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## Identifying increasing risks of hazards for northern land-users caused by permafrost thaw: integrating scientific and community-based research approaches

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## LETTER

## Identifying increasing risks of hazards for northern land-users caused by permafrost thaw: integrating scientific and community-based research approaches

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E-mail: [cgibson3@ualberta.ca](mailto:cgibson3@ualberta.ca)**Keywords:** permafrost thaw, land-users, knowledge integration, community based, thermokarstSupplementary material for this article is available [online](#)**Abstract**

Understanding the causes and consequences of environmental change is one of the key challenges facing researchers today as both types of information are required for decision making and adaptation planning. This need is particularly poignant in high latitude regions where permafrost thaw is causing widespread changes to local environments and the land-users who must adapt to changing conditions to sustain their livelihoods. The inextricable link between humans and their environments is recognized through socio-ecological systems research, yet many of these approaches employ top-down solutions that can lead to local irrelevance and create tensions amongst groups. We present and employ a framework for the use both of scientific and community-based knowledge sources that provides an enriched and thematic understanding of how permafrost thaw will affect northern land-users. Using geospatial modeling of permafrost vulnerability with community-based data from nine rural communities in Alaska, we show that permafrost thaw is a major driver of hazards for land-users and accounts for one-third to half of the hazards reported by community participants. This study develops an integrated permafrost-land-user system, providing a framework for thematic inquiry for future studies that will add value to large-scale institutional efforts and locally relevant observations of environmental change.

**1. Introduction****1.1. Multiple knowledge systems**

Worldwide, communities are increasingly coping with altered environmental conditions due to climate change (IPCC 2018). Identifying the causes and consequences of these environmental changes is a research priority as this information is needed by decision-makers to help support adaptation planning in an uncertain future. This need is particularly evident in northern regions where rapid climate warming is causing widespread permafrost thaw (IPCC 2018). Given that people and nature are inextricably linked, overcoming environmental challenges, such as

thawing permafrost, will inevitably require the use of both social and ecological sciences (Liu *et al* 2007, Milner-Gulland 2012, Fischer *et al* 2015).

Social-ecological systems (SES) research has been widely accepted and touted as the direction research and funding agencies are headed (Chapin *et al* 2016). Many approaches to SES (see review by Guerrero *et al* 2018) focus heavily on the integration of disciplines but do not require or incorporate insight from local communities, public interest groups, or non-scientist communities that may be affected by problems and attempted solutions (Fischer *et al* 2015, Turner *et al* 2016). By linking scientific expertise and sophisticated large-scale modeling and data



**Figure 1.** Conceptual model of the attributes of scientific and community-based knowledge sources and the emergent properties from the use of these two knowledge sources. The knowledge properties of each knowledge system are not mutually exclusive.

capabilities with community-based local knowledge of finer-scale change and adaptation histories, power, experience, and wisdom can be shared in a bidirectional way to enhance understanding and outcomes (Chapin *et al* 2016, figure 1). Here we use a case study from interior Alaska that couples modeling of permafrost vulnerability with community-derived data of landscape hazard experiences by land-users to demonstrate how enhanced understanding of the permafrost land-user system can occur through bidirectional knowledge sharing.

### 1.2. Permafrost as a SES

Traditional harvest resources are the natural and cultural resources used by households to support their livelihoods and include the traditional use of wild resources for food shelter, fuel, clothing, tools, transportation, handicraft articles, customary trade, barter, and sharing (Huntington and Fox 2005, Ford

and Furgal 2009). For many northern residents, traditional harvest plays a vital role in social, economic, nutritional, and spiritual wellbeing (Wolfe and Walker 1987, Brinkman *et al* 2016). Traditional harvests in the Arctic-Boreal region of Alaska have declined by 30%–50% in the past 30 years (Wolfe and Walker 1987, Fall and Kostick 2018). While this decline is likely due to a combination of complex interactions amongst social, economic, regulatory, and environmental factors (Ford and Smit 2004), land-users have routinely identified environmental change as a key factor impacting their ability to efficiently and safely access traditional harvest resources (Brinkman *et al* 2016, Cold *et al* 2020).

While climate change is causing widespread and diverse types of environmental changes, one change that is particularly relevant to northern environments is the increasing rate of thawing of permafrost (Carnill 2005, Jorgenson *et al* 2006, Sniderhan and Baltzer 2016, Gibson *et al* 2018, IPCC 2018, Schuur and

Mack 2018, Biskaborn *et al* 2019, Lewkowicz and Way 2019). The area of permafrost in the northern hemisphere is expected to decline by 20%–35% by the mid-21st century (IPCC 2018). There is mounting evidence that permafrost thaw is driving widespread landscape change (IPCC 2018 and references therein), and anecdotal evidence that permafrost thaw creates hazards for land-users when out on the land. There is limited quantitative data to test the relationship between permafrost thaw and the generation of landscape hazards for land-users, posing a barrier to northern government's and communities' ability to plan and adapt to the impacts of permafrost thaw.

Land-users can observe and immediately attribute some environmental changes to permafrost thaw. We consider those changes to be direct impacts. These can include land slumping, riverbank erosion, falling over or 'drunken' trees, and changes to infrastructure such as damage to roads or buildings (Kokelj *et al* 2013, Baltzer *et al* 2014). Land-users may also experience, but not immediately attribute some changes to permafrost thaw, though more in-depth investigations may reveal the linkage to changes in the permafrost. We defined those as indirect impacts. Indirect impacts can include changes in river flow, altered vegetation communities (Schoor *et al* 2007), fluctuations in wildlife abundance and distribution (Chin *et al* 2016), or changes in water quality (Tank *et al* 2016).

Past research has explored how permafrost thaw either directly or indirectly affects land-based ecosystem services, food security (Chapin *et al* 2006), archeological sites (Andrews *et al* 2016), community relocations (Maldonado *et al* 2013), use of traditional travel routes (Andrews *et al* 2016, Proverbs *et al* 2020), and wildlife distribution (Tape *et al* 2016). While these studies provide insight into how land-users may be affected, our understanding remains largely qualitative, anecdotal, or conceptual with limited research quantifying the magnitude and frequency of specific impacts. Being able to quantify the extent of permafrost-driven impacts for land-users is important as it will allow us to couple this understanding with large-scale climate models to predict future impacts for communities, ultimately allowing for more generalizable, proactive, and effective adaptation planning.

Effective adaptation planning will require quantifying the extent to which permafrost thaw creates hazards for land-users as well as the severity of the consequences for human access to those resources. A key component of ecosystem service 'availability' is the safe and reliable access to a given resource (Brinkman *et al* 2016). For example, residents of northern communities perceived that climate-related changes in the environment are having significantly greater impacts on access to resources than the abundance and distribution of those same resources (Brinkman *et al* 2016).

Alaskan communities have identified safety considerations while on the land (Brubaker *et al* 2011, Clark *et al* 2016, Cold *et al* 2020) and unpredictable conditions in the physical environment (Brinkman *et al* 2016) as key concerns regarding current and future harvesting activities. For example, wildfire has been shown to restrict access, topple traplines, and burn shelters that are critical to safe travel (Chapin *et al* 2006). These represent 'hazards'; any environmental condition that negatively affects a land-user's travel, access to a given area, or their safety. Permafrost thaw can likely create new hazards and exacerbate ones that are already affecting land-users.

To quantify the extent to which permafrost thaw generates hazards for land-users, we apply an integrated framework (figure 1) to address three core objectives. Firstly, we quantified the extent to which permafrost thaw was a source of hazards within a dataset of hazards identified by land-users. Secondly, using data derived from interviews with land-users, we then aimed to understand how these permafrost-driven hazards affect land-user's activities, access to the land, and their safety. Finally, by combining local-level land-user data with large-scale models of permafrost thaw vulnerability we quantified the extent and the potential for permafrost thaw to generate hazards for land-users.

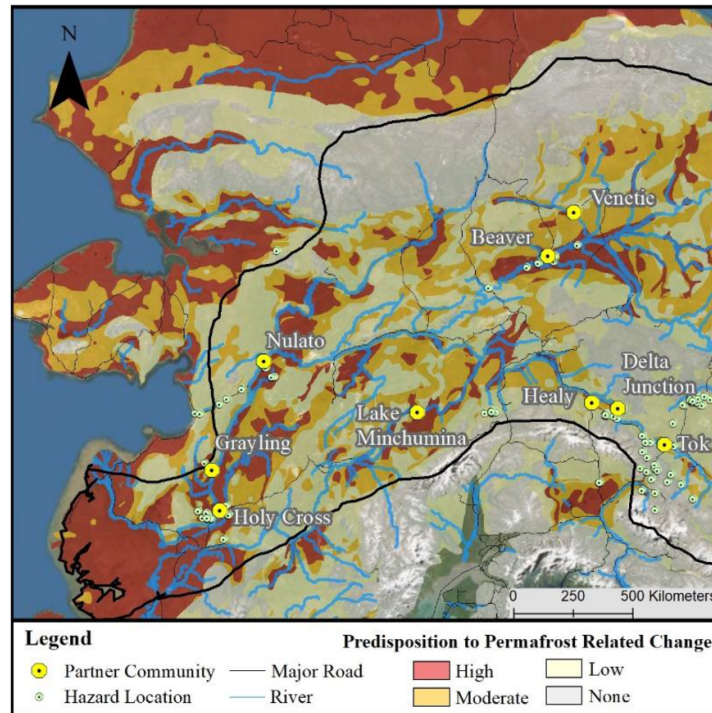
## 2. Methods

### 2.1. Partner communities and data collection

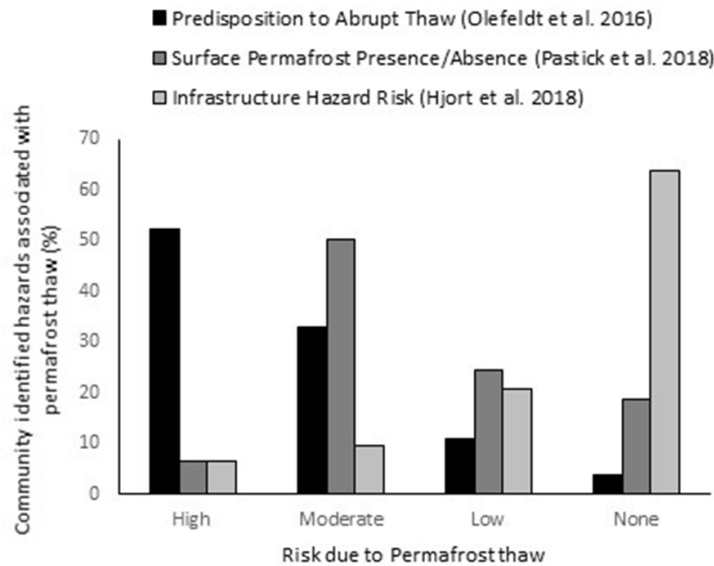
The Yukon River basin of interior Alaska (figure 2) was used as the study area to quantify the extent to which permafrost thaw generates hazards for land-users (supplemental 1 (available online at [stacks.iop.org/ERL/16/064047/mmedia](https://stacks.iop.org/ERL/16/064047/mmedia))). As part of a NASA ABoVE project (ID # NNX15AT72A), an intensive year-long partnership was developed with nine rural communities that are representative of a range of social and ecological conditions within the study area (Cold *et al* 2020, figure 2, table S1). The data collected by the communities provide a personal photo, written, and oral documentation of experiences with landscape hazards in the study area (i.e. community-based knowledge, figure 1). All interviewees and participants gave their informed written consent to participate in this study in accordance with the University of Alaska Fairbanks Human Institutional Review Board (IRB # 700936). Only participants who consented to have their data points presented have been included visually in figures in this study. Therefore, we will be reporting statistics on all data collected, but only visually displaying the geospatial data points and photos that have been approved by the participants to share with public audiences (figures 2, 4 and 6).

The population size across the nine communities as of 2010/2011 was between 46 and 1239 residents, and are a mix of European descent and Native





**Figure 2.** Yukon River basin study area outlined in black with nine partner communities. Hazard locations identified by land-users are shown in green circles. Only a subset of the hazard locations ( $n = 184/442$ ) that have been approved for publication by the land-users are shown. These are underlain with the Olefeldt *et al* (2016) permafrost thaw probability data. Base map provided by Esri, DigitalGlobe, Geo eye (ArcGIS version 10.3).



**Figure 3.** Proportion of community-identified hazards associated with permafrost thaw (high or highly likely). These points are used as a proxy for ground truth points and compared to each thaw vulnerability class in Olefeldt *et al* (2016), the Pastick *et al* (2015), and the Hjort *et al* (2018) permafrost vulnerability datasets. The Olefeldt *et al* (2016) data best represented the ‘ground truth’ points and thus is used in subsequent analyses.

Alaskan (Koyukon, Holikachuk, Deg Hit’an Athabascan, and Gwich’in). Traditional harvest practices are a way of life for all partner communities and residents use a series of roads, trails, and navigable waterways to access local wild resources. Travel along these routes consists of passenger vehicles, snowmobiles, ATVs, and boats. The nine communities vary in their

connectivity to roads, and per capita consumption of wild food is known to increase as the distance from the road system (Burnsilver *et al* 2016). Given this, we report results at both the regional level (pooling all communities) and for road-connected and non-road-connected (remote) communities. Tok, Delta Junction, and Healy are connected via a road network

and have greater access to commercial resources such as fuel and groceries, and the cost of commercial goods is less compared to the remote communities (Goldsmith 2007) of Nulato, Grayling, Holy Cross, Lake Minchumina, Beaver and Venetie.

Land-users that were actively participating in traditional harvest activities and that had experience and knowledge of the traditional areas around their community received a camera-equipped GPS. Using their camera, they collected photos and spatial coordinates of any environmental condition that affected their travel and access to a given area on the land, referred to herein as 'hazard' data (supplemental 2). Land-users then filled out a form about each photo that explained their interpretation of what was pictured, how the conditions pictured influenced their travel or access, how frequent this environmental condition was observed in other places around their community, and to what extent the condition affected their travel safety. Eighteen individuals recorded environmental conditions affecting their land use for 17 months from March 2016 to July 2017.

## 2.2. Identifying permafrost-driven hazards from community-based knowledge sources and determining how permafrost-driven hazards affected land-users and their safety

Land-users' hazard data that were missing GPS coordinates or photos ( $n = 34$ ) were removed, resulting in a total of 479 hazard locations for subsequent analyses. To determine if permafrost thaw directly generated hazards for land-users, an expert assessment was used to code the photos based on the likelihood that the hazard was related to a permafrost thaw event (supplemental 3).

To understand how permafrost-driven hazards affect land-user's activities, access to the land, and their safety we used the local participant's description of the effect of each observation on travel and access to resources. Quotations from the participant narratives were used to provide important context relevant to the hazards and the situations land-users faced. Descriptions were organized into three broad categories: impacts to equipment (e.g. damage to a motor), access (e.g. the blockage of a trail), and access to areas used historically (e.g. previous traditional harvest locations). For this data, only conditions from hazards that were 'highly likely' or 'likely' to be caused by permafrost were reported, as other conditions could be caused by other forms of environmental change.

## 2.3. Quantifying the extent of and potential for permafrost-driven hazards from scientific knowledge sources

To quantify the extent to which permafrost thaw directly created hazards for land-users we used descriptive and summary statistics for the number hazards 'highly likely' or 'likely' caused by permafrost thaw.

Due to differences in the reporting frequency and engagement by communities (table S1), we reported on the proportion of permafrost hazards from a given community type (i.e. road connected or non-road connected) or region, as opposed to the raw number of all hazards observed.

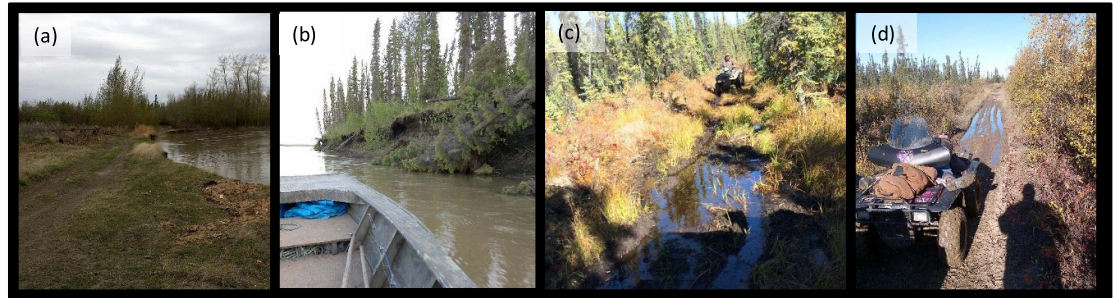
To quantify the extent to which permafrost thaw may indirectly create hazards for land-users it was recognized that there is no one best permafrost vulnerability assessment data product. Therefore, we first assessed three geospatial permafrost vulnerability data products (Pastick *et al* 2015, Olefeldt *et al* 2016, Hjort *et al* 2018) to determine which one was most suited for this study. Hazard locations that were classified as either highly likely or likely to be caused by permafrost thaw ( $n = 144$ , considered to act as proxy ground truth points) were overlaid on each spatial product, and the proportion of these hazards that fell within each permafrost vulnerability category was summarized (figure 3). We found that the Olefeldt *et al* (2016) dataset best represented the 'ground truth' points and thus was used in all subsequent analyses. This dataset assesses predisposition to abrupt thaw. Many of the spatial proxies used to predict abrupt thaw can also be used as proxies to predict gradual thaw (for example ground ice content). Given this, we consider this dataset to provide a coarse-scale estimate of landscapes that are predisposed to permafrost-related change.

Using the Olefeldt *et al* (2016) dataset, we estimated the area of none, low, moderate, and high predisposition to permafrost-related change within each community's resource harvesting range. A spatial join was completed in ArcGIS (Version 10.6) to assign a predisposition to permafrost-related change to each hazard point. For this analysis, we assumed that all hazards located in high-thaw vulnerability areas are either directly or indirectly caused by permafrost thaw. We used the Neufeld *et al* (2019) dataset that provides a modeled traditional harvest—area for each community and assume that the availability of the use area is equal among land-users from that community (supplemental 4). A chi-square test was then used to determine if the proportion of hazards in a given thaw vulnerability class are greater than would be expected based on the areas of that vulnerability class within their harvesting range. For example, a significant chi-square statistic ( $\alpha < 0.05$ ) would indicate that when a land-user traverses a higher predisposition to permafrost-related change area, the chances of encountering a hazard are disproportionately higher compared with traversing a lower thaw probability area.

## 3. Results

### 3.1. Identification of permafrost-driven hazards

Over the one-year period (2016–2017), 18 land-users from nine partner communities collected GPS



**Figure 4.** Example of hazards encountered by land-users while on the land that were ‘highly likely’ or ‘likely’ to be caused by permafrost thaw. (A) Lake edge erosion encroaches on a travel route. The land-users will soon need to reroute the trail. (B) Riverbank thaw increases river sediment load and trees dislodged into the river become a hazard for motorboats. (C) and (D) Thawing soils create muddy trails that impede ATV travel.

data associated with 479 hazard locations (figures 2 and 4), including a total of 441 with GPS locations and photos. Using the expert assessment of the photos and descriptions collected by the land-users to determine if permafrost thaw generated hazards for land-users, it was revealed that there were numerous instances ( $n = 142/441$  hazards) and ways in which permafrost thaw created hazards (figure 4).

### 3.2. Determination of how permafrost-driven hazards affected land-users and their safety

The written and oral descriptions documented by land-users provided insight into how permafrost-driven hazards affected land-user’s activities, access to the land, and their safety. Land-users described how permafrost-driven hazards affected them in these different ways:

#### *Impacts to equipment*

‘[It] adds debris to the water. This can ruin your day, or your whole fishing summer in fact ([boat] propeller, lower unit). Makes for tougher gathering and fishing. Fills your wheel or net with stuff. Have to pull net and wheel’—66.34° N, −147.59° W.

#### *Impacts to access*

‘Debris in water makes boating more dangerous and makes it harder to dock the boat to access the area’—66.33° N, −147.59° W.

#### *Impacts to historical areas*

‘Changes navigable channels. Need to find new fishing spots. Trees falling on you, rolling waves. Changes to historic fishing area for the first time’—66.33° N, −147.59° W.

Of the hazards that were ‘highly likely’ or ‘likely’ attributed to permafrost thaw ( $n = 157$ ), land-users

reported 61% had a strong or moderate effect on their safety. Land-users reported that of the hazards located within high or moderate thaw probability area ( $n = 256$ ), 68% had a strong or moderate effect on their safety. One common hazard that was reported and had a strong effect on land-user safety was the impact of thaw and subsidence on ATV trails. The conversion of solid ground to wet, muddy areas makes it extremely difficult, time-consuming, and potentially dangerous to traverse as ATVs can tip over. These impact travel routes as it does not support travel using any form of motorized vehicle (e.g. truck, quad/ATV). When this occurred, land-users had to break new trails to find alternate routes, seek out new harvesting areas or change the timing of access to the resource (i.e. wait for drier or colder conditions). These hazards increased the amount of time a land-user was out on the land and reduced harvesting efficiency. Land-users described how permafrost thaw generated these conditions and the impacts it might have on their safety:

‘This causes great difficulty as new trails must be cut around washouts or dangerous riding occurs’—63.84° N, −145.21° W.

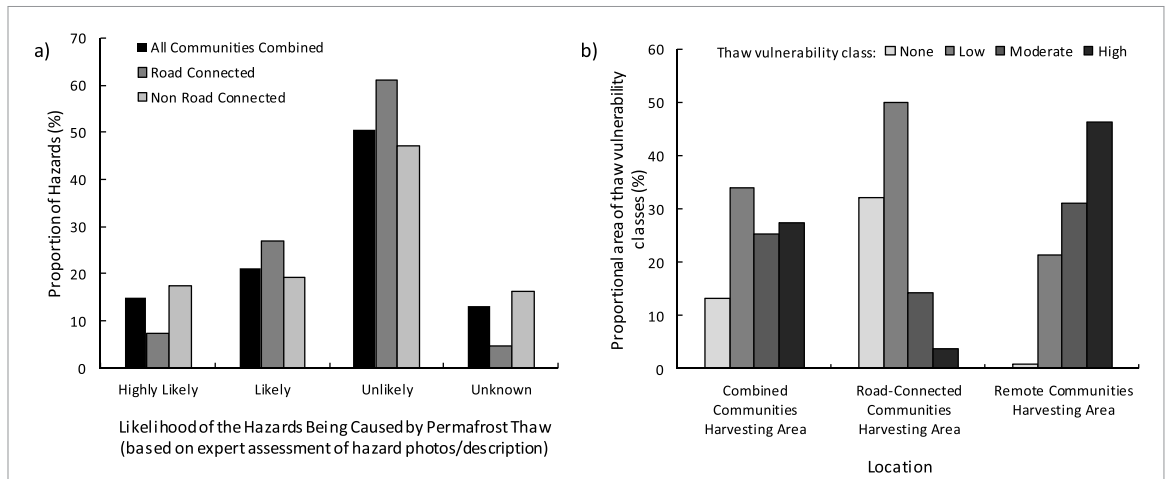
‘Trail is very wet and muddy—got stuck several times, other years it has been dry in September’—64.12° N, −141.89° W.

‘Need to use ATV instead of vehicles, takes longer when you are harvesting’—67.03° N, −146.48° W.

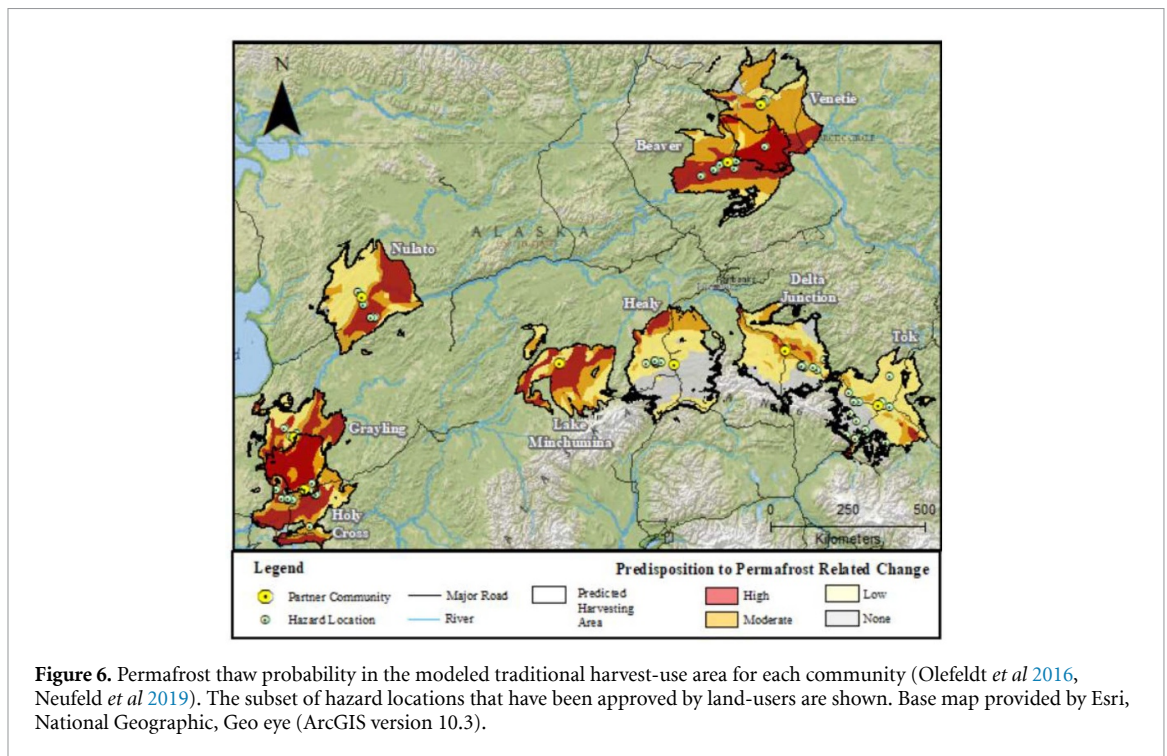
### 3.3. Quantification of the extent of and potential for permafrost-driven hazards

The extent to which permafrost thaw directly created hazards for land-users throughout the entire region (i.e. the frequency of ‘highly likely’ or ‘likely’ caused by permafrost thaw) was 33% ( $n = 153$ ) across the entire region (figure 5(a)). This frequency varied greatly between road-connected





**Figure 5.** Proportion of hazards that were highly likely, likely, unlikely to be caused by permafrost thaw (including unknown) based on the land-user’s photos and descriptions, and expert determination of relation to permafrost thaw (a). The proportion of traditional harvest use areas that are covered by each thaw vulnerability class is based on the Olefeldt *et al* (2016) dataset (b). Results are reported for all communities combined as well as for road-connected communities and remote communities.



**Figure 6.** Permafrost thaw probability in the modeled traditional harvest-use area for each community (Olefeldt *et al* 2016, Neufeld *et al* 2019). The subset of hazard locations that have been approved by land-users are shown. Base map provided by Esri, National Geographic, Geo eye (ArcGIS version 10.3).

and non-road-connected communities. In general, road-connected communities had a lower frequency of ‘highly likely’ or ‘likely’ compared to rural communities.

The extent to which permafrost thaw both directly and indirectly created hazards for land-users throughout the entire region (i.e. the proportion of hazards located in high thaw vulnerability areas) was 52% (figure 5(b)). For context, high thaw vulnerability areas covered only 21% of the study region and 27% of the combined harvesting area of each community (table S2, figure 4). In nearly all the remote communities, there were more hazards located in

higher thaw vulnerability areas than would be expected based on the area of high thaw vulnerable permafrost in a community’s harvesting range (chi-squared test, table S2). The proportion of high thaw probability within communities harvesting areas ranged from 2% to 61% (table S2). Road-connected communities had lower proportions of their harvesting ranges composed of high thaw probability areas (mean ± SD = 3.6 ± 1.5%) compared to remote communities (mean ± SD = 45.5 ± 12.8%) (figure 6). This phenomenon was particularly evident in Beaver where all the hazards occurred in high thaw probability areas despite high thaw probability areas only



occupying 51% of phenomenon was more muted in road-connected communities with a higher proportion of hazards occurring in low probability areas compared to no-thaw probability areas (chi-squared test, table S2), but with relatively few hazards occurring in the limited moderate and high thaw probability areas.

#### 4. Discussion

Through a partnership with nine rural communities in interior Alaska, we showed that permafrost thaw is a major driver and accounts for at least a third of all hazards and potentially as great as 50% of hazards. The proportion of permafrost-driven hazards is higher than what would be predicted based on the area of high-thaw vulnerable permafrost within a community's harvesting range.

A common effect of permafrost thaw documented by land-users in this study was the thawing/erosion of riverbanks. The hazards generated by this form of permafrost thaw are of particular concern for rural communities that have few roads/trails and are highly dependent upon rivers for access to the land (Cold *et al* 2020). Additionally, as riverbanks erode, traditional landing spots become inaccessible and river channel flow and navigation become less predictable (Kokelj *et al* 2013, Walvoord and Kurylyk 2016). It is important to note that in addition to these impacts, riverbank erosion will also create ecological consequences that land-users will need to adapt to such as high sediment and nutrient loading that may ultimately affect upper trophic level species (Chin *et al* 2016). Therefore, while not part of this study, it is evident that an understanding of the cumulative effects for land-users and their traditional harvest resources is needed.

Another common effect of permafrost thaw identified by land-users was ATV trails becoming muddier and 'soggy'. This is likely due to the destabilization of the permafrost and thaw settlement/subsidence below the trail that increases soil moisture (Zoltai 1993). The cause of this destabilization can be driven by a complex interaction of permafrost conditions, climate conditions, and anthropogenic disturbance to the land. Modern, mechanized means of transportation are known for removing surface layers of vegetation that insulate and protect permafrost. This anthropogenic disturbance cause can trigger or enhance the thawing of permafrost (Williams *et al* 2013) which further exacerbates the hazards to land-users. Given that the use of these modes of transportation is critical to supporting traditional harvesting activities, further work is needed to enhance understanding of how different mitigation approaches can be implemented to preserve permafrost landscapes and prevent accelerated degradation of permafrost thaw from anthropogenic sources.

This form of hazard was reported in a lower frequency than river-associated hazards, potentially due to differences in the source or mechanism of the permafrost thaw: gradual active layer deepening versus abrupt thermokarst formation (Grosse *et al* 2011, Turetsky *et al* 2020). Past studies have shown that when asked to report environmental conditions, land-users are more likely to report instantaneous (abrupt) changes as opposed to sustained (gradual) changes (Bender *et al* 1984, Collins *et al* 2016). Active layer thickening occurs over decades, with only a few cm a year of thaw each year (Camill 2005). Comparatively, thermokarst formation can erode whole riverbanks in a matter of years (Kanevskiy *et al* 2016). Given this, it could be hypothesized that land-users are more likely to report hazards associated with abrupt permafrost thaw than those associated with gradual active layer thickening. This is not to say, however, that active layer thickening is not affecting land-users. Adaptation to these sorts of landscape changes may be gradual and occurring over many years causing it not to appear as a 'hazard'. To gain a more holistic understanding of how permafrost thaw affects land-users, future research should aim to document how permafrost has changed in the region to provide the critical context on how traditional harvesting activities are being altered. These qualitative data may be merged with quantitative analysis of past remote-sensing scenes (Brown *et al* 2020) to reveal patterns of change in human-environment interactions.

In addition to the safety hazards created by these conditions that the land-users identified, there are also likely several unintended economic consequences of permafrost thaw related hazards. The 'soggy' conditions that are created during the non-frozen months when permafrost thaws, or the debris that is dislodged due to riverbank thaw, are known to challenge access by any motorized vehicle and may damage motors that will require financial resources to repair them. Additionally it may create an impediment that forces people to devote more time and effort to rerouting their travel path (additional gas and tool requirements), switching their mode of access (upgraded or new modes of transportation), or abandoning the use of that travel segment (additional resources required to develop new segment).

Cold *et al* (2020) showed that the rate of environmental hazards are higher for remote communities. For permafrost-driven hazards, while this study observed a similar pattern, this is not conclusive, as road-connected communities had substantially less high-thaw probability areas within their harvesting range. This is not surprising as major roads, and subsequently, communities on those roads, are unlikely to be built in areas that have large areas of vulnerable permafrost. Given this, it is evident that, while the impacts of permafrost thaw are widespread, they

also vary by community, suggesting that singular, regional wide, and top-down approaches to adaptation may not be sufficient. Beyond the scope of this study, broader-level applications of local-level planning will be necessary.

The Olefeldt *et al* (2016) data used in this study provides a good estimate of large regions that may be predisposed to permafrost-related landscape change. We use this dataset to provide a first-order assessment of if hazards are more broadly occurring in these high predisposition landscapes. Caution should be used when interpreting or using these data for fine-scale assessments of hazard locations (i.e. this data should not be used to inform land-use planning at regional scales). Rather, what the information from this study identifies is that areas highly predisposed to permafrost-related changes have higher rates of hazards. The exact magnitude of this cannot be determined with the Olefeldt *et al* (2016) data, and a more localized understanding of permafrost conditions and change are needed to provide more spatial predictive power for future hazard planning. Finer scale understanding of permafrost thaw related patterns, that couple probability of near-surface permafrost (e.g. Pastick *et al* 2015), and thaw probability (e.g. Hjort *et al* 2018) will allow for a greater understanding of the link between permafrost thaw and hazard generation, and support spatially explicit recommendations related to planning and mitigation efforts into the future.

## 5. Conclusion

Here we show that permafrost thaw is a major driver of hazards for land-users and accounts for one-third to half of all hazards land-users face while on the land. These permafrost-driven hazards are diverse and can range from damage to equipment, to affecting access to traditional harvest areas, to causing safety concerns for land-users. This integrated understanding of both the quantitative and qualitative impacts of thaw is a unique emergent property of this study and allows for an amplified understanding of the permafrost environment. This study is one of the first to connect the impacts of permafrost thaw to hazard generation for land-users. This work addresses an important knowledge gap by systematically assessing and quantifying the association between changing environmental conditions and the impact on traditional harvest practices. Because land management cannot halt the thawing of permafrost, adaptation to these changing conditions will be critical. To plan, adapt to, and manage safety concerns related to permafrost thaw-driven hazards, communities and governments will require decision support tools that can assess permafrost thaw risk. As shown by this study, these risk assessments will be most effective if they combine scientific knowledge of thaw vulnerable areas with

community-based knowledge of the consequences of this thaw.

## Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: [https://cmr.earthdata.nasa.gov/search/concepts/C1631048384-ORNL\\_DAAC.html](https://cmr.earthdata.nasa.gov/search/concepts/C1631048384-ORNL_DAAC.html).

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