily Ogden	MSc – completed	NSERC
Alexis Jorgensen	MSc – completed	ESRF
Jessica McCuaig	MSc – completed	NSERC
Jason Paul	Research Technician – completed	CIMP and Wilfrid Laurier
Genevieve Degre-Timmons	Research Technician – completed	CIMP and Wilfrid Laurier
Ana Sniderhan	Research Associate	Global Water Futures
Maria Belke-Brea	Postdoc	Polar Knowledge Canada
Ceres Barro	Postdoc	CIMP and Global Water Futures
Raquel Alfaro Sanchez	Postdoc	NSERC
Mehdi Moslemi Aqdam	Postdoc	Global Water Futures – Northern Water Futures

Community consultation:
Thermokarst and wildfire were both identified as key community concerns at the Sahtú Environmental Monitoring Research Forum meeting in Tulita that our team attended in February 2018. To enhance our capacity for community consultation and engagement, in collaboration with the Sahtú Renewable Resources Board, Leon Andrew and Jennifer Baltzer co-lead a Global Water Futures project to support on the land camps that will lead to improve knowledge sharing between researchers and community members. The first of these camps took place on Tek’áícho Dé (Marten River) in August 2019 and involved members of our ESRF team (Ogden, Gibson, and collaborator Grey). COVID and community capacity issues prevented a camp from happening in 2020-2022 but we are currently engaged in virtual planning meetings with the SRRB and the community of Fort Good Hope organizing a cross cultural

event being held from July 4-12, 2023. This will involve over 50 individuals from across the Sahtú as well as government and academic researchers.

***Figure 1**. On-the-land cross cultural camp on Tek'áícho Dǝ́ (Marten River) held as a collaboration between the community of Tulita, the Sahtu Renewable Resources Board and the Global Water Futures Water Knowledge Camps program.*

Research progress:

Below, we provide updates on four distinct though interconnected components of this project:

1) Thermokarst vulnerability assessments – completed
2) Linking long-term changes in permafrost conditions to landcover change and water quality - new
3) Vulnerability of lichen peatlands to fire and thaw - ongoing
4) Post-fire forage recovery - ongoing

1) Thermokarst vulnerability assessments

This portion of the project is complete. Using gridded data, Gibson et al. 2020, 2021 greatly improved predictions of lowland thermokarst vulnerability from for the entire Taiga Plains, including the areas around Tulita and Norman Wells compared to previous global scale products of thermokarst vulnerability. The comparison of these two data products and their differences is presented in Fig. 2.

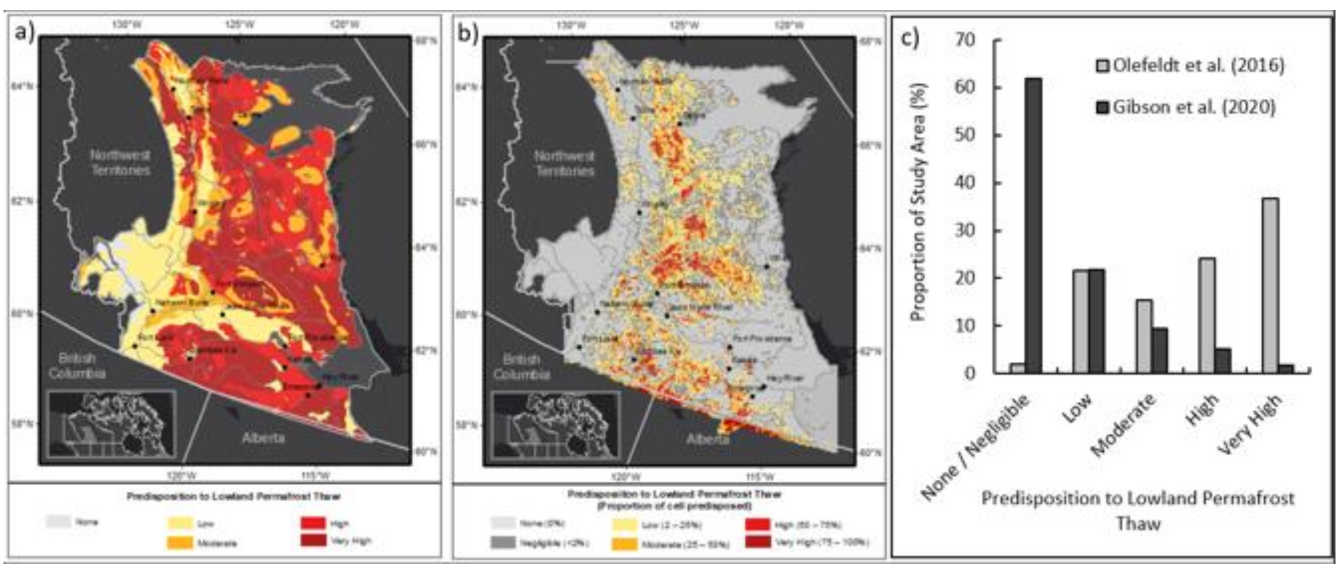

***Figure 2**. Comparison of geospatial products of lowland thermokarst probability in permafrost peatlands in the discontinuous permafrost zone of the Taiga Plains Ecozone within the Northwest Territories, Canada. (A) The Olefeldt et al. (2016) framework was developed for use at circumpolar scales. (B) Results from this study uses a gridded approach and was developed for use at regional or*

community-relevant scales. (C) Comparison of these two approaches binned by predisposition classes. Note that a negligible class does not exist within the Olefeldt et al. (2016) framework; thus, we combined none and negligible classes in this analysis. This figure is taken from Gibson et al. 2021.

As an extension of the work conducted through this ESRF-funded project, Jason Paul and Ana Sniderhan have been actively mapping thermokarst features throughout the NWT as part of the NWT Thermokarst Collective, including in the Norman Wells/Tulita region and leading analysis of these data. This work was presented at the 2022 Global Water Futures Annual Science Meeting (see associated poster; funded through Northern Water Futures and GNWT CIMP) and the first peer reviewed paper from this effort has been accepted with minor revisions.

Outputs to date:

Kokelj, SV, Gingras-Hill, T, Daly, S, Morse, P, Wolfe, S, Rudy, A, van der Sluijs, J, Weiss, N, Baltzer, JL, Cazon, D, Gibson, C, Fraser, R, Froese, D, Giff, G, Klengenberg, C, Lantz, TC, Lamoureux, S, O'Neill, HB Chiasson, A, Ferguson, C, Newton, M, Pope, M, Paul, J, Wilson, A, Young, J. 2023. The Northwest Territories Thermokarst Mapping Collective: A northern-driven mapping collaborative towards understanding the effects of permafrost thaw. Arctic Science, accepted with minor revisions.

Paul, JR, Kokelj, SV, Wolfe, S, Morse, P, Rudy, A, Gibson, C, Baltzer, JL, van der Sluijs, J, O'Neill, BB, Wiess, N, Gingras-Hill, T, Daly, S, Lantz, T, Quinton, W, Chiasson, A, Ferguson, C, Newton, M, Pope, M, Wilson, A, Young, JM. 2022. Mapping thermokarst land systems. E-lightning talk and poster presentation. Global Water Futures Annual Science Meeting.

Gibson, C, Cottenie, K, Gingras-Hill, T, Kokelj, SV, Baltzer, J, Chasmer, L, Turetsky, M. 2021. Mapping and understanding the vulnerability of northern peatlands to permafrost thaw at sclaes relevant to community adaptation planning. Environmental Research Letters, in press, https://doi.org/10.1088/1748-9326/abe74b.

Open Data Report: Gibson, C., Morse, P.D., Kelly, J.M., Turetsky, M.R., Baltzer, J.L., Gingras-Hill, T., and Kokelj, S.V., 2020. Thermokarst Mapping Collective: Protocol for organic permafrost terrain and preliminary inventory from the Taiga Plains test area, Northwest Territories; Northwest Territories Geological Survey, NWT Open Report 2020-010, 24 pages, appendix, and digital data. https://tinyurl.com/nwfreport2020

Figure 3*. Permafrost coring and peat sampling in a collapse scar in the Sahtú region. Photos courtesy of Emily Ogden.*

2) Linking long-term changes in permafrost conditions to vegetation productivity, landcover change, and water quality

Along the Mackenzie Valley corridor exists unparalleled permafrost monitoring infrastructure established by Dr. Sharon Smith of the Geologic Survey of Canada (Fig. 4). These sites were established starting in 1984 to better understand changing permafrost conditions in response to hydrocarbon exploration and development in this region. At each site, a borehole was drilled and either a ground thermal cable or a thaw tube was installed to monitor changes in permafrost conditions. These sites have been continuously monitored for between 20 and 38 years providing an incredible, long-term record of change. We are making use of these records in two ways to address questions relevant to this ESRF project: 1) Pairing temporal permafrost records with Landsat-based records of vegetation productivity to evaluate the response of boreal forest productivity to changing permafrost conditions; 2) Accessing a subset of these sites to quantify ecological conditions, including caribou forage availability, and sample adjacent ponds/lakes to evaluate relationships between water quality and permafrost thaw.

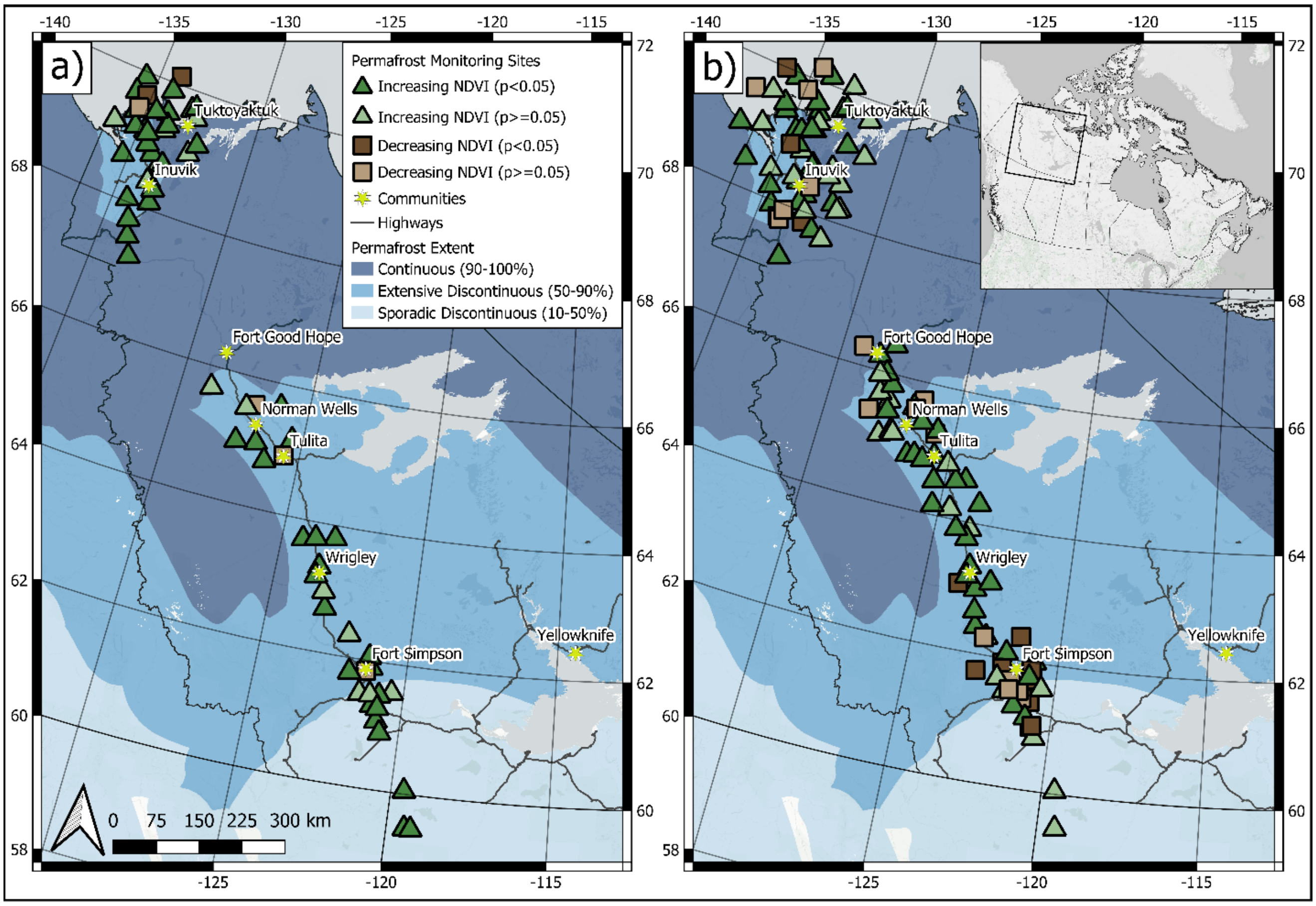

Figure 4. *Map of permafrost monitoring sites established by the Geological Survey of Canada located along a latitudinal transect of the Northwest Territories, Canada. Trends in normalized difference vegetation index (NDVI) from a) 1984 to 2000 (n=66), and b) 2001 to 2019 (n=117). Site locations are jittered to show overlapping locations. Inset shows the location of the study area within Canada. Permafrost extent from Brown et al (1998). Map created using QGIS version 3.16.16 (QGIS Development Team 2022).*

The first part comprised the MSc thesis of Emily Ogden who defended her thesis in March 2022. Over the past several decades, various trends in vegetation productivity, from increases to decreases, have been observed throughout the northern boreal biome. While some of this variation can be explained by recent climate warming and increased wildfire, very little is known about the impacts of permafrost thaw on vegetation productivity. Active layer thickness data from the GSC sites were paired with a NASA Landsat time-series of normalized difference vegetation index from 1984-2019 to quantify the impacts of changing permafrost conditions on vegetation productivity. We found that active layer thickness explained some of the observed variation in vegetation productivity in recent decades in the northern boreal forests, with the highest rates of greening occurring at sites where near-surface permafrost had recently thawed. However, the greening associated with permafrost thaw was not sustained for prolonged periods of thaw. Highest rates of greening were found at the mid-transect sites in the Sahtu region, suggesting that more southerly sites may have already surpassed the period of beneficial permafrost thaw, while more northern sites may have yet to reach a level of thaw that supports enhanced vegetation productivity. These results indicate that the response of vegetation productivity to permafrost thaw is dependent on the extent of active layer thickening and increases in productivity may be short-lived. Last month, this work was accepted at Global Change Biology for publication.

Outputs to date:

Ogden, E, Smith, S, Turetsky, M, Cumming, S, Baltzer, J. 2021. Impacts of changing permafrost conditions on plant productivity in the Northern boreal forests. Canadian Remote Sensing Symposium.

Ogden, E, Smith, S, Turetsky, M, Cumming, S, Baltzer, J. 2021. Impacts of changing permafrost conditions on plant productivity in the Northern boreal forests. International Boreal Forest Research Association Meeting.

Ogden, E.L., Cumming, S.G., Smith, S.L., Turetsky, M.R., Baltzer, J.L. 2022. Too much of a good thing: Permafrost thaw induces short term increase in vegetation productivity in the northwestern boreal forest. Global Change Biology, in press.

For the second part, we accessed a subset of permafrost monitoring sites (Fig 5) within the Sahtu region to evaluate ecological conditions associated with different permafrost conditions and rates of thaw. We measured/sampled the following: forest structure, composition, age, and productivity, ground vegetation community (including important caribou forage taxa), active layer and permafrost cores, water, and sediment samples from adjacent ponds/lakes (Figs. 6-8). We will also access historical air photos from these sites to quantify landcover change. With these data in hand, we are asking questions about permafrost thaw induced landcover change and the implications of this for caribou forage, tree growth response to thaw rates using tree ring analysis, and the relationship between thaw rates/active layer thickening and water and sediment quality. There was a set-back with this part of the project as the associated PhD student withdrew from the program owing to COVID challenges. Laboratory analyses of soil and water samples are partially completed and we have a new postdoctoral fellow (PDF), Mehdi Moslemi Aqdam, in place to lead the terrestrial-aquatic connectivity components of this work. PDF Raquel Alfaro Sanchez has been actively working with tree ring samples from these sites and across our broader network of sites in the NWT and has demonstrated that overall we are seeing enhanced tree growth but that this varies regionally and in response to permafrost thaw. Specifically, thawing permafrost drives growth declines as a results of the physical disruption associated with ground destabilization during thaw.

During summer 2023, we have received PCSP support to access additional sites in the Inuvialuit region that are part of this same set of monitoring sites. This additional fieldwork will cover a broader range of permafrost and climate conditions and double our sampling effort. A new MSc student, Katerina Coveny has been recruited to support the analysis of ground vegetation, notably caribou forage responses and assess historical landcover changes at these sites.

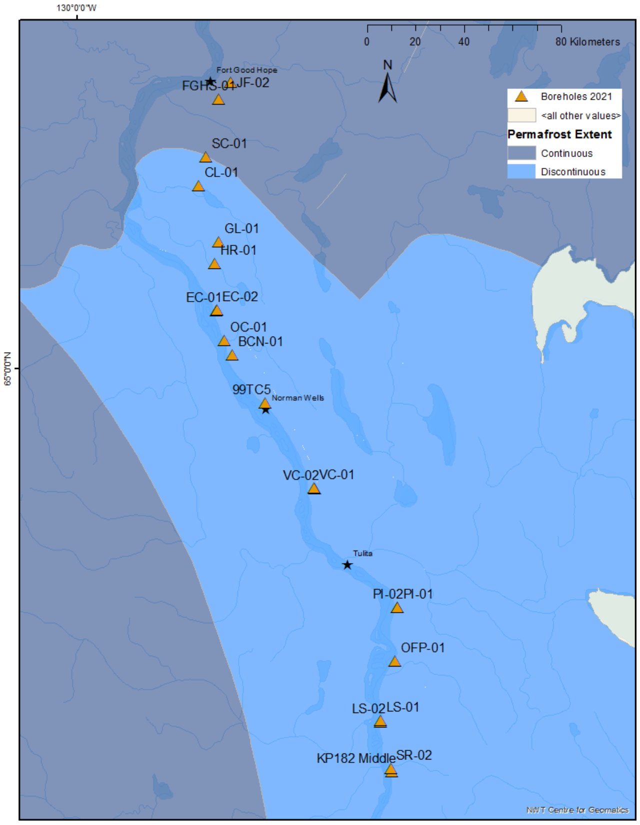

Figure 5. *Subset of permafrost monitoring sites accessed in 2021 for vegetation, soil, permafrost, sediment and water sampling.*

Figure 6. *Borehole (permafrost monitoring) location with 2021 sampling team.*

Figure 7. *Two permafrost cores from permafrost monitoring sites. Top panel: a very ice-rich permafrost core. Bottom panel: a very carbon rich permafrost core.*

Figure 8. *Water quality sampling in waterbodies adjacent to borehole sites. Top panel: In situ water quality measurement with YSI meter. Bottom panel: Water sample filtering selfie.*

3) Vulnerability of lichen and peatlands to fire and thaw in the Sahtú

As described in past reporting, in 2019, we established field plots in lowland permafrost environments in the Sahtú region. Images and descriptions below are from the 2019 field campaign. These efforts were focused on permafrost peatlands dominated by caribou lichen cover (Fig. 7). Our sample design involved characterizing vegetation communities and soil carbon stocks for peatlands ranging in fire-free interval (from sites that burned in 2014 to those that have not burned since 1969). Within each location, we sampled thermokarst bogs (Fig. 8) that were stable and those showing evidence of rapid permafrost thaw, permafrost plateau locations, and surrounding forest environments (Fig. 7). These sample efforts included:

1) measurement of soil organic layer thickness and carbon content and collection of permafrost cores for characterization of ground ice and permafrost carbon (Fig. 1, 9)
2) Measurement of carbon stocks in thaw features (Fig. 10).
3) Stand structure and composition (where relevant) and ground vegetation characterization (Fig. 1, 11) in all sampled features

Figure 7. *Sampling locations within each lichen peatland including stable and unstable thermokarst bogs, permafrost plateau, and forest interior. This sampling included sites that burned in 2014, 2007, 1993, 1969, and "unburned controls" for which we will assess burn date based on stand age.*

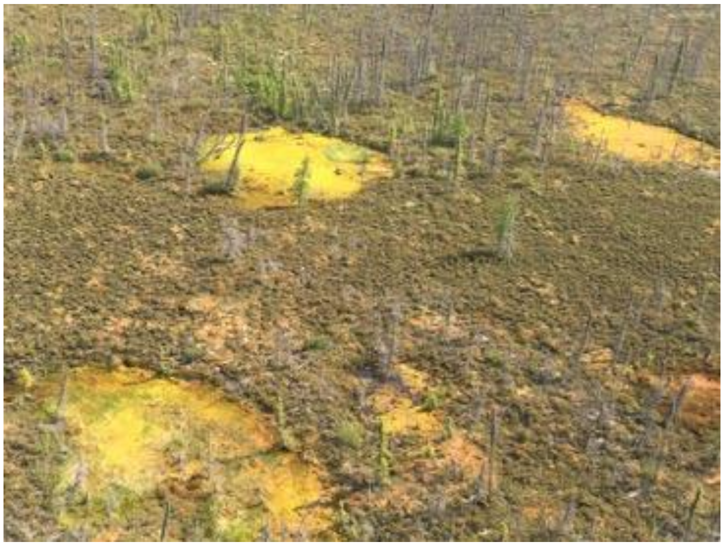

Figure 8. *Thermokarst bogs in a recently burned lichen permafrost peatland. Brighter green areas indicate regions of active thaw.*

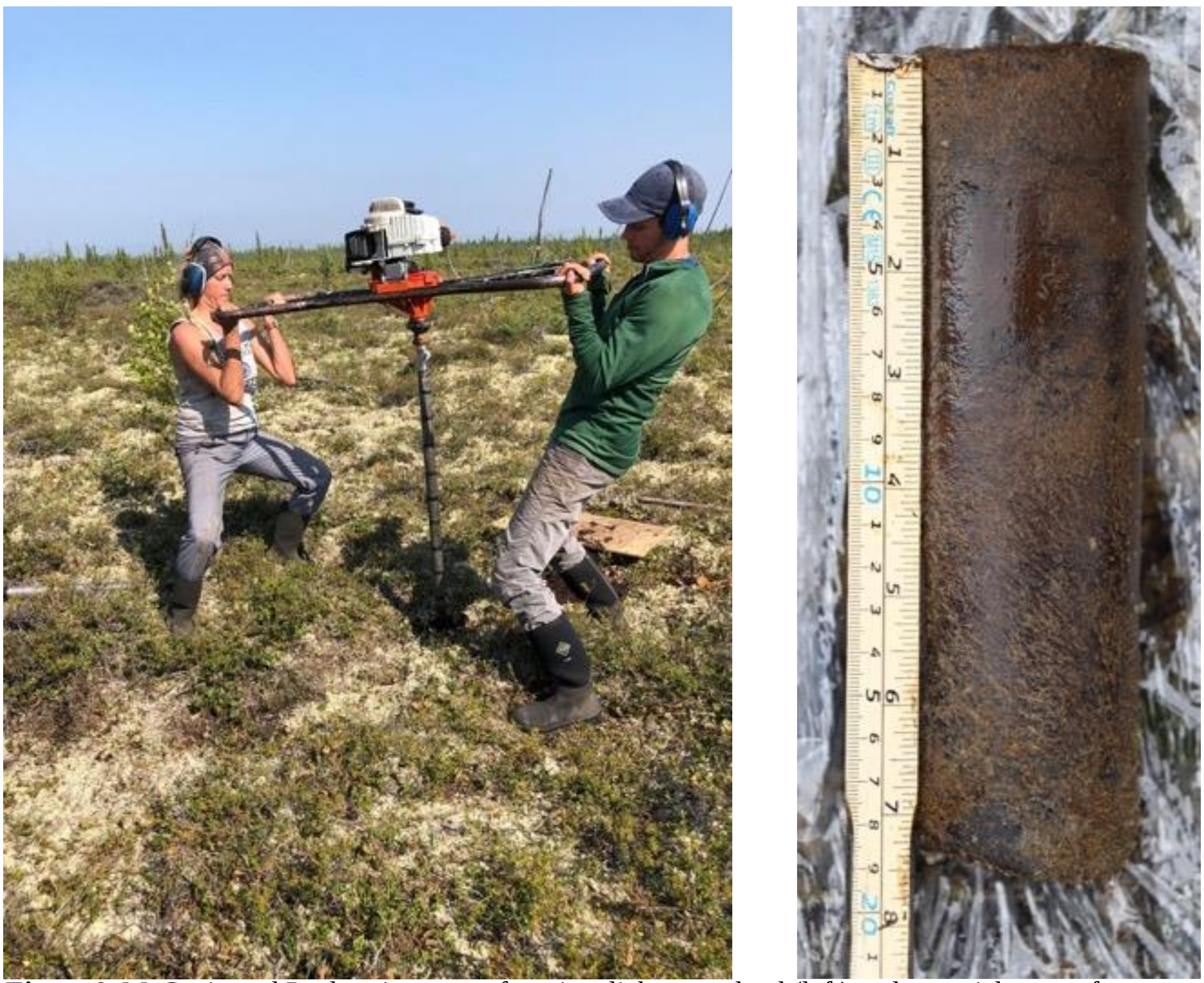

Figure 9. McCuaig and Paul coring permafrost in a lichen peatland (left) and peat-rich permafrost core segment (right).

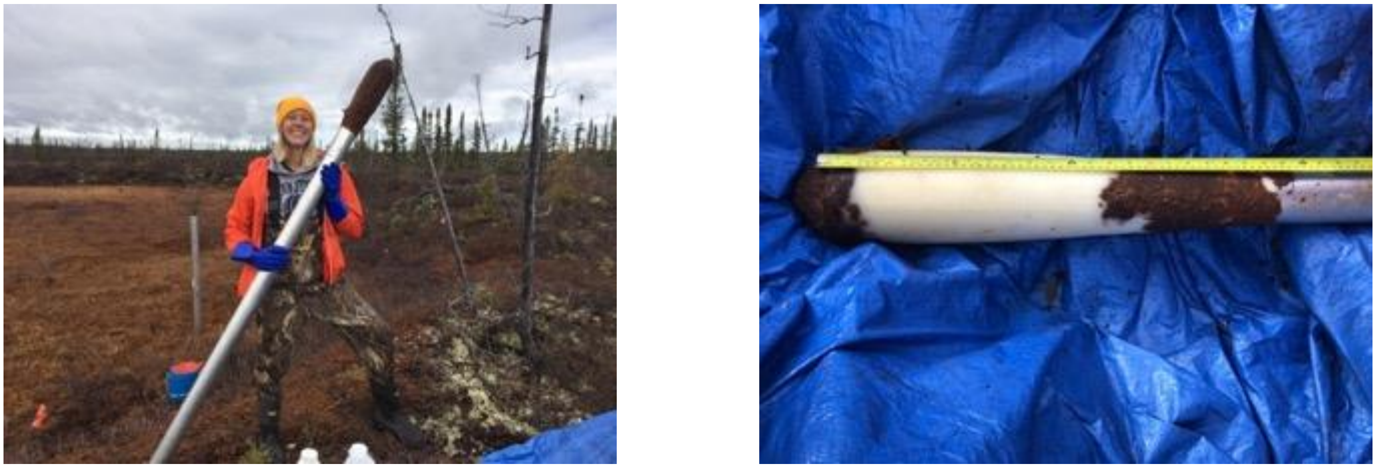

Figure 10. Frozen finger sampling in thermokarst bog features. McCuaig with frozen finger sampler (right) and a sample with water (frozen due to the sampling technique) between peat layers demonstrating the structure of these peatlands.

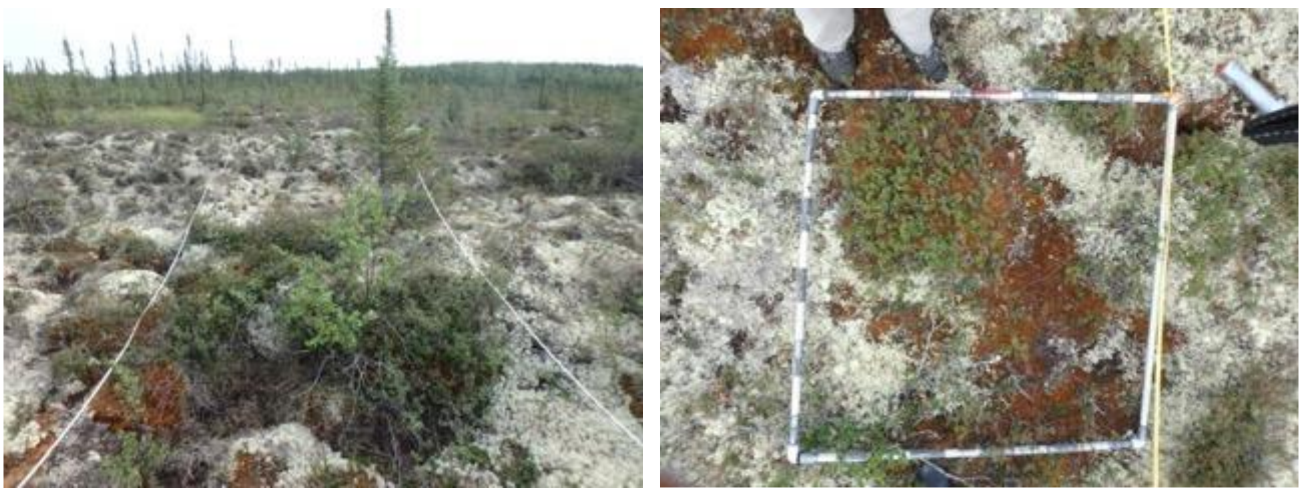

Figure 11. Vegetation sampling transect (left) and quadrat (right) in a lichen permafrost peatland.

Analysis of soil carbon stocks in permafrost peatlands in the Sahtú is ongoing. This work is focused on quantifying drivers of carbon stock recovery following fire in these peatlands. As part of this, the following analyses have been undertaken:

- 800 soil samples from permafrost plateaus and >1000 soil samples from thawed wetland features spanning the entire soil organic layer have been processed for bulk density and loss on ignition (LOI). LOI provides us with an organic matter content measurement for each sample. The wetland samples are currently undergoing elemental analysis and 14C dating to evaluate age of the features. These analyses have already been completed for the permafrost plateaus, the results of which are reported below.
- Basal peat layers were identified using LOI, bulk density, and horizon type data for 15 samples across fire scars. They were processed using bulk peat sampling processes and sent for radiocarbon (14C) dating. Basal dates have been quantified to allow us to relate site history to other more contemporary drivers of recovery.

- We have built key relationships with estimated C content and time-following-fire. It appears these permafrost plateau sites are not recovering following fire and are continuing to lose, or at least not gain carbon for at least 80 years post-fire (Figure 12). These preliminary results, though surprising, are in keeping with analyses from the southern NWT (Bill et al, in press) and Alaska (Mack et al. 2021. Science 372: 280-283) and draw into question the resilience of these peat-rich environments to disturbance.

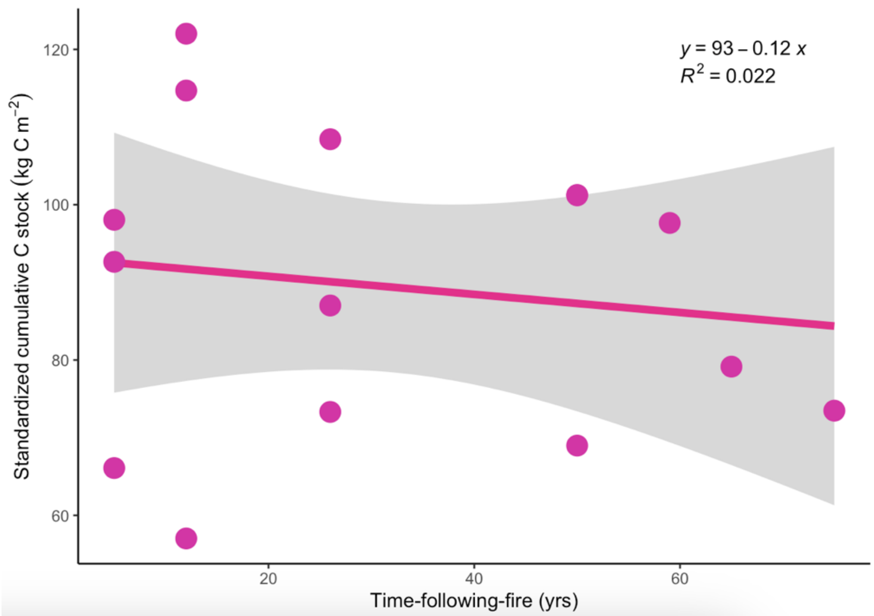

Figure 12. *Carbon content of permafrost plateaus does not recover for at least 80 years following fire.*

- We did find that carbon stocks were well predicted, not surprisingly, by the thickness of the organic layer, which ranged from 80 to >200cm of peat. Organic layer thickness was a function of peatland age (i.e., the time following peat formation initiation), so this variable was also a highly significant predictor of carbon stocks (Figure 13).
- This in part is controlled by the vegetation community, which was also closely linked with the peatland initiation date. Sites rich in caribou lichens corresponded with more carbon rich locations.

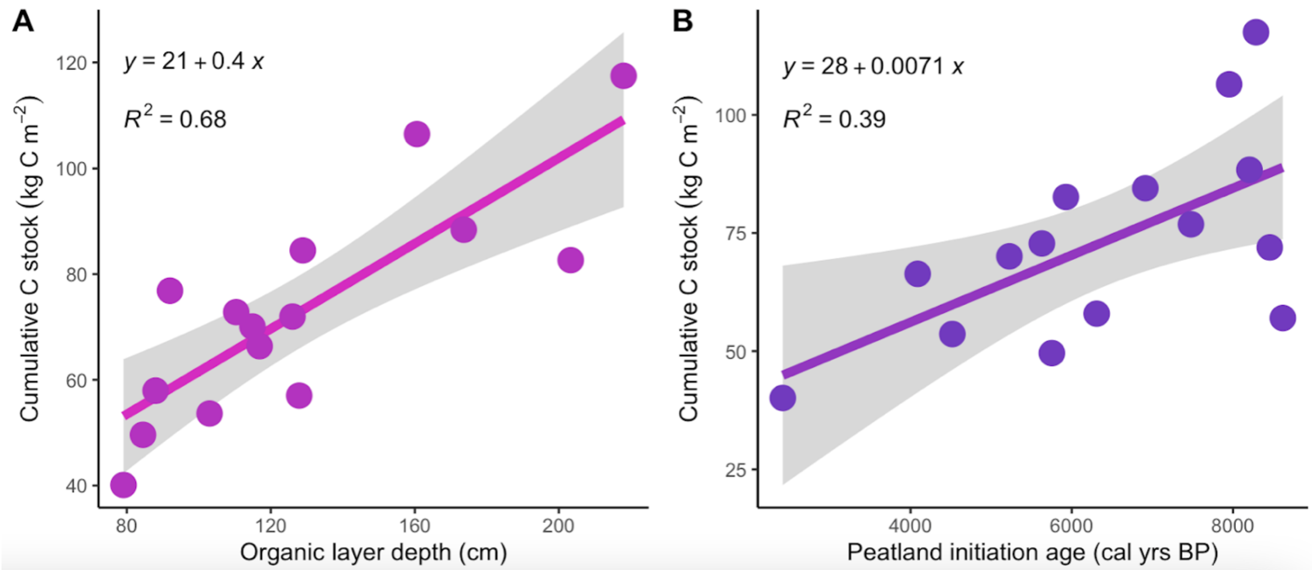

Figure 13. *Relationships of carbon stocks on permafrost plateaus with organic layer thickness and peatland initiation age.*

4) Post-fire forage recovery

In 2018, we established sites in which we sampled stand age, ground vegetation, soils development and forage lichen biomass recovery (points in the Sahtú region in Fig 14. We used methods identical to an ongoing study in the southern NWT, allowing us to compare these processes in the Sahtú, Tlicho and Dehcho regions. Further, for the lichen biomass sampling, a collaborator had comparable data from northern Saskatchewan facilitating a regional comparison of lichen biomass accumulation rates in northwestern Canada. This combined dataset has supported the first comprehensive evaluation of forage lichen recovery times following fire for the NWT and provides Sahtú-specific estimates as well. The resulting manuscript was developed by Degré-Timmons. Some of the key results from the paper are included in Fig 15. We created the following infographics to communicate the lichen biomass recovery results (below are provided the English and North Slavey versions).

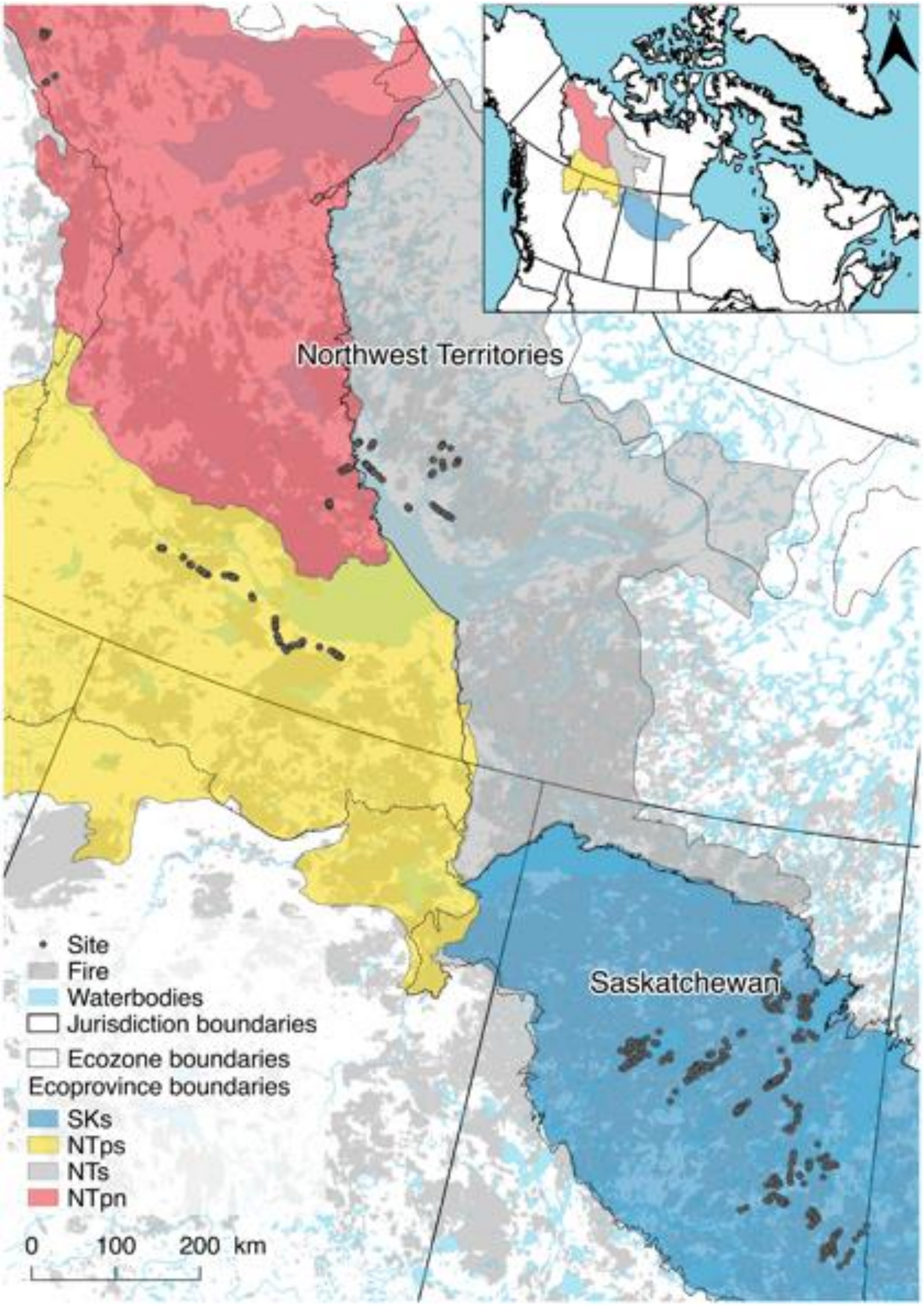

Figure 14. *Locations of all sampling locations used to evaluate post-fire recovery of lichen and its generalizability across northwestern Canada. Included in this broader analysis are our sampling efforts to date in the Sahtú region. From Gruel, Degre-Timmons et al. 2021.*

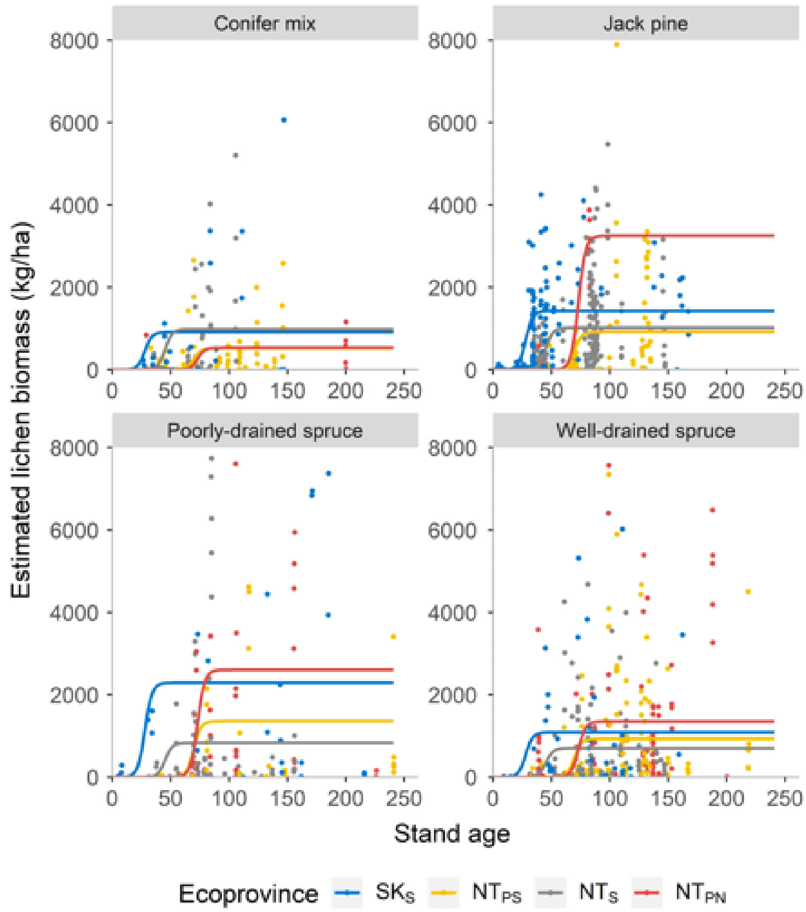

Figure 15. *Lichen biomass accumulation through time (stand age in years) in each ecoprovince for each stand type. Ecoprovince: SK_S = Saskatchewan Shield, NT_{PS} = Northwest Territories Plains South, NT_S = Northwest Territories Shield, NT_{PN} = Northwest Territories Plains North. We see the importance of poorly drained spruce in supporting high maximum lichen biomass accumulation across all regions. From Gruel, Degre-Timmons et al. 2021.*


EDÀNI ADZÌÌ NAESE NDÈ WEK'ÈIK'Q ŁAKQ DÈ?
GREUEL, DEGRÉ-TIMMONS ET AL. 2021
DOI: 10.1002/ECS2.3481
WETS'Q GONEDE: GENEVIEVE.DEGRE-TIMMONS.1@ULAVAL.CA
NDÈ ŁADĮ AT'Į ADZA EYIT'À NDÈ NECHÀ WEK'ÈK'Q ADZA. ĮDAA NĮDÈ EKWÒ GHA ADZĮĮ EDÀTŁQ NADEHSE WEXÈIDI HA. NDÈ WEK'ÈĮK'Q ŁAKQ DÈ, ASĮĮ ADZĮĮ ĮWHĄ NAESE GHA WEK'ATS'ÈHTQ:
EDÀHT'È NDÈ WEK'ÈĮK'Q ĮLE.
EDĮĮ NDÈ WEK'ÈĮK'Q ĮLE.
NDÈ K'È AYÌÌ DEHSE ĮLE.
NDÈ ATŁ'È DĮ, CHĮK'ÈDA TS'QNĘ, CANADA K'ÈZÌÌ
EKWÒ GHA ADZĮĮ EDÀTŁQ DEHSE – EYITS'Q EDÀNI ĮWHĄ NAESE – ASĮĮ NDÈ K'È ASIÌ ŁADĮ DEHSE.
NDÈ WEK'ÈĮK'Q TŁ'AKQ DÈ, DAKWE TS'IWÀ NAESE EYIT'À WET'À DE Q ADZĮĮ DEHSE, TS'IWÀ WEDECHĮ WHEGÒQ, GÒQ DECHĮ WENÀHK'E.
ADZĮĮ ĮWHĄ NAESE – ĮZÌÌ NDÈ K'È GÒ Q (30 XO GOTS'Q NAESE) ĮDÒO NDÈ K'È GÒ Q NAHK'E (45 XO GOTS'Q NAESE)
ADZÌÌ ŁÒQ KÀ A NDÈ K'È DEHSE EYITS'Q TS'I ŁÒQ KÀ A DEHSE WET'À A HQT'E, EKWÒ HOTÌ EDEDA HA TS'ÌIWQ DÈ WEGHÀÀ EGHÀLATS'ÈEDA NÀAWO HOHŁE HA HQT'E, IDÀA NIDÈ DE Q GÒKÒ EYIT'À DE Q NDÈ WEK'ÈK'Q ADE HA.
0-29 XO NDÈ K'ÈIK'Q TŁ'AKQ
0-110 kg/ha
30-40 XO NDÈ K'ÈIK'Q TŁ'AKQ
0-1196 kg/ha
41-70 XO NDÈ K'ÈIK'Q TŁ'AKQ
9-1551 kg/ha
71-241 XO NDÈ K'ÈIK'Q TŁ'AKQ
243-2850 kg/ha
ADZĮĮ ŁADĮ ADZA TS'I ŁÒQ NDÈ K'ÈĮK'Q TŁ'AKQ NDÈ K'È ASIÌ NAESE
ALIGN ILLUSTRATION

Upscaling and forecasting: We are currently in the process of developing ecological forecasting tools to provide managers the ability to evaluate changes in forage lichens under different wildfire scenarios. During 2021, we began efforts to scale our ground plot data with NASA ABoVE high-resolution hyperspectral data (AVIRIS) (Fig 16). Our current work on the interaction between fire and permafrost thaw will allow that to be extended to include scenarios of fire and thaw.

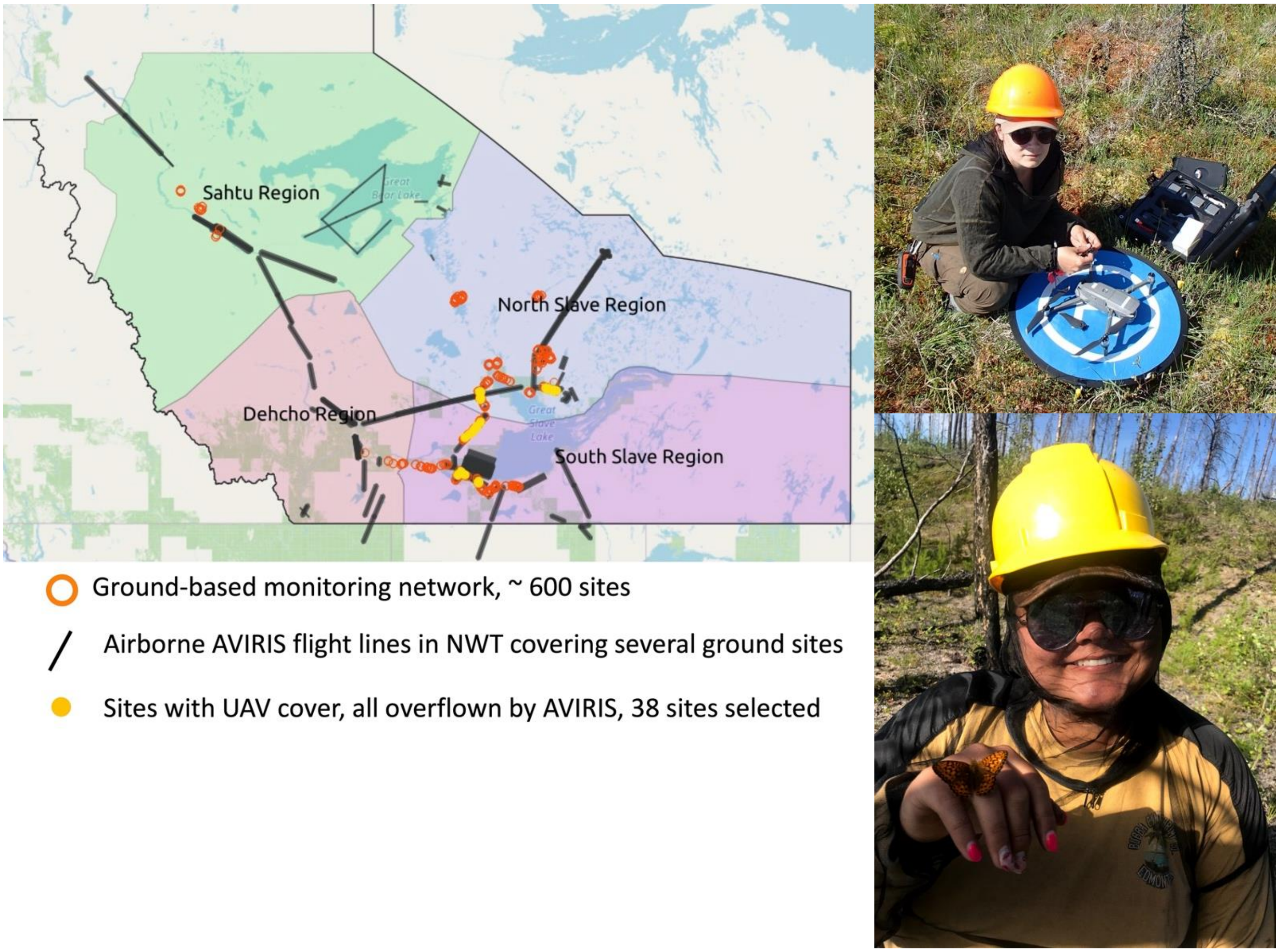

Figure 16*. Locations of lichen biomass plots overlain with UAV and Airborne sampling efforts. Team members conducting UAV data collection over lichen biomass plots.*

This work has progressed substantially during the 2022/23 fiscal year. Drone images have been classified and are currently being used to validate a Landsat-based map of lichen biomass available for the NWT. This effort will be completed in the coming months.

Using the data from Greuel et al. (2021), PDF Belke Brea has also developed a lichen biomass recovery module for the SpaDES ecological forecasting framework (www.predictiveecology.ca) (Figure 17) which will be published in the coming months. The predicted decline in areas of lichen biomass through time goes hand in hand with forest compositional changes that we are seeing in conjunction with changing wildfire activity.

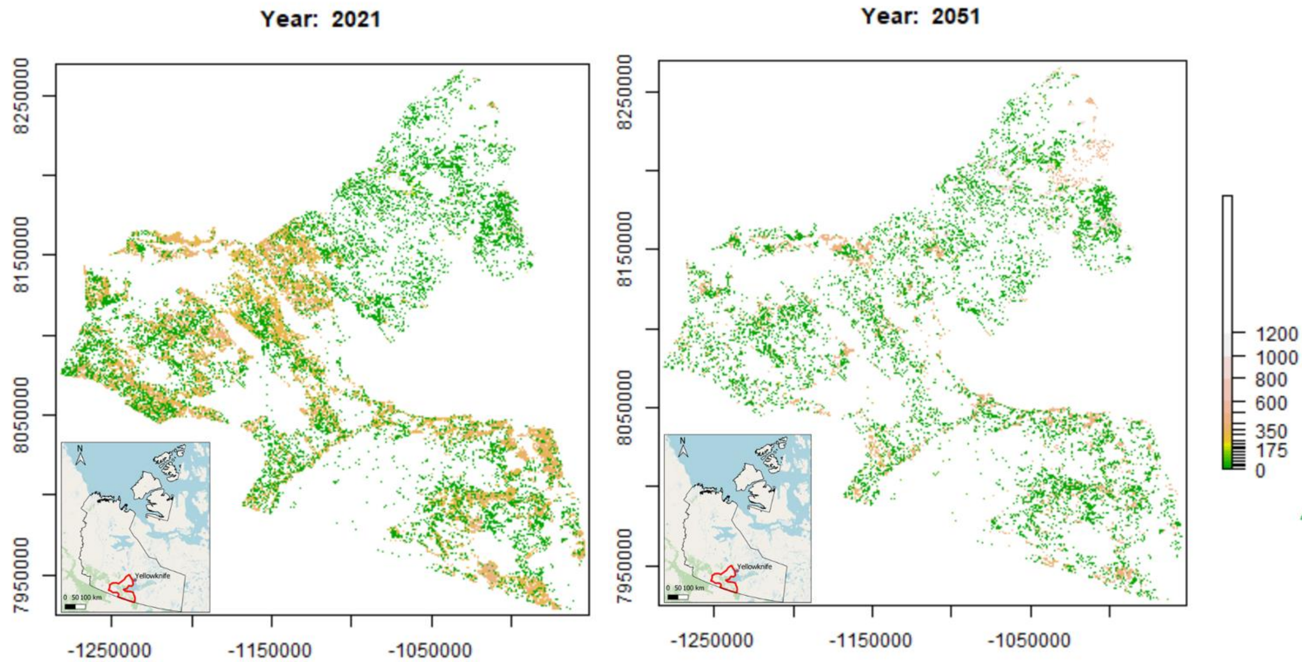

Figure 17. Example lichen biomass map based on LandR input data. White areas represent landcovers for which we have no lichen biomass information.

PDF Ceres Barros has similarly been developing a permafrost thaw module within the SpaDES framework using data produced in Gibson et al. (2021). To this end, we have integrated predictive models of ice-rich permafrost thaw and forest-fire dynamics, for caribou habitat projections within southern NWT. Variable importance analysis indicated that mean annual temperature was an important predictor of thermokarst formation, as well as the % cover of wetlands, mean stand biomass, mean elevation, and edge effects (Figure 18). Time after fire was not an important predictor of thermokarst in this model, highlighting that at large spatial scales (1) it likely provides redundant information with respect to stand biomass and other drivers, and that (2) warming surface temperatures are prompting permafrost thaw events in this part of the NWT. Initial mapping products highlight potential changes in permafrost and the risk of thermokarst formation within regions of southern NWT (Figure 19).

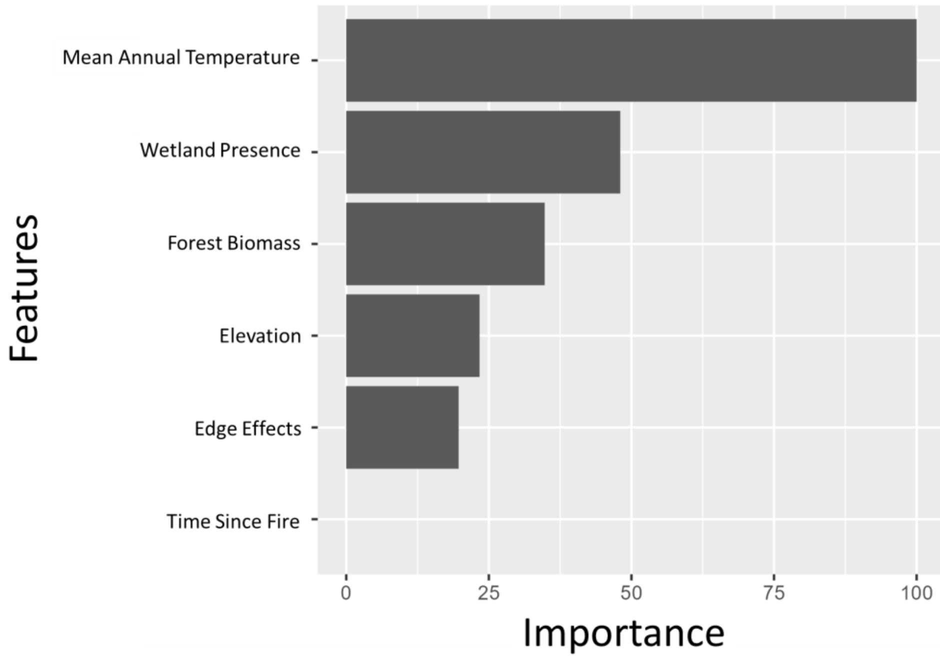

Figure 18. Variable importance plot for features used in the predictive SpaDES module for lowland permafrost thaw in southern NWT.

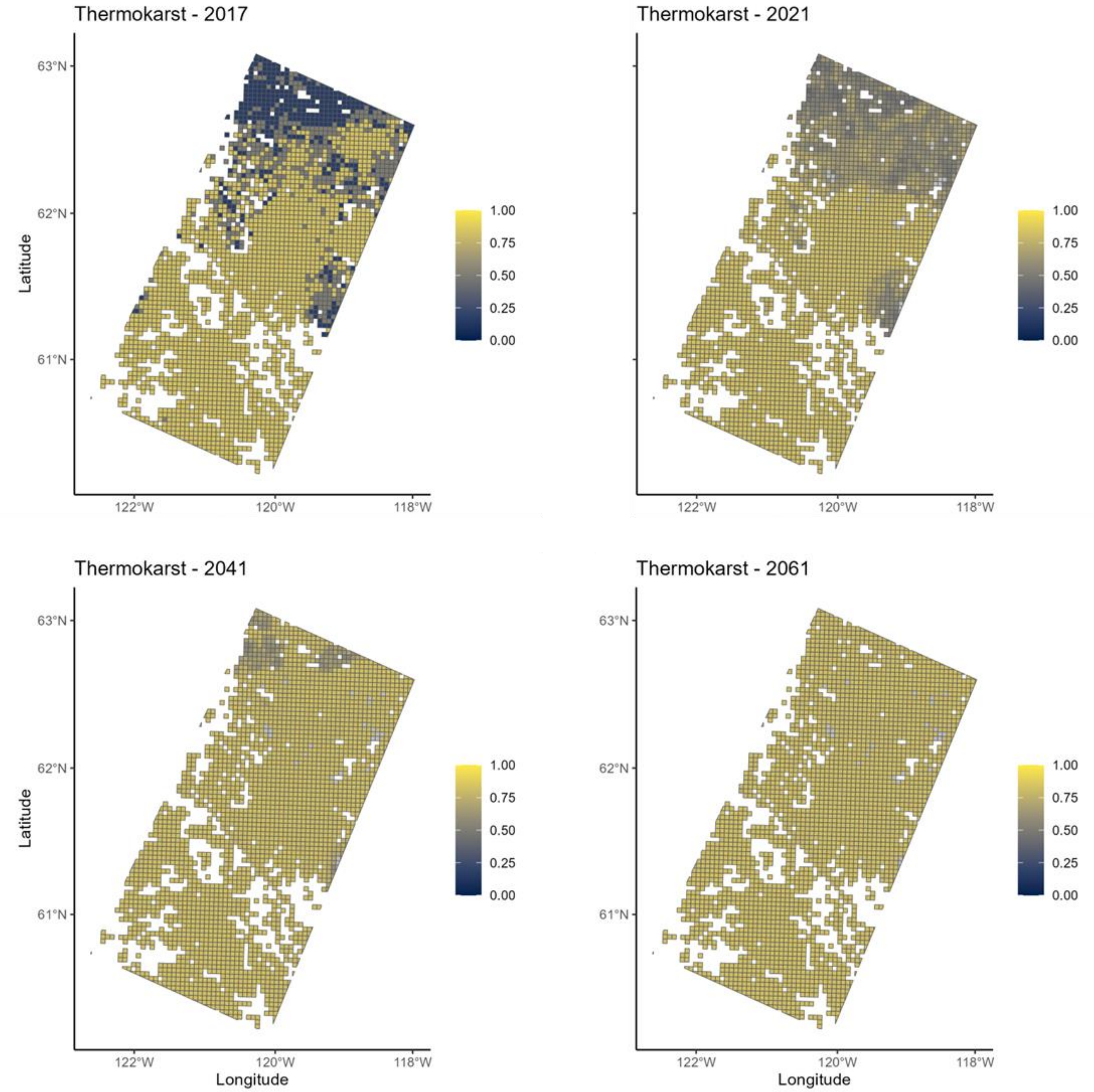

Figure 19. Maps of forecasted lowland thermokarst formation % (with respect to total peatland permafrost cover in 2017) in southern NWT under a scenario of climate-change only.

Finally, MSc Jorgenson evaluated the recovery of wildlife forage following fire. For this work, we used a network of sites throughout the NWT that vary in time since fire to evaluate recovery (Figure 20). In general, recovery times of preferred forage did not correspond well with estimates of wildlife return, except for boreal caribou. Our vegetation data indicate that preferred caribou forage reaches peak abundance in stands > 80 years, which corresponds with wildlife behaviour-based estimates of the same thing (Figure 21). Interestingly, many forage taxa showed different recovery trajectories through time when considering different site drainage conditions highlighting the importance of this variable in understanding wildlife habitat recovery (Figure 22).

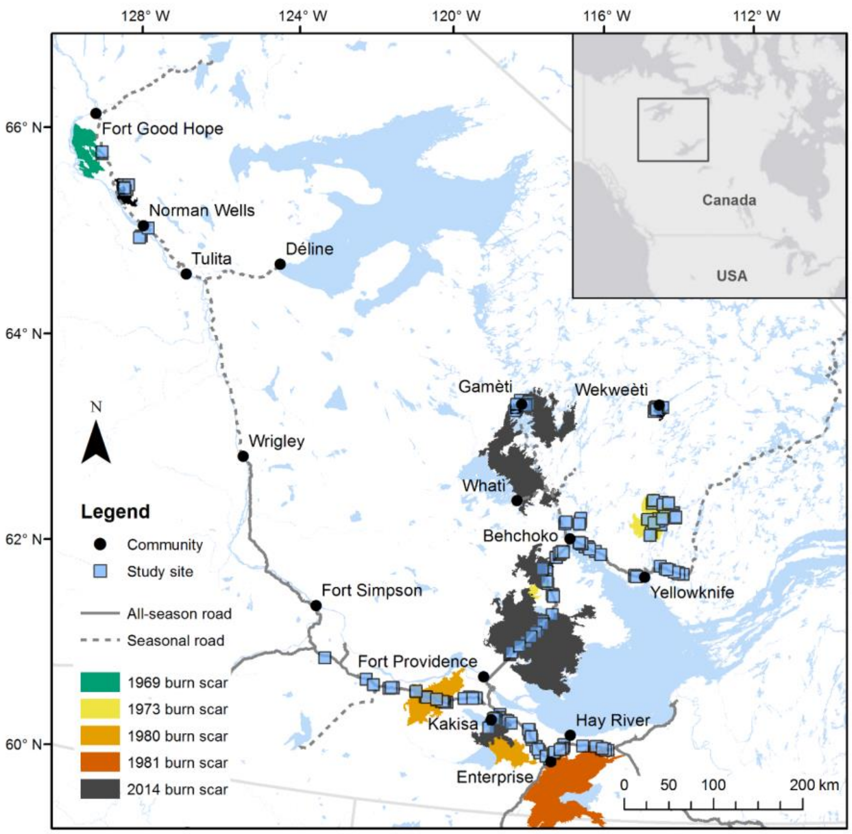

Figure 20. *Map of study locations for post-fire forage recovery study. Sites in the Sahtu region were established using ESRF funding.*

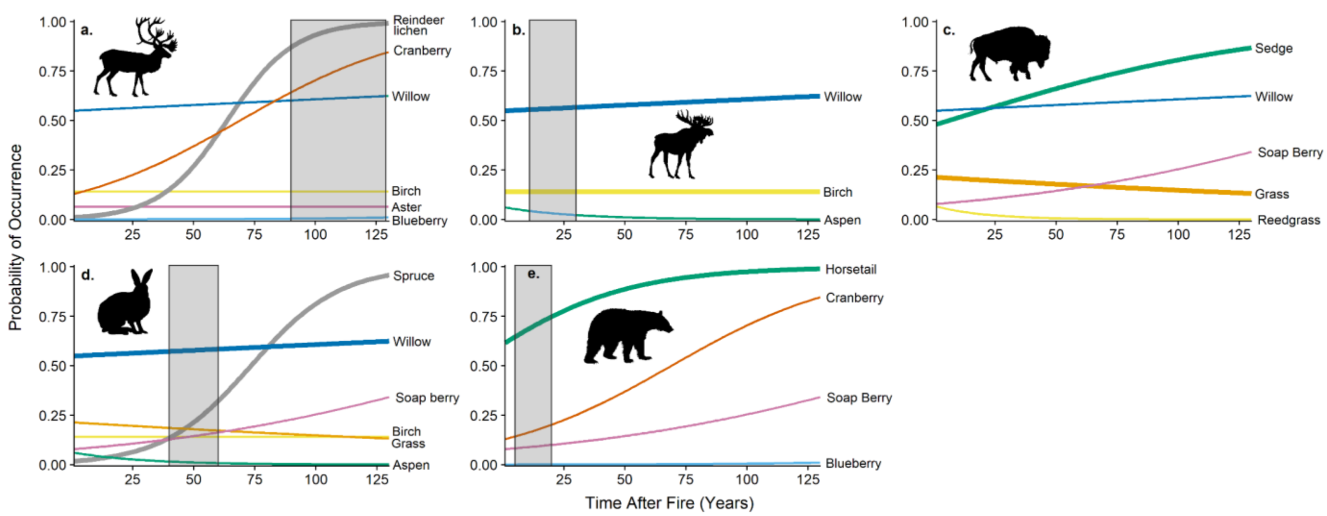

Figure 21. Predicted probability of occurrence over time after fire for forage species of **a.** woodland caribou, **b.** moose, **c.** wood bison, **d.** snowshoe hare, and **e.** black bear in the Taiga Plains ecoregion of the NWT, Canada. Thicker lines indicate forages that were noted as most consumed or selected during at least one season in multiple studies from literature review. Grey bars indicate timelines of top habitat use based on taxa-specific review of the wildlife literature. Forage species: aspen - *Populus tremuloides*, aster – *Aster* spp., birch – *Betula* spp., blueberry – *Vaccinium uliginosum*, cranberry – *Vaccinium vitis-idaea*, horsetail – *Equisetum* spp., reindeer lichen – *Cladina*/*Cladonia* spp., grass – *Poaceae* spp.,

reedgrass - *Calamagrostis* spp., sedge – *Cyperaceae* spp., soap berry – *Shepherdia canadensis*, spruce – *Picea mariana*, and willow – *Salix* spp. Image credits: caribou – clipart-library.com, moose and bison – public domain, hare – Anastassia CC BY 4.0, bear - Bob Comix CC BY 4.0 – full details in Appendix 3.6).

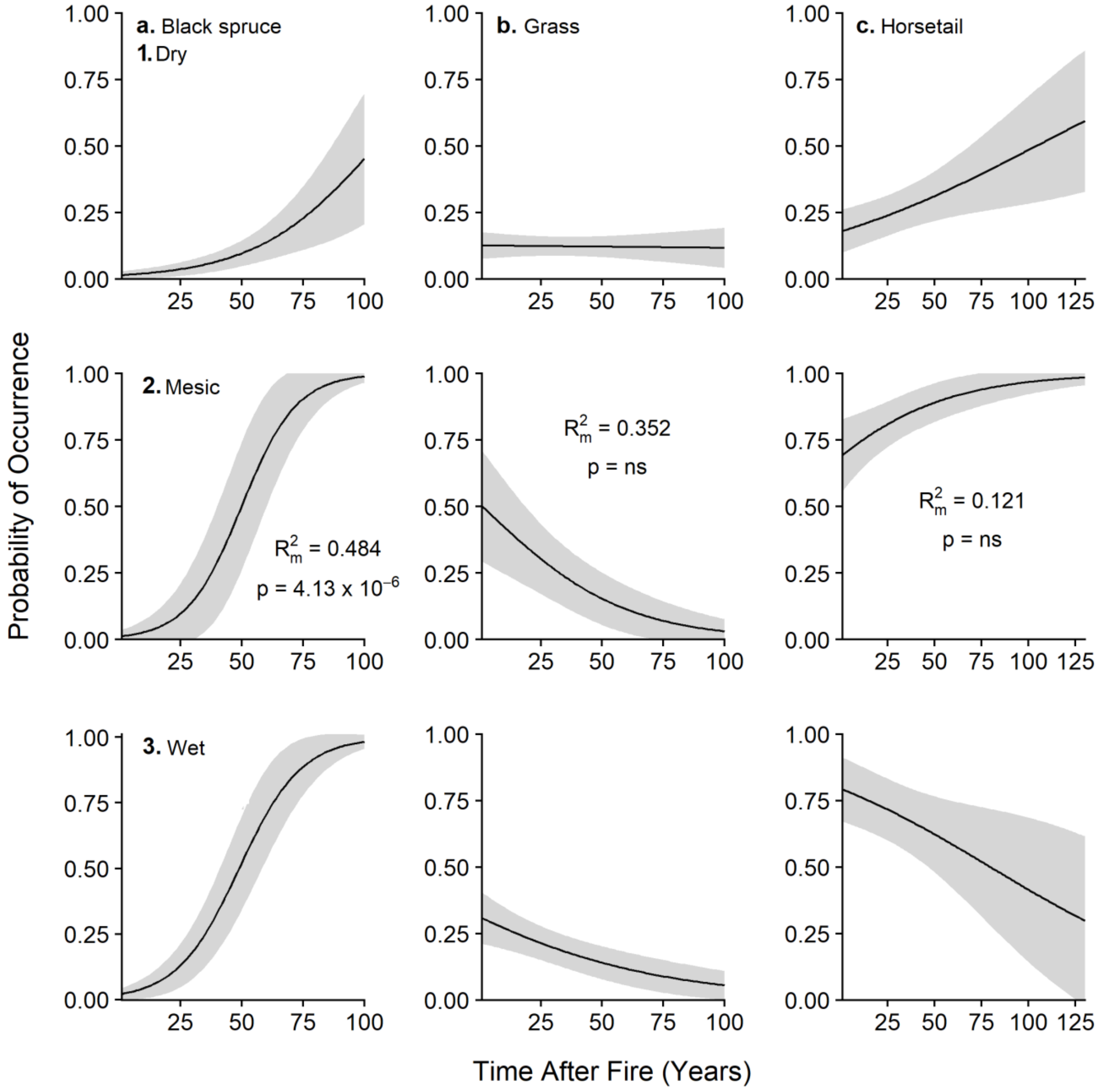

Figure 22. Predicted probability of occurrence of a. *Picea mariana* (black spruce) in the Taiga Shield (n = 198), b. *Poaceae* spp. (grasses) in the Taiga Shield (n = 198), and c. *Equisetum* spp. (horsetail), in the Taiga Plains (n = 323) ecoregion, at 1. dry, 2. mesic, and 3. wet plots in the NWT, Canada. Predictions from binomial generalized linear mixed effects model with logit link – all covariates other than time after fire held constant at the median value. Ribbons indicate 95% confidence intervals.

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Outputs to date:

Gruel, RJ, Degrè-Timmons, GE, Baltzer, JL, Johnstone, JF, McIntire, EJB, Day, NJ, Hart, SJ, McLoughlin, PD, Schmiegelow, FKA, Turetsky, MR, Truchon-Savard, A, van Telgen, MD, Cumming, SG. 2021. Predicting patterns of terrestrial lichen biomass recovery following boreal wildfires. Ecosphere, 12: e03481
https://esajournals.onlinelibrary.wiley.com/doi/epdf/10.1002/ecs2.3481

Associated open Dataset: Baltzer, J, Degré-Timmons, G, Day, N, Cumming, S, Turetsky, M, Johnstone, J. 2021. Terrestrial lichen data for Northwest Territories, Canada, Dryad Dataset, https://doi.org/10.5061/dryad.t1g1jwt15

Jorgenson, A, Alfaro-Sanchez, R, Cumming, S, White, A, Degre-Timmons, GW, Day, NJ, Turetsky, M, Mack, M, Johnstone, J, Walker, X, Baltzer, JL. The influence of post-fire recovery and environmental conditions on boreal wildlife forage. Ecosphere, accepted.

Jorgensen, A, Cumming, S, Day, N, Alfaro-Sanchez, R, White, A, Degré-Timmons, G, Johnstone, J, Turetsky, M, Mack, M, Walker, X, Schmiegelow, F, Baltzer, J. 2021. Plant recovery and wildlife return to the boreal forest after fire. International Boreal Forest Research Association Meeting.

Next steps:

- Completion of laboratory analysis. COVID-19 has slowed progress on sample processing and additional team members have been hired to accelerate this progress.
- With all drone-based data in hand, we will begin to couple our classified images with hyperspectral data from the ABoVE flights to evaluate the potential for improving lichen biomass estimates derived form satellite data
- Publication of the SpaDES lichen biomass ecological forecasting module and the development of appropriate scenarios for this forecasting.
- On-the-land camp led by the community of Fort Good Hope.
- Thermokarst vulnerability mapping and modelling efforts will continue through this and partner projects including Northern Water Futures as part of our collaboration with the NWT Thermokarst Collective.
- New team member Evan Schijns (MSc with collaborator Catherine Dieleman) will finalize analysis of soils from thaw features of different ages within the NWT.
- New data collection from long-term permafrost monitoring sites will be undertaken in the Inuvialuit region and new team member Katerina Coveny will analyse vegetation data in the Sahtu and Inuvialuit regions to better understand how rates and trajectories of permafrost thaw alter ground vegetation communities and by extension the wildlife communities who rely on these forage species.

Progress toward proposed project deliverables
As evidence, we are making substantial progress toward the stated project deliverables:
1) Yrs 1-4: Collaborative community workshops in Tulít'a to identify areas important for caribou on the landscape

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- Completed for 2017/18, 2019, postponed for 2020 and 2021 due to COVID-19. Planning in progress for 2022.
2) Yr 1: Research team involvement in the Sahtú Environmental Monitoring Research Forum meeting to engage the community further in the proposed research
- Completed; it is noteworthy that our extended project also supported a Forum call in 2019.
3) Yr 1: Review and synthesis of literature, data, and images on permafrost, fire, and caribou habitat in the Sahtú
- Completed – This formed part of MSc Alexis Jorgensen's thesis project and is currently being revised for publication.
4) Yr 1-3: Field surveys and analysis of data to establish relationships between fire, permafrost, and vegetation
- Completed. Fieldwork is completed and sample analysis is well underway. In addition to analysis of vegetation data, we will advance our understanding of post-fire soil carbon stocks and recovery and are developing upscaled products useful for managers operating across the NWT.
5) Yr 2-3: Point based photointerpretation of change characteristics
- completed – PhD Carolyn Gibson's work cited above
6) Yr 3-4: Develop maps and related decision-aids for predicting and detecting areas with a high potential for thermokarst and land subsidence post-thaw
- Completed. PhD Carolyn Gibson's work has mapped the vulnerabilities and PDF Ceres Barro is has developed the decision support tools using the SpaDES framework (www.predictiveecology.ca) in collaboration with Eliot McIntire, NRCan and Steve Cumming (ULaval)
7) Yr 3-4: Produce spatially explicit information on post-thaw landscape change and subsidence in critical caribou habitat
- Nearly complete. PhD Carolyn Gibson's work was central to this and 2019 and 2021 fieldwork will produce the data to finalize this goal. PDF Ceres Barro has been hired to undertake the ecological forecasting tool development as described above, which is nearing completion. The module for lichen biomass has been completed by Maria Belke Brea and should be submitted for publication in summer 2023.

Leveraged funding to date

ESRF funds are being heavily leveraged against other funding sources as outlined below making the proposed research feasible.

1) Global Water Futures (~$20,000/year)
    - The salary of Dr. Ana Sniderhan is being supported by core funding to Wilfrid Laurier University from Global Water Futures. Dr. Sniderhan led the vegetation sampling in the Sahtú in 2019. During 2019, Ana spent ~25% of her time on this project.
    - Travel support for Sniderhan
2) Northern Water Futures (~$50,000 per year)
    - The salary of Dr. Anna Coles was supported through Northern Water Futures until November 2018 at which point Anna took a position with the GNWT. Anna was dedicating roughly 50% of her time to this project.
    - Support for community outreach and engagement is available (during 2017, $10,000 was provided to support the Nę K'ə Dene Ts'ıl̨ ı̨ Forum workshop)
    - Field expenses for the teams
    - Northern Water Futures has been renewed until 2024, providing additional support for this work including the salary of MSc Katerina Coveny and that of PDF Mehdi Moslemi Aqdam.

3) Water Knowledge Camps ($100,000/year for 3 years)
   - This Global Water Futures funded program will help to ensure community engagement and knowledge exchange between our teams and the community members on whose lands we are working.
   - There will be one camp per year in Tulita (2019), Fort Good Hope (2023), and Deline (2024)
4) Polar Continental Shelf Program ($45,438 for 2018 field work; $64,428 for 2019 field work, $58,695 for 2021 fieldwork)
5) University of Guelph – Carolyn Gibson's salary was supported through a prestigious scholarship at the University of Guelph and sample analysis costs for Jess McCuaig's soil carbon analysis was supported by Turetsky's funds at University of Guelph. Evan Schijns is supported through UofG start-up funding provide to Dieleman.
6) Government of the Northwest Territories ($150,000 in 2018, $75,000 in 2019)
   - These year-end contributions helped to support the establishment of this field program and those of Drs. Rudolph and Gray. These resources supported helicopter time to access disturbance features on the landscape. The inaccessible nature of much of the landscape makes this sampling particularly challenging and costly.
7) Wilfrid Laurier University ($15,000) and GNWT CIMP ($25,000) – Jason Paul led the ground ice sampling in the Sahtú in 2019 and is supporting sample processing. His predecessor Genevieve Degre-Timmons led the effort to understand changes post-fire in forage lichen biomass. They both spent ~25% of their time on this work and their salaries are funded through Baltzer's Canada Research Chair funding provided through Laurier. Jason's work with the NWT Thermokarst Collective is supported through GNWT CIMP funding.
8) NSERC funding supported the project of Emily Ogden.