ASSESSING EFFECTS OF CLIMATE CHANGE ON ACCESS TO ECOSYSTEM SERVICES IN RURAL ALASKA

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A Thesis Submitted in Partial Fulfillment of the Requirements

for the Degree of

Master of Science

in

Wildlife Biology & Conservation

University of Alaska Fairbanks

December 2018

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Abstract

Across the planet, climate change is altering the way human societies interact with the environment. Amplified climate change at high latitudes is significantly altering the structure and function of ecosystems, creating challenges and necessitating adaptation by societies in the region that depend on local ecosystem services for their livelihoods. Rural communities in Interior Alaska rely on plants and animals for food, clothing, fuel and shelter. Previous research suggests that climate-induced changes in environmental conditions are challenging the abilities of rural residents to travel across the land and access local resources, but detailed information on the nature and effect of specific conditions is lacking. My objectives were to identify climate-related environmental conditions affecting subsistence access, and then estimate travel and access vulnerability to those environmental conditions. I collaborated with nine Interior Alaskan communities within the Yukon River basin and provided local residents with camera-equipped GPS units to document environmental conditions directly affecting access for 12 consecutive months. I also conducted comprehensive interviews with research participants to incorporate the effects of environmental conditions not documented with GPS units. Among the nine communities collaborating on this research, 18 harvesters documented 479 individual observations of environmental conditions affecting their travel with GPS units. Environmental conditions were categorized into seven condition types. I then ranked categories of conditions using a vulnerability index that incorporated both likelihood (number of times a condition was documented) and sensitivity (magnitude of the effect from the condition) information derived from observations and interviews. Changes in ice conditions, erosion, vegetative community composition and water levels had the greatest overall effect on travel and access to subsistence resources. Environmental conditions that impeded travel corridors, including waterways and areas with easily traversable vegetation (such as grass/sedge meadows and alpine tundra), more strongly influenced communities off the road network than those connected by roads. Combining local ecological knowledge and scientific analysis presents a broad understanding of the effects of climate change on access to subsistence resources, and provides information that collaborating communities can use to optimize adaptation and self-reliance.

Table of Contents

Abstract i

Table of Contents ii

List of Figures iii

List of Tables iv

List of Appendices v

Introduction 1

Literature cited 4

Chapter 1: Assessing vulnerability of subsistence travel to effects of environmental change in Interior Alaska 7

Abstract 7

Introduction 8

Methods 10

Study area 10

Community engagement 11

Documentation of environmental conditions 13

Comprehensive interviews 14

Data analysis 15

Results 18

GPS data 18

Coded interview data 19

Merged GPS and interview data 20

Discussion 21

Effect of road connectedness on vulnerability 25

Broader implications for Interior Alaskan social-ecological systems 27

Literature cited 29

Conclusion 54

Literature cited 56

List of Figures

Figure 1: Map of project study area depicting the nine collaborating communities within the Yukon River basin 35

Figure 2: Descriptions and photographic examples of the seven categories developed by researchers of conditions associated with environmental changes 36

Figure 3: Visual example of data groupings used for different analyses 37

Figure 4: Graph and associated mean values for vulnerability analysis of GPS data among 18 individuals (4a) nine communities (4b), three road-connected communities (4c) and six remote communities (4d). 38

Figure 5: Graph and associated mean values for vulnerability analysis of interview data among 22 individuals (5a) eight communities (5b), two road-connected communities (5c) and six remote communities (5d) 42

Figure 6: Graph and associated mean values for vulnerability analysis of combined GPS and interview data at the individual (6a) community (6b), road-connected (6c) and remote (6d) levels 46

List of Tables

Table 1: Components of vulnerability index equation used to rank effects of environmental conditions on travel and access to natural resource use areas 50

Table 2: Example of how final vulnerability value was calculated for a single condition (ice conditions) documented by a single harvester during the 12-month GPS data collection period 51

Table 3: Numbers of participants and GPS/interview observations documented for each collaborating community 52

List of Appendices

Appendix 1: NASA Mapping Project GPS data collection form 53

Appendix 2: Institutional Review Board protocol approval letter 57

Appendix 3: Institutional Review Board protocol closure/final report 58

Introduction

Climate change is altering natural environments across the planet, and researchers are just beginning to untangle the complex web of cascading effects. Over the last 100 years the Earth has seen a general warming trend, but the effects of global temperature changes differ based on regional factors. Some locations have experienced increased frequency of drought conditions over recent decades (Stringer et al. 2009, Gamble et al. 2010), whereas others experienced extreme flooding (Douglas et al. 2008, Mirza 2011). New patterns of precipitation can shift entire biomes by latitude and elevation (Parmesan and Yohe 2003). Warming temperatures are accelerating glacial melt and influencing hydrologic regimes due to their effects on precipitation patterns (Barnett et al. 2005, Immerzeel et al. 2010).

In northern regions, global-level changes in climate are having significant local-level consequences. Boreal forests that historically saw wildfires every 150-450 years are now experiencing more intense, frequent fire events (Barrett et al. 2013, Kelly et al. 2013), which is impacting the geology (permafrost, soil organic matter), hydrology, and vegetative communities of the region (Jorgensen et al. 2013). Earlier thaws and later freeze-ups mean a shorter cold season, and warmer temperatures are conducive to encroachment of vegetative communities common to lower latitudes and elevations into more northern and alpine environments (Beck et al. 2011). When acting synergistically, the consequences of these changes can become amplified.

Rural communities are particularly vulnerable to environmental changes that affect ecosystem services. Ecosystem services can be defined as the conditions and processes through which natural ecosystems sustain human life (Daily 1997). In Alaska, these services include subsistence resources, which state (Alaska Statute 16.05.258) and federal (Alaska National Interest Lands Conservation Act [ANILCA]; Public Law 96-487, Title VIII) law define as the customary and traditional use of fish and wildlife for food, shelter, fuel, clothing, tools, transportation, handicraft articles, customary trade, barter, and sharing. Subsistence plays important social, economic, nutritional, and spiritual roles in the lives of many rural residents, and is integral to the overall wellbeing of communities (Lambden et al. 2007, Johnson et al. 2009, Smith et al. 2009).

Alaskans living in rural locations are increasingly voicing concerns over the impacts of environmental changes on resources availability. Among their concerns are declining fish and wildlife populations, spatial or temporal shifts in populations, and restricted access to resources. Relationships between climate change and changes in populations of plant and animal species have been the focus of many scientific studies. However, recent research suggests that climate-related changes in accessibility of resources may disproportionately influence the abilities of rural residents to meet their subsistence needs (Brinkman et al. 2016). The effect of changing environmental conditions on resource access has received some attention, with most studies focusing on a select few conditions or resource types in lieu of a more comprehensive approach. For example, Carothers et al. (2014) describe how changing hydrology in Interior Alaska is reducing travel capabilities and increasing safety risks for rural residents. Climate-related shrub expansion and encroachment (Huntington and Fox 2005), landscape changes associated with more frequent and intense wildfires (Nelson et al. 2008), changes in the amount and timing of snowfall (Hinzman et al. 2005) and increased variability and unpredictability of weather patterns (Krupnik and Jolly 2002) have also been shown to reduce the accessibility of subsistence resources. Although the impacts of specific environmental changes on resource access have been qualitatively investigated, studies that quantitatively describe environmental conditions affecting access using spatially and temporally specific information are lacking. The results of such studies can inform climate models and be used by resource managers to guide the creation or augmentation of regulations governing the use of subsistence resources.

Recognizing the concerns and information gaps addressed above, my research sought to further investigate the importance of access to subsistence resource harvest practices. More specifically, my objectives were to: 1) identify and classify conditions affecting access during a variety of subsistence activities, 2) quantify the vulnerability of travel and access to each class of condition, and 3) determine whether connectedness to the road system influences communities' vulnerability to conditions. To accomplish this, I took a community-based research approach and formed partnerships with residents of nine rural communities within Alaska's Yukon River Basin to identify conditions affecting resource access. Using GPS units equipped with cameras, project collaborators documented environmental conditions that they encountered while engaging in subsistence activities over a 12-month period. To complement the information they gathered, I conducted interviews with project participants and other knowledgeable individuals in each community to increase the breadth and depth of information for analysis. I then classified the environmental conditions they identified into discrete categories, and conducted a vulnerability analysis that resulted in a ranking system for conditions based on relative impacts to subsistence resource access.

One of the central tenets of my research involved using community-based participatory research (CBPR) to answer questions leading to practical solutions to real-life challenges. CBPR is a research methodology that involves equitable partnerships among academic, community, agency, and non-government entities (Conrad and Hilchey 2011, Johnson et al. 2015) and allows for the inclusion of local knowledge and perspectives on the implications of ecosystem changes. Through collaborations with the Council of Athabascan Tribal Governments, the Alaska Department of Fish and Game, the National Aeronautics and Space Administration, and faculty and staff at the University of Alaska Fairbanks, I used multiple knowledge sources to holistically reveal relationships among changing environmental conditions on resource access that can help inform management decisions by all entities.

The ability to rank environmental conditions on magnitude of effect on subsistence is a first step in addressing challenges posed by those conditions. My work takes broad-scale information on the social-ecological effects of climate change and distills it in a way that provides direction to the future work of resource managers, community planners, and academics. I coordinated the collection of spatially and temporally-explicit observations of the actual conditions that were affecting rural residents of Interior Alaska, which allowed me to assess the actual characteristics of climate-related change in real time. Communities may use projections by climate models informed by our spatially and temporally explicit data to decide where to best spend time and money in the enhancement of local infrastructure, or pursue proposed regulatory changes supported by research results. Using the information my collaborators and I have provided, specific community concerns may be addressed by identifying issues that pose the greatest access threats to subsistence resources, and all entities involved collectively deciding on potential solutions.

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Chapter 1

Assessing vulnerability of subsistence travel to effects of environmental change in Interior Alaska[1]

ABSTRACT

Amplified climate change at high northern latitudes is creating challenges for and necessitating adaptation by societies that depend on local provisional and cultural ecosystem services (e.g., subsistence resources) for their livelihoods. Previous research suggests that climate-induced changes in environmental conditions are challenging rural residents' ability to travel across the land and access to local resources, but detailed information on the nature and effect of specific conditions is lacking. Our objectives were to identify climate-related environmental conditions affecting subsistence travel and access, and then estimate travel and access vulnerability to those environmental conditions. We collaborated with nine Interior Alaskan communities within the Yukon River basin of Alaska and provided local residents with camera-equipped GPS units to document environmental conditions directly affecting access for 12 consecutive months. We also conducted comprehensive interviews with research participants to incorporate the effects of environmental conditions not documented with GPS units. Environmental conditions reported by rural residents were categorized into seven condition types, and we ranked categories of conditions using a vulnerability index that incorporated both frequency (number of times a condition was documented) and sensitivity (magnitude of the effect from the condition) information derived from observations and interviews. Changes in ice conditions, erosion, vegetative community composition, and water levels had the greatest overall effect on travel and access to subsistence resources. Environmental conditions that impeded natural travel corridors (e.g., waterways) more strongly influenced communities off the road network than those connected by roads. Combining local ecological knowledge and scientific analysis presents a broad understanding of the effects of climate change on access to subsistence resources, and provides information that collaborating communities can use to optimize adaptation and self-reliance.

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[1] Cold, H.S., Brinkman, T.J., Brown, C.L., Heeringa, K.R., Hollingsworth, T.N., Verbyla, D.L. and Brown, D.R.N. Assessing vulnerability of subsistence travel to effects of environmental change in Interior Alaska. Prepared for submission to *Ecology and Society*.

INTRODUCTION

Accelerated climate change affects how human societies interact with their natural environments (Ford and Pearce 2012, Brinkman et al. 2016). In the last 50 years, amplified and unprecedented climate shifts in northern biomes have altered the structure and function of ecosystems, and this trend will likely accelerate over the next century (Bieniek et al. 2014, IPCC 2014). These rapid rates of change in ecosystems are altering human-environment interactions, creating the need for societies to adapt to new conditions (Ford and Pearce 2012). In northern regions, climate-related changes in the environment are resulting in significant consequences for many rural communities that depend on resources obtained from the natural environment (Berkes and Jolly 2002, Ford and Pearce 2012). These provisional and cultural resources on which households rely are often jointly referred to as subsistence resources (Huntington et al. 2005, Ford and Furgal 2009). State (Alaska Statute 16.05.258) and federal (Alaska National Interest Lands Conservation Act [ANILCA]; Public Law 96-487, Title VIII) law defines subsistence as the customary and traditional use of fish and wildlife for food, shelter, fuel, clothing, tools, transportation, handicraft articles, customary trade, barter, and sharing.

Over the last 30 years, subsistence harvests in the Arctic-Boreal region of Alaska have declined by 30-50% (Wolf and Walker 2016, Fall 2014). Although the harvest declines are likely due to a variety of interconnected social, economic, regulatory, and environmental factors, subsistence harvesters have increasingly expressed concerns regarding challenges to their ability to traverse the landscape to reach subsistence use areas. These travel-related concerns include safety considerations (Brubaker et al. 2011, Schneider et al. 2013, Clark et al. 2016, Driscoll et al. 2016), amount of time necessary to access specific resources (Holen et al. 2012), monetary costs of accessing and harvesting resources (Brinkman et al. 2014), changes in the quantity and distribution of resources (Berman and Kofinas 2004), and unpredictable conditions in the physical environment (Berkes and Jolly 2002, Porter et al. 2014, Brinkman et al. 2016). Each of these factors contributes to accessibility of subsistence resources. To date, the descriptions of relationships between changes in accessibility and environmental conditions have been mainly qualitative. Few studies contain spatially and temporally explicit details on environmental conditions affecting resource access, and few data exist on the frequency, causes, and implications of such changes. Also, the relative impacts of different environmental conditions on resource access have received minimal attention. For example, recent research illustrated the importance of considering how general changes in seasonality, sea ice, snow, and forest conditions influence the accessibility of subsistence resources by subsistence hunters, but the extent and characteristics of conditions that are impacting access were not documented (Berman and Kofinas 2004, Brinkman et al. 2016). Work by Magdanz et al. (2016) suggests that community characteristics, such as connectedness to road networks, may influence subsistence resource harvests. This could be due in part to increased competition from urban resource harvesters and a wider variety of transportation modes available to residents of road-connected communities. Studies such as these illustrate the importance of considering how changes in access factor into resource availability, and can identify ways in which management entities may be able to address some key issues to help alleviate challenges in resource acquisition.

Community-based participatory research (CBPR) is a research methodology that involves equitable partnerships among any number of academic, community, agency and non-government entities (Conrad and Hilchey 2011, Johnson et al. 2015). It can allow for the inclusion of local and traditional ecological knowledge (LEK, TEK), which involve ways of experiencing the natural world accumulated over several decades to many generations and offer perspectives on connections between climate trends and subsistence resources from those people intimately connected to the land and natural processes (Huntington 2000, Huntington and Fox 2005, Pearce et al. 2015). Considering the time necessary to conduct scientific research, and the relatively narrow focus of most scientific endeavors, LEK may have a greater ability to help identify the social implications of the heterogeneous environmental changes we see today and prepare for those we experience in the future (Pearce et al. 2009, 2012). LEK is an integral part of the coproduction of knowledge, a process that brings a variety of types and sources of knowledge together to address a defined problem through an integrated understanding of the issue (Armitage et al. 2011). When successfully implemented, this process results in climate science knowledge that all entities can use to help inform resource management and community planning initiatives (Herman-Mercer et al. 2011, Cornell et al. 2013, Meadow et al. 2015, Chapin et al. 2016).

Many of the social and ecological implications of environmental changes reported by rural Alaskans have been studied individually. Some examples of this include less snow accumulation hindering winter travel (Hinzman et al. 2005, Moerlein and Carothers 2012, Carothers et al. 2014), thawing permafrost accelerating land slumping and riverbank erosion, hindering travel on water and land (Hinzman et al. 2005, Moerlein and Carothers 2012, Knapp et al. 2014, Brinkman et al. 2016), and climate-related shrub expansion and encroachment obstructing travel (Huntington and Fox 2005, McNeely et al. 2011, Brinkman et. al. 2016). However, we lack a comprehensive understanding of the relative influence of different environmental conditions on travel and access to subsistence resources. Using a vulnerability assessment approach (McCarthy et al. 2001) to analyze complementary datasets, including data collected by harvesters as they encounter changes to the landscape and information extracted from interviews, can identify which environmental changes have the greatest effect on resource access for rural Alaskans.

We incorporated LEK through CBPR and then conducted a vulnerability analysis to understand how changes in environmental conditions driven by climate change restrict or facilitate access to traditional and customary use areas. Our research objectives were to: 1) identify and classify conditions affecting access during a variety of subsistence activities, 2) quantify the vulnerability of travel and access to each class of condition, and 3) determine whether connectedness to the road system influences communities' vulnerability to conditions. The results of such analyses can help direct the development of adaptive strategies specific to subsistence activities and communities, and enhance the relevance of future biophysical research on climate change to Northern communities.

METHODS

Study area

We investigated how environmental change influences travel and access to subsistence resources for residents of nine rural communities within the Yukon River basin of Interior Alaska (Figure 1). Our study area spans the central portion of the state from the Canadian border in the east to the Bering Sea in the west and covers approximately 832,700 km^2 - roughly the area of Texas and Oklahoma combined. Mean average temperatures range from –29°C in January to 17°C in July, and mean annual precipitation is approximately 50 cm, including an average snowfall of 160 cm. Because of the size of our study area, it incorporates six climatic zones, 20 ecoregions (Brabets 2000) and the vegetation mosaic is complex, with many different vegetation types (Viereck 1992). These vegetation types include all six Interior Alaska tree species (*Picea glauca, P. mariana, Betula papyrifera, Populus balsamifera, P. tremuloides, Larix laricina*), taiga shrublands, and both fens and bogs. The watershed contains primarily discontinuous permafrost and experiences extensive and frequent wildfire disturbance. The study area contains communities both on and off the road network. Communities connected to roads have different socio-economic demographics than communities off the road network, and the presence of roads can affect both level of dependence on subsistence resources and mode of transportation used to access harvest areas. Although the importance a particular resource plays in the culture and economy of each community varies, general categories include birds, fish, plants, and mammals harvested for food, fiber, fuel, and medicinal purposes.

Community engagement

We invited individual communities to partner with us by way of community-wide informational meetings organized through local governing bodies (e.g., Tribal Council, Fish and Game Advisory Councils) within each community (University of Alaska Fairbanks IRB 700936-7). We sought to partner with communities that would adequately represent the full range of social and ecological conditions found in Interior Alaska. We made initial contact by phone or email to determine if communities were interested in collaborating with us. If communities expressed interest, we scheduled on-site information meetings with communities to provide details on the goals, methods, and expectations of the project. Formal written approval (e.g., Tribal Resolution) from a representative entity (e.g., Tribal Council, Fish and Game Local Advisory Committee) within the community was required from each community prior to beginning research. Each representative entity selected 2-3 residents (hereafter "harvesters") within their community to participate as citizen scientists. Individual residents were selected that actively participated in subsistence and had in-depth experience and knowledge of traditional harvest areas around each community. Although we carefully sought involvement of communities that perceived a local benefit from engagement, recruitment efforts also were synchronized across the region in an attempt to capture: 1) a broad representation of differences in resource use and landscape characteristics across Interior Alaska, and 2) representation of communities both on and off the road system.

Road-connected communities

Tok (pop. 1258), Delta Junction (pop. 934) and Healy (pop. 1021) are all located along major highways (US Census Bureau, 2010). Tok and Delta Junction are also adjacent to the Tanana River, whereas Healy does not have close connectivity with large water bodies. Most residents are of primarily European descent, while the remainder identify as Native Alaskan or Asian. Nearly all households in these communities report using some level of subsistence resources, which consist primarily of large land mammals such as moose (*Alces alces*) and caribou (*Rangifer tarandus*) and both salmon (*Oncorhynchus kisutch, O. nerka)* and non-salmon fish (Holen et al. 2012). For instance, in Tok and Healy, residents harvested an estimated 79 and 24 kgs of wild foods per capita per year in 2011 and 2014, respectively (Holen et al. 2012, Brown et al. 2016). Subsistence harvests are facilitated by a series of roads, trails suitable for motorized traffic, and navigable waterways. Modes of travel consist of passenger vehicles, boats, snowmobiles, and ATVs. Access to commercial resources including fuel and food is facilitated by proximity to the larger road network, and costs are considerably less for these resources than they are for more remote communities. These factors often work in conjunction to decrease the dependence of road-connected communities on subsistence resources (Magdanz et al. 2016), although these resources remain important to the cultures, nutrition, and economies of road-connected communities.

Remote communities

In all of the collaborating communities located off the road system, subsistence harvest occurs year-round, with harvest areas being accessed mainly by boat, snowmobile, or ATV. Travel for residents and transportation of commercial goods and services for all remote study communities is restricted to light aircraft and limited boat service during summer months.

Nulato (pop. 259), Grayling (pop. 213) and Holy Cross (pop. 173) are villages located along the Yukon River in the western reaches of the Yukon River basin (US Census Bureau 2016). Residents identify as primarily Koyukon, Holikachuk, and Deg Hit'an Athabascan respectively, and are heavily reliant on subsistence resources. Salmon, including chinook (*O. tshawytscha*) and chum (*O. keta*), as well as moose are particularly important local food resources. Trapping of furbearering mammals including wolf (*Canis lupus*), marten (*Martes americana*), wolverine (*Gulo gulo*), lynx (*Felis candadensis*), beaver (*Castor Canadensis*), and muskrat (*Ondatra zibethicus*) provide both food and economic opportunity through fur sales for many residents (Ikuta et al. 2014, Brown et al. 2015).

Lake Minchumina (pop. 13) is located just outside of the northwestern corner of Denali National Park, bordered to the southeast by the Alaska Range and to the west by the Kuskokwim mountains (US Census Bureau 2010). Today residents are mostly of European ancestry, although the community was historically Koyukon Athabascan. As the only community in this study not located adjacent to the Yukon River or a direct tributary, the lake is the focal point for most community activities, including transportation and acquisition of food and drinking water. Primary subsistence resources include non-salmon fish species and moose (Holen et al. 2006).

Venetie (pop. 166) and Beaver (pop. 84) are remote villages that represent the northeastern region of the study area (US Census Bureau, 2010). These communities were historically very involved in fur trading with Russian settlers, and residents today continue to trap furbearing mammals for sale and personal use. Residents are primarily Gwich'in and Koyukon Athabascan, and a vast majority (>90%) is active in subsistence harvest activities. Similar to the remote study communities on the lower reaches of the Yukon, primary resources harvested for consumption include moose and caribou, as well as chum and king salmon (Holen et al. 2012).

Subsistence harvests tend to be larger in remote communities. For example, according to recent data, residents of Grayling harvested 112 kgs of wild foods per capita in 2011 (Ikuta 2014). Nulato residents harvested 108 lbs. per capita of wild foods in 2010 (Brown et al. 2014), and residents of Lake Minchumina harvested 135 kgs per capita in 2001 (Holen et al. 2006). In Beaver, per capita harvests of wild foods topped 163 kgs in 2011 (Holen et al. 2012).

Documentation of environmental conditions

Following protocols established by Brinkman et al. (2018), each harvester received a camera-equipped GPS unit to collect photos and spatial coordinates of environmental conditions affecting travel and access. The date and coordinates associated with each photo were combined with information recorded on paper data forms by each harvester that helped researchers interpret each photo (Appendix 1). Harvesters described the photograph, subsistence activity during the encounter, how access to specific resources was affected, how frequently the condition has been observed, when the condition was first observed, and to what spatial extent they witnessed this condition. These data were used to parameterize components of the equation used to assess vulnerability of communities to different environmental conditions. Harvesters documented observations of environmental conditions affecting access for a 12-month period. As communities began participating on a rolling basis, data were collected from March 2016 through July of 2017. In some cases harvesters preferred to capture spatially and temporally explicit images using personal smartphones in lieu of the provided GPS units, and the information collected via either method was identical.

When reviewing the data provided by collaborating communities, it was necessary to create a distinction between causes and effects relating to environmental conditions influencing access to subsistence resources. At the request of participants during the onset of the project, we provided participants with a list of potential conditions that they might consider documenting. We were explicit that the list was not exclusive, as a central tenet of the research involved incorporating participant understanding of environmental changes by allowing for individual identification and interpretation of the situations documented. Thus, we made it clear that local participants determined what conditions were important, rather than the researchers. A purposefully open design also reduced the possibility of bias in the documentation process. If harvesters were asked to choose from a list of defined categories, they would likely be biased towards these classes.

Comprehensive interviews

In addition to documentation of spatially and temporally explicit observation of specific conditions, we also conducted semi-structured interviews (Huntington 2000, Carothers et al. 2014) to document environmental changes that may not have been obtained using GPS documentation. As there are many dynamic factors influencing subsistence resource harvesting in each community, it was important that we took a comprehensive approach to understanding how environmental disturbances affected resource access. Some environmental conditions can disrupt subsistence activities enough to keep harvesters from participating, resulting in a lack of documentation of highly relevant information. For example, a lack of snow during the first few weeks of the furbearer-trapping season could inhibit snowmachine travel by harvesters trying to access trap lines. Therefore, there may be time periods when local residents are unable to get out on the land and document observations with GPS units.

We conducted interviews with project participants in every collaborating community except Healy, as those individuals were unavailable for interviews during this part of the study due to other commitments. We also followed the suggestion of community leaders in Nulato, Grayling, and Venetie to interview several individuals that had not collected GPS data but were considered representative sources for LEK and TEK. Interview questions followed a seasonal-calendar approach, which involved discussing subsistence activities performed and environmental disturbances encountered during every season within an annual cycle. Questions targeted both information regarding environmental disturbances encountered during the timeframe of the study (12-month period) and the broader local ecological knowledge that harvesters had regarding how the landscape and their subsistence behaviors had changed over time. Our semi-structured interviews were designed to complement and allow direct comparisons with the GPS unit approach.

Data analysis

Categorization of conditions

For analyses, we created categories that were inclusive of the data yet provided enough detail for meaningful analysis. Using both the GPS and interview data provided by harvesters, we developed seven categories to capture and describe all the different kinds of environmental conditions documented by harvesters (Figure 2). These included the following: ice conditions, snow conditions, water levels, vegetative community composition, erosion, sedimentation, and weather. This process involved distinguishing causes (the processes that lead to the presence of a condition on the landscape) from effects (the result of a process, which represents the actual on-the-ground situation affecting travel and access for the harvester). A network of relationships exists among causes and effects, and the two are not mutually exclusive. For example, Brown et al. (2018) describe how long-term changes in mean air temperature have contributed to variation in freeze-up and break-up dates (i.e., ultimate cause) on the Yukon River, and how those changes are affecting river travel (i.e., proximate effect) for rural communities. Another example includes the potential impact of wildfires in Alaska on the hydrology, permafrost extent, and overall ecosystem function of the landscape. These environmental changes might influence travel and access to subsistence resources through physical obstruction by regenerating vegetation (Huntington et al. 2005, McNeeley and Shulski 2011, Johnson et al. 2016), land slumping and riverbank erosion related to permafrost degradation (Hinzman et al. 2005, Moerlein and Carothers 2012), and increasing prevalence of toppled trees and ground slash that obstruct trail networks (Nelson et al. 2008, Brinkman et al. 2016).

Vulnerability index

To better understand the relative impact that each condition had on access to subsistence resources, we used a vulnerability index to assess individual observations (i.e., GPS data point) as well as the quantitative components of coded interview data for each harvester. Vulnerability can be defined as the extent to which a system is unable to cope with adverse effects (McCarthy et al. 2001). Vulnerability indices have been widely used for risk analysis studies spanning many environmental science disciplines, from assessing the effects of climate hazards on communities (Ford and Smit 2004, Ford and Furgal 2009) to prioritizing issues regarding fisheries management (Fletcher 2005, Allison et al. 2009). Key parameters of vulnerability include the likelihood (frequency) that the system (e.g., person, community) is exposed, the sensitivity of a system to the stressor, and the adaptive capacity of the system (Adger 2006). As the relationship among these components is highly context specific, it is important to carefully consider the analytical approach chosen to calculate vulnerability (Allison et al. 2009). For our study, we calculated vulnerability values (V) for each of the seven environmental condition classes as the sum of the likelihood (Li) that a harvester would experience a condition and the sensitivity (S) of the activity to the presence of the condition.

$$V = Li + S$$

We decided on an additive (Adger and Vincent 2005) rather than multiplicative (Allison et al. 2009) approach to equally weight likelihood and sensitivity. A multiplicative approach would allow an extremely low or high value for either component to disproportionately influence final vulnerability values. For our analyses, Li was equal to the number of times an observation of an environmental condition was recorded over the course of the study. For S, we developed a 7-point scale that considered the implications of the condition encountered on the subsistence activity in which the harvester was engaged, and the effect that each condition had on harvester travel efficiency, safety, and the opportunity to harvest provisional resources (Table 1). The information used to develop the scale was extracted from responses to interview questions and data collected on GPS data forms. We normalized the likelihood and the 7-point sensitivity scale values to span between 0 and 1 to ensure that sensitivity and likelihood values would be of equal weight when the final vulnerability value was computed. When considering the normalized scale, likelihood values below 0.5 moving toward zero have increasingly positive outcomes on travel and access, and values above 0.5 moving toward one have increasingly negative outcomes. Higher cumulative values (Li+S, range of 0-2) indicate greater vulnerability to a condition during the entire study period. We computed margins of error for vulnerability values to understand our ability to use study results to represent rural Alaskans as a whole. As some individuals and/or communities did not document some conditions, we determined margins of error for each condition at the individual, community, and road-connected/remote levels. Those values, as well as average standard deviation values calculated for vulnerability values were used to determine final margins of error at a 95% confidence interval (z value = 1.96). We assumed that conditions with overlapping ranges of vulnerability values, after accounting for margins of error, were similar because differences in absolute values may be related to sampling error.

Although we analyzed both GPS and interview data using the equation presented, each set of data required different strategies for preliminary analysis. GPS-based observations and data from the forms harvesters completed in association with each photo (Appendix 1) facilitated assignment of sensitivity values to each observed condition. For each harvester, we calculated an overall sensitivity value for each condition by calculating the weighted average of sensitivity values for all observations of each condition (Figure 2). We used proportional values to calculate likelihood (Li) for each condition category out of the total number of documented observations across conditions (number of data points within a condition per harvester/total number of points collected by a harvester) rather than a simple count of the number of times a harvester documented a condition. This allowed a direct comparison of vulnerability values of individual harvests, regardless of the number of observations each individual contributed. Finally, values calculated for sensitivity and frequency were summed to determine final vulnerability values for each condition documented by each harvester (Table 2). We analyzed the data across all individuals and across all communities in an attempt to capture variability in vulnerability values at different scales. For analysis of data at the individual level, this involved taking the final vulnerability values for each condition documented by each harvester and averaging them to create an overall vulnerability value for each condition. Vulnerability values for each condition were calculated for each community by averaging the vulnerability values calculated for each harvester within that community. We also compared observations from road-connected communities to those from remote communities to identify potential differences in vulnerability of access by either group to environmental conditions. For these analyses, we averaged community vulnerability values for each condition for road-connected and remote communities. A visual example of these analysis groupings is illustrated in Figure 3.

The first step in interview analysis involved developing a coding structure for extracting data from interview transcripts. Coding is a commonly used technique for the analysis of qualitative data present in interviews, and involves assigning meaning to descriptive or inferential information gathered in a study (Miles and Huberman 1994). We coded transcribed interviews using software ATLAS.ti (Scientific Software Development GmbH, Berlin). We developed five code groups, including Environmental Condition, Season, Subsistence Activity, Sensitivity Index Value, and Adaptive Response. Environmental Condition, Subsistence Activity, and Adaptive Response all extracted contextual information that was also captured on the data forms associated with GPS photos. Likelihood of encountering an environmental condition was calculated by summing the number of times a condition was mentioned during an interview, resulting in a single value for each environmental condition at the individual harvester level. This summed likelihood value for an individual condition was compared to other conditions and assigned a relative normalized value between 0 and 1. Sensitivity values were assigned to conditions at the individual harvester level using information on how conditions encountered impacted their activities, which was extracted during the interview following criteria from the same 7-point scale used in the GPS approach (Table 1). Whenever likelihood and sensitivity values were associated with the same condition observation during the coding process, that association was considered a data point similar to each observation documented with GPS units. Identical to the GPS approach, we used sensitivity and likelihood values to calculate vulnerability index values for each environmental condition at the harvester level. The parallel designs in analysis between the GPS and semi-structured interview approaches facilitated both a direct comparison and a weighted merging of data from both approaches into a single vulnerability analysis. We averaged vulnerability values for both data sets for each environmental condition to determine a vulnerability values for the combined datasets. When either GPS or interview data was lacking from a particular individual or community, we used the single data set to represent vulnerability values for conditions. Merging the two datasets facilitated the opportunity to understand the relative influence of differences in analysis results for each, and potentially give a more holistic view of the effects of changes in environmental conditions over time.

RESULTS

GPS data

Among the nine communities collaborating on this research, 18 harvesters documented 479 individual observations of environmental conditions affecting their travel with GPS units (Table 3). The statistical range of averages for sensitivity values for environmental conditions was similar across communities (n=9) and across individuals (n=18), with values between 0.65-0.79 across communities and 0.65-0.78 across individuals. All values were greater than 0.5, indicating conditions were perceived by harvesters to have an overall negative impact on travel and access to subsistence resources (Figure 4). Harvesters were most likely (Li) to encounter ice conditions and erosion at the individual, community, and regional levels, and least likely to encounter weather and sedimentation. Ice conditions, erosion, and water levels had the three highest vulnerability values, although their rankings were different between individuals and communities. The vulnerability value for water levels remained the third highest for both the across-communities comparison and across individuals. Erosion had a higher vulnerability value than snow conditions when comparing data across individuals, and snow conditions ranked higher than erosion for the across-communities comparison. Likelihood values were similarly ranked for both groups with the exception of erosion, which had a higher value at the individual level. Although the sensitivity value for erosion was almost equal at both the community and individual level, the increased likelihood present at the individual level influenced the vulnerability value enough to give it the highest value among all seven conditions for the across-individual analysis (Figure 4a-b). The margins of error at a 95% confidence level for conditions ranged between 4.2% and 61.9%, with a mean value of 19%. Wide margins of error result in overlapping vulnerability value ranges for some conditions. The lack of overlap in margins of error between ice conditions and both vegetative community composition and weather suggest differences in vulnerabilities for these conditions in all but road-connected communities. Values for erosion and snow conditions also differ from those of vegetative community composition and weather in remote communities.

Both road-connected and remote communities were most vulnerable to the effects of ice conditions, but road-connected communities were found to be much less vulnerable to erosion than were remote communities, reporting comparatively lower likelihood and sensitivity values. For remote communities, snow levels ranked third on the vulnerability index, whereas vegetative community composition was more of a concern for communities on the road network. Sedimentation and weather had low vulnerability values for both community types, although sedimentation was comparatively more detrimental to access than vegetative community composition for remote communities (Figure 4c-d).

Coded interview data

We conducted 22 comprehensive interviews across eight communities (Healy was not represented) and extracted 294 data points containing likelihood and sensitivity data for environmental conditions affecting access to subsistence resources by project participants (Table 3). As with the GPS data, we grouped data generated from interviews to visualize differences in results across individuals and across all collaborating communities, and ranked vulnerability values using the same criteria.

The range of sensitivity values for environmental conditions documented through interviews was narrower for the across-communities and across-individuals comparisons than the range of values present in both for GPS data. This meant the outcome of the vulnerability value was frequently related to variability in likelihood. Patterns in sensitivity and likelihood values for all seven conditions across communities and across individuals resulted in the same ranking of vulnerability values (Figure 5a-b).

As with the results of GPS data analysis, sensitivity values and vulnerability values for all environmental conditions were lower for communities connected to the road network (n=2) than for remote communities (n=6). All conditions for all other analysis groupings across GPS, interview, and merged data analyses were reported to have negative impacts. Ice conditions had the highest vulnerability value for the analyses at the community and individual levels and for remote communities, whereas ice conditions ranked lowest for road-connected communities and water levels had the highest vulnerability value. Vegetative community composition moved from one of the lowest vulnerability rankings for all analysis levels with GPS data to the second highest vulnerability value for all interview analysis levels. Road-connected communities were found to have greater relative vulnerability to weather conditions than the other three groupings, where despite very similar overall vulnerability values the condition ranked third of seven versus seventh of seven for the other analysis levels. Erosion and sedimentation had low vulnerability values at all analysis levels, and sedimentation was not reported through interviews as a condition affecting access for harvesters in road-connected communities (Figure 5c-d). Margins of error at a 95% confidence level ranged between 1.9% and 26.3%, with a mean value of 8.4%. Accounting for margins of error, the vulnerability value for snow conditions was significantly different from all other conditions among communities, and weather and ice conditions differed significantly among individuals. In remote communities, vulnerability values for snow conditions, erosion, sedimentation and weather all differed from ice conditions, and vulnerability value ranges for snow conditions and erosion did not overlap.

Merged GPS and interview data

Combined GPS and interview data indicate that across all communities, all individuals, and for remote communities, ice conditions have the greatest influence on travel and access to subsistence resources, followed by water levels and vegetative community composition. Erosion and snow levels closely followed vegetative community composition with the same vulnerability value, and sedimentation and weather were the least influential on travel and access. For road-connected communities, erosion had less of an impact on resource access than it did for remote communities, with a relative vulnerability ranking of fifth versus second, and snow conditions had a higher vulnerability value than vegetative community composition. Although ice conditions were the most frequently reported condition in road-connected communities, sensitivity values of all conditions were again lowest for road-connected communities and highest for remote communities. Snow conditions had the highest likelihood value among all conditions for road-connected communities and erosion the lowest, whereas ice conditions were the most likely conditions for a harvester to encounter in remote communities and weather the least. A high sensitivity value for erosion compensated for lower likelihood values for that condition to allow that condition a high vulnerability value for the analysis for remote communities, whereas erosion was less impactful on access to resources for residents of road-connected communities (Figure 6a-d). Margins of error at a 95% confidence interval ranged between 1.2% and 41%, with a mean value of 11.8%. As with GPS and interview data analysis results, ranges for vulnerability values of environmental conditions often overlapped, with some statistically significant differences present primarily when comparing those conditions with the highest vulnerability values to those with the lowest. Examples of this include ice conditions differing from sedimentation and weather for all but road-connected communities, and significant difference in vulnerability values for vegetative community composition and erosion for road-connected communities.

DISCUSSION

Our findings identify and describe the changes in environmental conditions that rural residents are encountering when harvesting subsistence resources that are negatively affecting travel and access. Although there was considerable variability across the study region, conditions affecting winter travel on ice had the greatest impact on access to subsistence resources.

Ice conditions ranked as the most detrimental environmental condition across most analyses. The negative effects of changing ice conditions in the Arctic are supported by a substantial body of literature, although most previous research has focused on sea rather than inland ice (Laidler 2007, Laidler et al. 2009, Prowse et al. 2011). Considering the length of the cold season and the importance of frozen water bodies as natural travel corridors in northern latitudes (Berman and Kofinas 2004, Prowse et al. 2007), this result was not unexpected. Project participants indicated that winter season travel in subsistence harvest areas was often by snowmachine and occasionally dogsled, with few individuals using road vehicles or other heavy equipment. Travel via these methods was particularly susceptible to the influence of ice conditions on both the use of natural riverine or lacustrine travel corridors, and harvesters' abilities to cross hydrological barriers to reach other harvest locations (Schneider et al. 2013). In many cases, harvesters indicated that water bodies were freezing later or not freezing at all, and ice thickness has decreased in key travel areas along the Yukon River and other tributaries. These conditions create safety concerns that harvesters indicated often caused delays caused by the need to wait to conduct an activity until environmental conditions became more favorable (Brown et al. 2018). A participant in Nulato described the impact that changing ice conditions had on their winter travel:

> "I snowmachine on the river and I go to Koyukuk, Galena, or Ruby, couple of trips to Huslia. And the one thing that I notice is now I have to be really careful. Whereas I was just able to go by snowmachine (and) just follow the trail, not worry about holes or anything. But now I notice that it's starting to be later that we can begin traveling by snowmachine on the river. I used to travel before Thanksgiving and not worry about an open hole. And it used to be 20 below, sometimes 40 below, but now it's warmer. And you can travel only later on, around Christmas I'm going up now."

Another participant from Beaver describes the effect of abnormal ice conditions on trapping:

> "The spring comes too quickly and the snow, you can't travel (by) snowmachine. And later, if it was later, we can get to our trap line. Going to my trap line, after you get over that mountain, there's a creek there that comes out that big lake. I know the last 4, 5 years I couldn't go early like at, you know, usually you want to go trap marten, you trap marten like in the 2nd half of October, 'cause that's when their coats make parkas. And I haven't been able to get an early start, because when February comes 'round then you gotta ease off on them cause all the females start moving. That creek, I can't get across it. And the trap line starts on the other side of that creek."

High vulnerability values for water levels reflect both the usefulness of waterways as natural travel corridors in rural locations (especially where roads are few or absent), and the close association of subsistence activities such as hunting, trapping, and fishing with aquatic environments (Johnson et al. 2016). All communities in this study reported using rivers, lakes, and streams to reach subsistence resources harvested during warm-season months. In general high water levels were associated with increased access to harvest and hunting areas along major rivers and low water made travel difficult or impossible in many lakes, rivers, and streams.

Erosion also ranked high on the vulnerability index. Although this result was most striking for the GPS data analysis, erosion retained high vulnerability value for all sub-analyses groupings with the exception of road-connected communities for the combined interview and GPS dataset as well. The condition's sensitivity values remained high for both GPS and interview data analysis. Although erosion was reported less frequently during interviews, when it was encountered it posed substantial safety risks and access difficulties, resulting in high sensitivity values. Harvesters noted a wide variety of specific effects on subsistence resource access tied to erosion. River or lake bank changes can result in physical inaccessibility of travel corridors (Kanevskiy et al 2016, Payne et al. 2018). Harvesters also described how debris from eroding banks often decreased safety and damaged equipment used to harvest subsistence resources.

One harvester from Nulato describes how debris from erosion on the Yukon River near their home thwarted salmon fishing efforts for family and friends using fish wheel structures further downriver:

> "That's the main reason a majority of the wheels below us went. Because all the trees were floating down and they were floating into the wheels and busting up their baskets, busting up all of the braces, busting up the raft. It was horrible. Really horrible. It was really sad because a lot of these families depend on that for the winter. And it was frustrating a lot of the fisherman."

Vegetative community composition also had a great deal of influence on travel and access to subsistence resources. In contrast to the pattern that emerged for erosion, interpretation of GPS data illustrated that communities were markedly less vulnerable to changes in vegetative community composition than the parallel analysis of interview data indicated. Not only were participants more likely to describe encountering vegetative community composition changes in interviews, but they described those encounters as having a more severe effect on their abilities to successfully participate in subsistence activities.

A project participant from Tok discusses how shifts in vegetation are increasingly becoming problematic when hunting:

> ". . .the first thing that comes to mind is the amount of growth of brush. I really noticed trails or creeks we would walk up to sheep hunting areas when I was a kid over 20 years ago, it was fairly mild. There were places where the brush was just thick probably eons. But now days there's some of those creeks that we used to traverse that it's super thick. It's almost to the point where you should be carrying a machete all the time. And even if we do and you kind of chop out a trail it's growing back within 2 years minimum. It grows back fast."

That the encroachment of vegetative ecotones from southern regions into northern latitudes has occurred over the last 30-50 years is fairly well documented (Pearson et al. 2013, IPCC 2014), and these shifts are anticipated to continue for the next 50 years if growing conditions remain favorable (Tape et al 2006, Myers-Smith et al. 2018). However, the discrepancy between vulnerability values for erosion and vegetative community composition between GPS and interview data provides insight into the inherent differences between these two documentation approaches. It may be that when asked to report environmental conditions encountered in the moment with GPS units, harvesters were more likely to report "pulse" changes than "press" changes (Collins et al. 2011). These two terms can be differentiated temporally: "pulse" events are relatively instantaneous, and an ecological system may afterwards relax into an equilibrium state, whereas "press" events involve sustained alterations until the system reaches an equilibrium (Bender et al. 1984, Kofinas et al. 2010). It is plausible that pulse events such as erosion are more immediately visible and have a starker contrast when compared to normal conditions, which may have increased the likelihood that they would be reported. In contrast, changes in vegetative community composition happen at a comparatively slower pace, which may make respondents more likely to elaborate on them when they discussed changes over their lifetimes during interviews. The relatively slow process of vegetation succession may explain why wildfire, the largest natural disturbance in Interior Alaska (Viereck 1973), was not reported as an influential environmental condition.

Sedimentation and weather had minimal influence on subsistence activities as a whole. This could be due to a combination of factors, including lower documentation frequencies and a less severe influence on travel when they were encountered. We speculate that Interior Alaska is more buffered from the effects of extreme weather than coastal communities that need calm seas for travel (Hansen et al. 2013). Modern mechanical equipment used to access subsistence harvest areas (snowmachines, motor boats, ATVs) may be more resilient to harsh conditions than historical modes of transport (canoes, dog teams; Brinkman et al. 2014).

It is important to note that although the environmental conditions harvesters encountered were binned into one of seven categories, these conditions are interrelated and their influences are not isolated. For example, although there were few cases in which weather directly influenced access to resources, increasing mean temperatures and changing weather patterns in arctic and subarctic environments can affect hydrology and water levels (Rouse et al. 1997), ice quality, the timing and nature of river breakups

(Schneider et al. 2013, Brown et al. 2018), and vegetation encroachment (Myers-Smith et al. 2018). Therefore, although we can determine that some conditions are more deleterious to subsistence resource access, further investigating their often-complex causes may help prioritize efforts by communities and agencies to adapt to changing conditions.

The analysis of both GPS and interview data often resulted in overlapping margins of error for vulnerability values of environmental conditions, suggesting that vulnerability to many different environmental conditions was not statistically different. This is likely a result of the interplay of small sample sizes and high variability in the data at the individual observation level. For example, when considering the analysis of combined GPS and interview data, snow had a margin of error value that ranged between 3.2% for remote communities and 41% for road-connected communities. There were both fewer road-connected communities (n=3) than remote communities (n=6) participating in this study, and greater variation in vulnerability values for conditions in road-connected communities, each of which contributed to the high margin of error. In the case of erosion, sedimentation, and weather data for road-connected communities, margins of error could not be computed due to extremely low sample sizes. The complex characteristics of the dataset limit the usefulness and practicability of statistical analysis of uncertainty. Although all environmental conditions affected access to subsistence negatively overall, in some instances harvesters reported a positive relationship between conditions and access. Examples of this include low snow levels increasing the accessibility of caribou by ATVs, and changing water levels allowing for increased accessibility of waterfowl hunting areas by ATVs (low water) or boats (high water). These observations emphasize the importance of context when interpreting the effects of changing environmental conditions on access, and show that even though the vast majority of environmental changes documented indicated negative effects on access to subsistence resources, the story is a rich and complicated one.

Effect of road connectedness on vulnerability

Access to road networks appears to influence both the kinds of environmental conditions that communities are vulnerable to, and the degree to which they are vulnerable. Our results suggest that remote communities are more vulnerable to all of the environmental conditions encountered, especially abnormal ice conditions and erosion. This phenomenon may be linked to differences in modes of travel among individuals living in remote vs. road-accessible communities. Travel is limited to natural corridors such as river systems for remote communities, and environmental conditions that restrict use of these corridors reduce the accessibility of resources (Magdanz et al. 2013, Carothers et al. 2014, Brinkman et al. 2016). Road-connected communities have a greater number of transportation options than remote communities, as they can use both the naturally occurring travel corridors available in rural locations and the often extensive road and trail systems in place in more developed areas. Roads are maintained by government agencies, whereas individual users of trails and waterways in remote areas are responsible for maintenance. This makes it more likely that residents of road-connected communities can use an alternative route or method to access a resource, whereas residents of remote communities may be restricted by limited transportation options. Additionally, similar environmental conditions may be interpreted differently by individuals depending on the mode of transportation used. For example, during interviews several harvesters from road-connected communities described situations where high water would be detrimental to vehicular crossing of a water body. In contrast, high water was often described as a favorable travel condition for participants that were using watercraft to access harvest locations.

Our research results demonstrate the relative vulnerabilities of subsistence harvesters to changing environmental conditions in Interior Alaska. However, these results cannot be used to infer the actual vulnerability of a specific individual or community to a specific change. This distinction is important, because although we may know subsistence access as a whole is most vulnerable to changes in ice conditions, measuring the societal consequences of restricted access on rural communities would involve further investigating the cultural and economic aspects of the wide array of subsistence activities. For example, although the trapping season and trapping locations for furbearers may be greatly reduced in some years due to unfavorable ice conditions, perhaps those harvesters are able to compensate for the lack of expected income by harvesting another resource (such as firewood) or obtaining wage employment. However, as financial gain is rarely the sole factor driving subsistence engagement, the social impacts (including cultural identity, the healthcare system, etc.) of reduced participation in subsistence warrants equal consideration (Kruse 1991).

Most harvesters participating in this research represented those individuals that had the heaviest involvement in subsistence activities, and their behaviors do not necessarily represent the community as a whole. Although subsistence activities play a role in the economies and cultures of most rural communities to some degree (Wolfe and Walker 2016), the importance of subsistence as a whole and by individual activity varies considerably by location. Future research could use the results of our ranking system to pursue narrower questions that focus on how vulnerability to conditions is affected when considering more specific criterion that may differ by community, such as predominant subsistence activities and modes of travel. Parallel research concerning the economic and cultural implications of these effects would provide a holistic understanding of the actual vulnerability of communities to environmental change.

In most cases, the range of vulnerability values for all environmental conditions was greater for GPS data than interview data, which could be indicative of possible limitations in the GPS data. During the GPS data collection period (March 2016- June 2017), harvesters occasionally reported encountering environmental conditions that were so severe that they could not conduct a certain subsistence activity, and therefore were unable to collect photo documentation of the condition. This resulted in gaps in data that could be interpreted very differently if no context was provided, as it could signify that an activity was either: 1) not affected and therefore no conditions were documented, or 2) the condition encountered was so extreme that it caused a cessation in attempts to conduct the activity. It is therefore likely that GPS data underrepresented water levels, ice conditions, and snow conditions due to the extreme nature of these events inhibiting normal subsistence activities. In these cases, coded interview data may present a more accurate picture of the relative effects of environmental disturbance over the entire calendar year. We speculate that merging GPS with interview data provided the most comprehensive and accurate overall assessment of rural resident vulnerability to environmental conditions.

Broader implications for Interior Alaskan social-ecological systems

Understanding which environmental conditions have the greatest effects on travel and access to subsistence resources by rural residents of Interior Alaska provides information that they can use to begin to construct adaptive solutions. Because climate change is projected to continue at a relatively rapid rate (IPCC 2014), further environmental challenges are likely to follow. Although in many cases there is little that can be done to halt climate changes, understanding which environmental conditions are resulting in the greatest challenges can help direct research to identify barriers to access that can be changed. Often project participants provided information regarding steps they have already taken to address the challenges they are facing, including changing the timing of harvest, mode of transportation, and travel route taken to harvest specific resources. However, in many cases social, economic, and regulatory obstacles impede efforts to adapt to challenges encountered. Studies such as ours can provide information that communities could potentially use to advocate for policy changes that may address some of these issues. For example, subsistence harvests of king salmon are subject to fishing closures along various portions of the Yukon River and its tributaries when it is projected that escapement goals will not be met. This often leaves rural residents with a narrow window in which to attempt to harvest salmon (Loring and Gerlach 2010), and encountering unfavorable environmental conditions during that time (such as changes in water levels or increased erosion) can further limit harvest success. Considering the effect of local environmental conditions on harvest success of subsistence resources when creating and enacting regulatory controls may allow for successful subsistence harvest by rural residents that coincides with necessary resource management practices. Scientific efforts to model future environmental change could incorporate our data into climate models, and potentially predict how the landscape will continue to change over time and the societal consequences of changing human access to ecosystem services. This knowledge can help communities identify subsistence harvest areas that may be vulnerable to future change and plan proactively.

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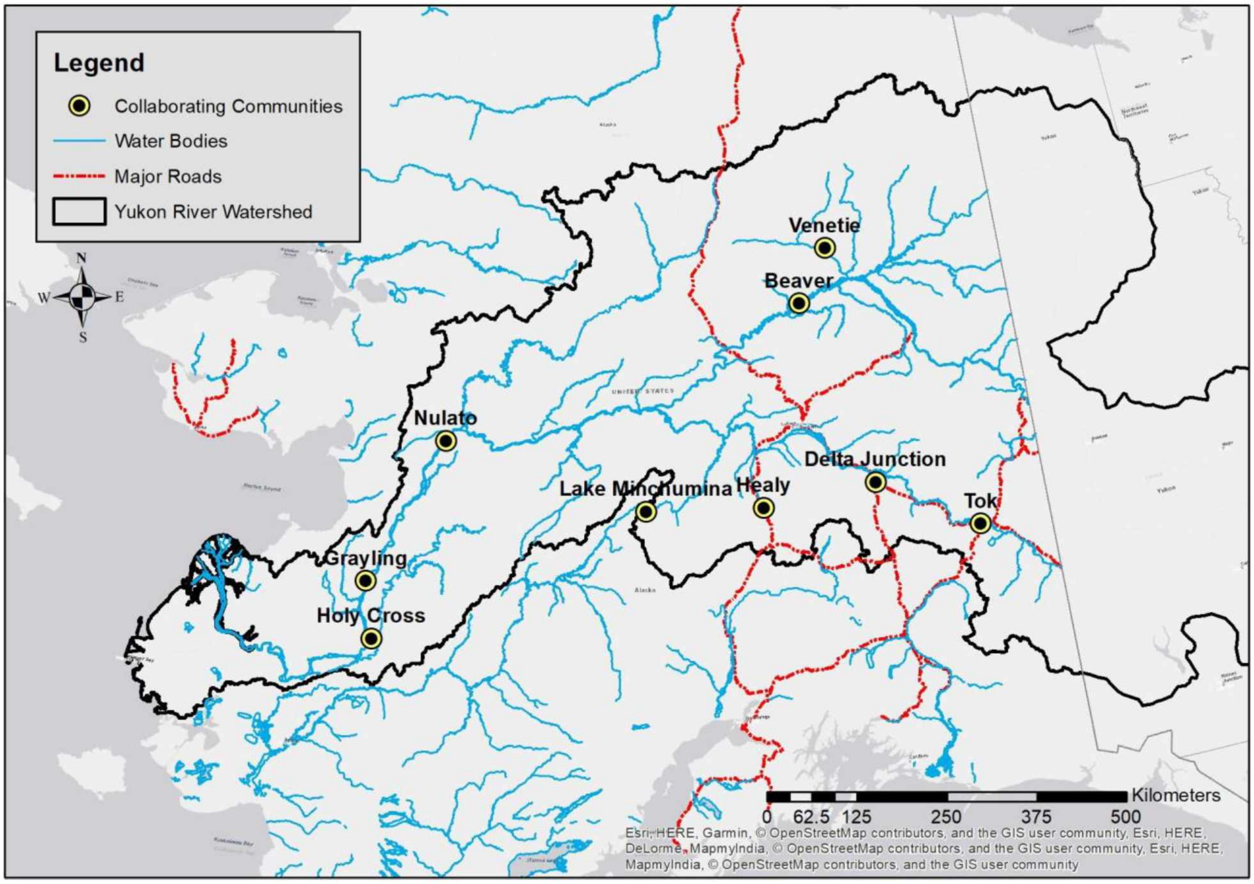


Figure 1. Map of project study area depicting the nine collaborating communities across the Yukon River basin.

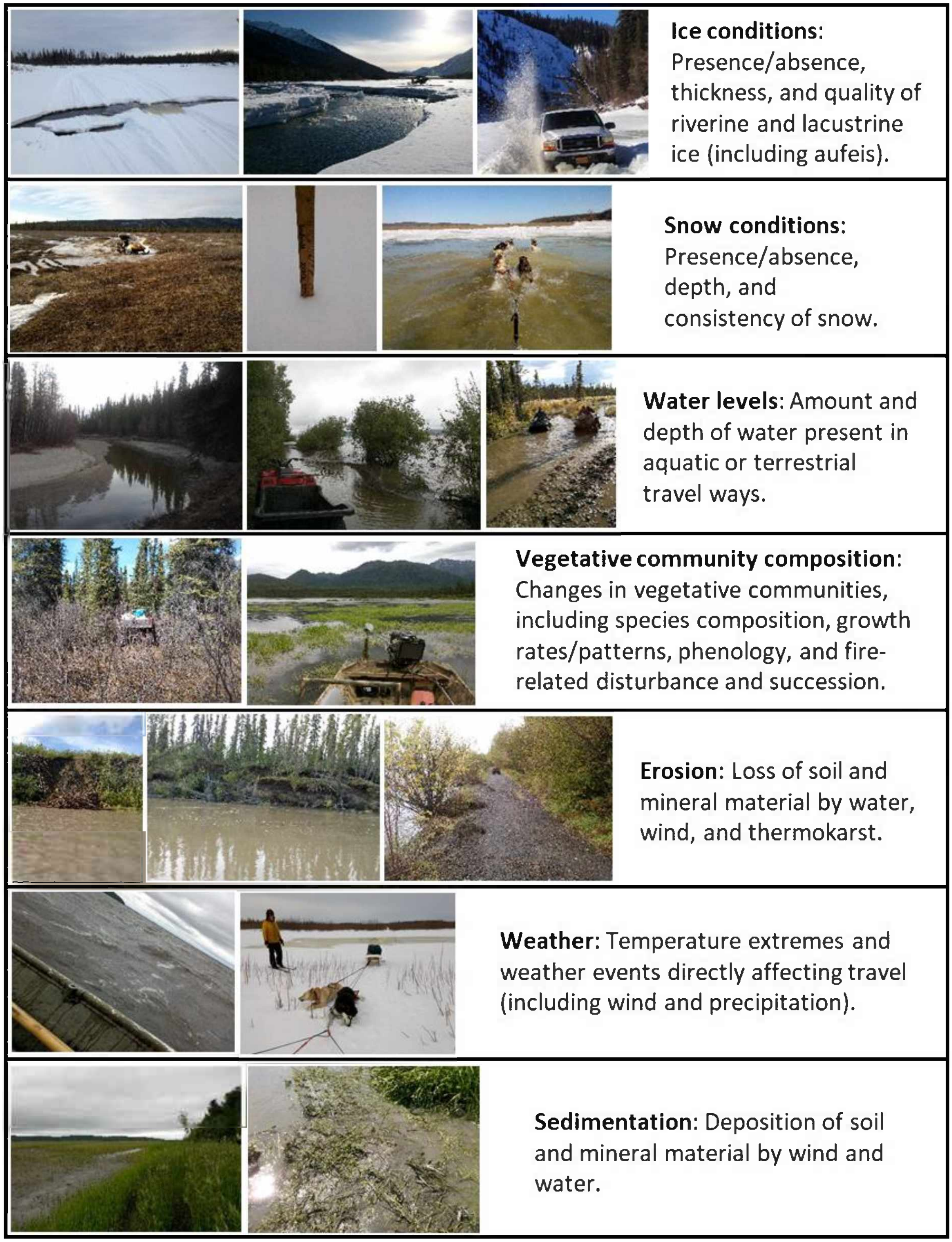


Figure 2. Descriptions and photographic examples of the seven condition classes developed by researchers of conditions associated with environmental changes that were reported to affect access to subsistence resources.

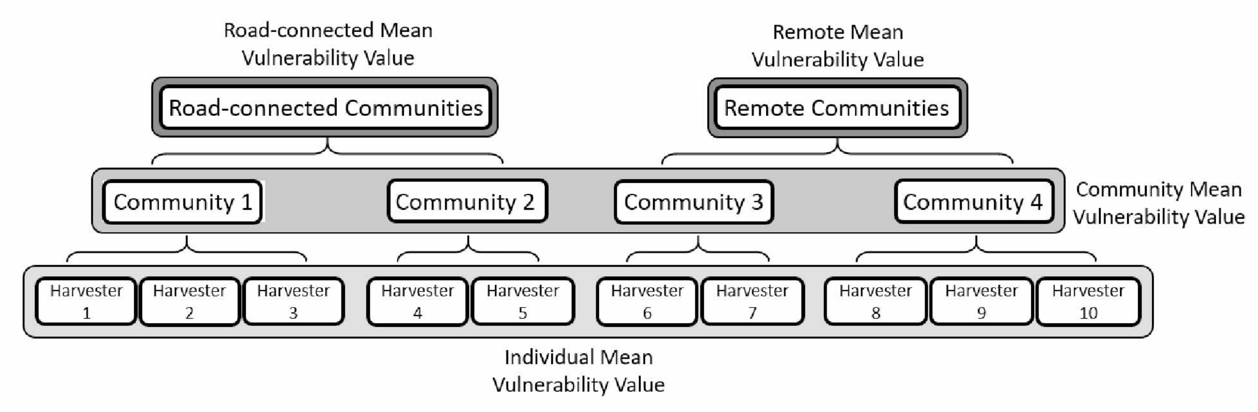
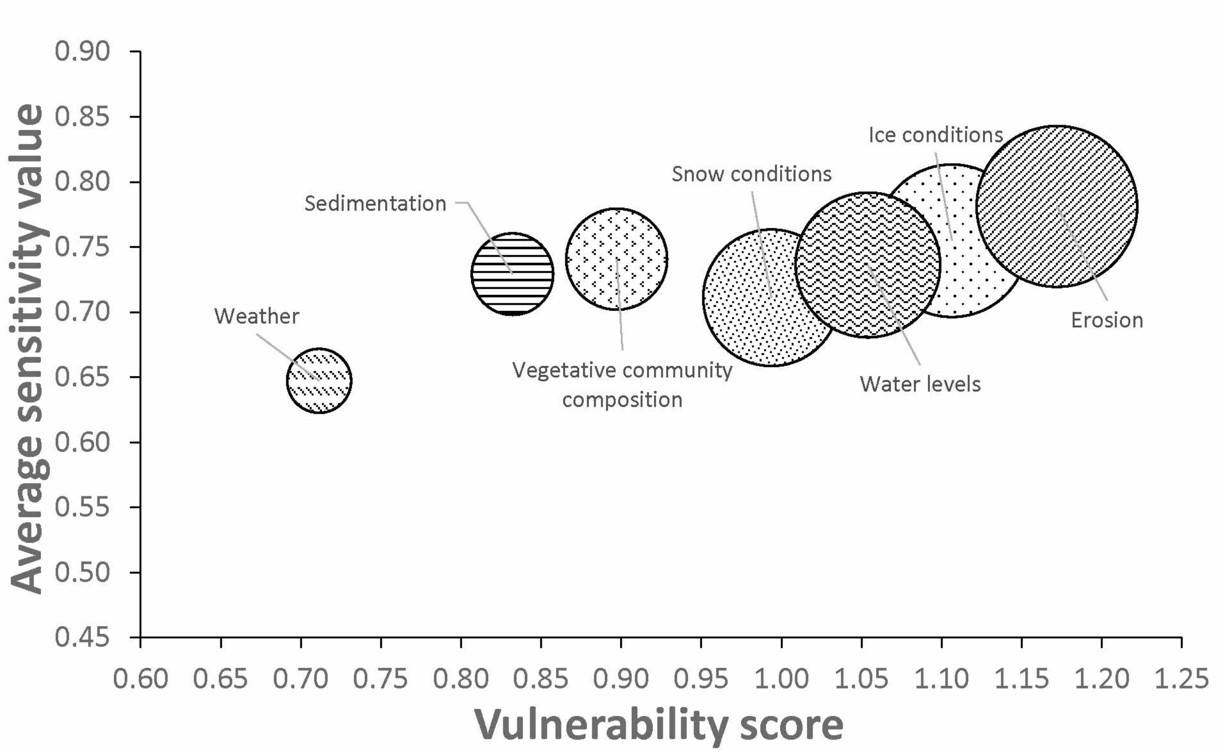


Figure 3. Visual example of data groupings used for different analyses. Mean vulnerability values for each environmental condition were averaged to create an overall vulnerability value for individuals, for all communities combined, for road-connected communities combined, and for remote communities combined.

4a.
All individuals

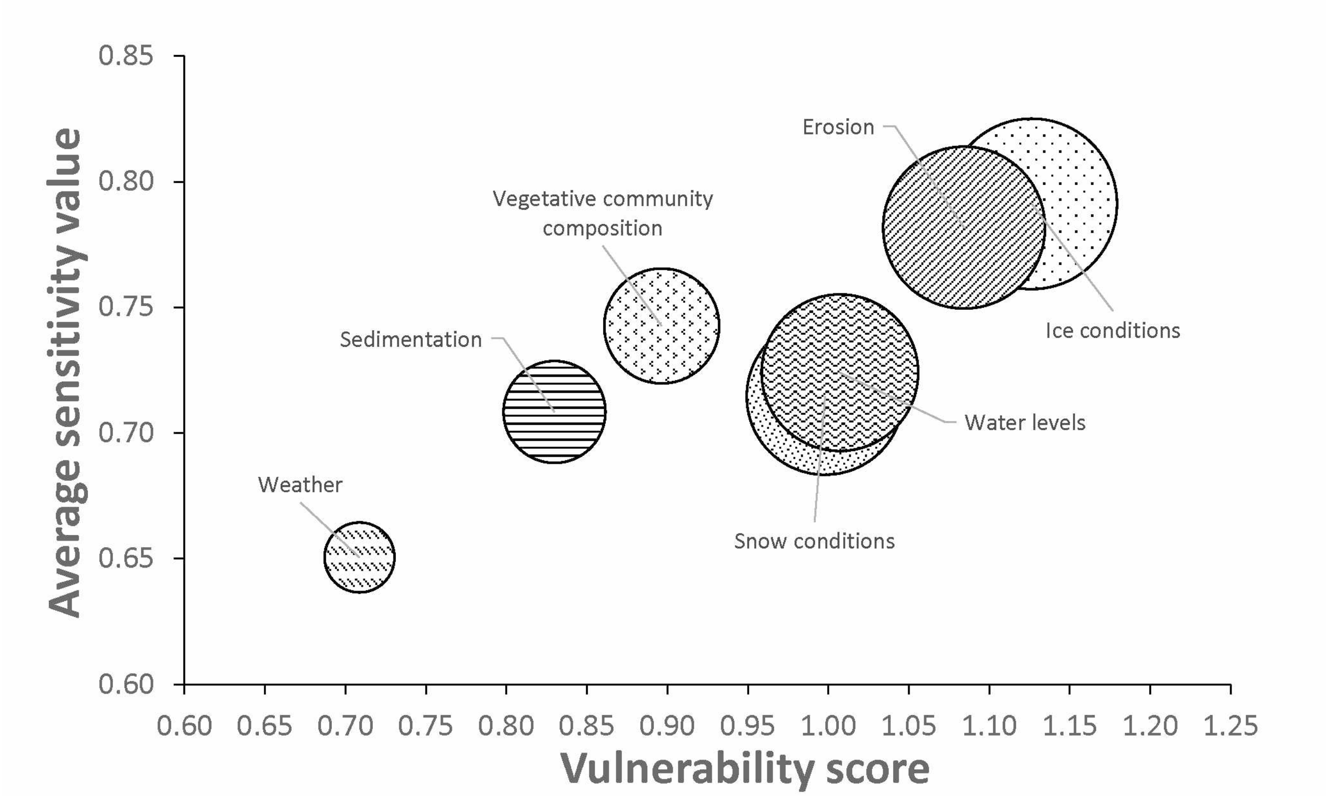


Condition	Average Likelihood (Li)	Average Sensitivity (S)	Vulnerability (V)†	Number of Observations	Margin of Error‡	V Value Range§
Erosion	0.39	0.78	1.17	63	17.7%	0.96-1.38[a]
Ice Conditions	0.35	0.75	1.11	124	11.6%	0.98-1.24[a]
Water Levels	0.32	0.74	1.05	98	13.5%	0.91-1.19[a]
Snow Conditions	0.28	0.71	0.99	108	14.2%	0.84-1.13[a]
Vegetative Community Composition	0.16	0.74	0.90	53	9.3%	0.82-0.98[a]
Sedimentation	0.10	0.73	0.83	16	20.1%	0.66-1.00[ab]
Weather	0.06	0.65	0.71	17	12.5%	0.62-0.80[b]

Figure 4. Graph and associated mean values for vulnerability analysis of GPS data among 18 individuals (4a) 9 communities (4b), 3 road-connected communities (4c) and 6 remote communities (4d). Bubble size is indicative of the decimal total for the number of observations in a category (N), sensitivity values (S) are depicted on the Y axis, and vulnerability values (V) are shown by the X axis.

† Vulnerability values may differ from those expected by adding Li and S values in graph due to rounding errors.
‡ Values at 95% confidence level.
§ V value ranges with different superscripts ([a,b]) denote significant differences (α=.05) from each other.

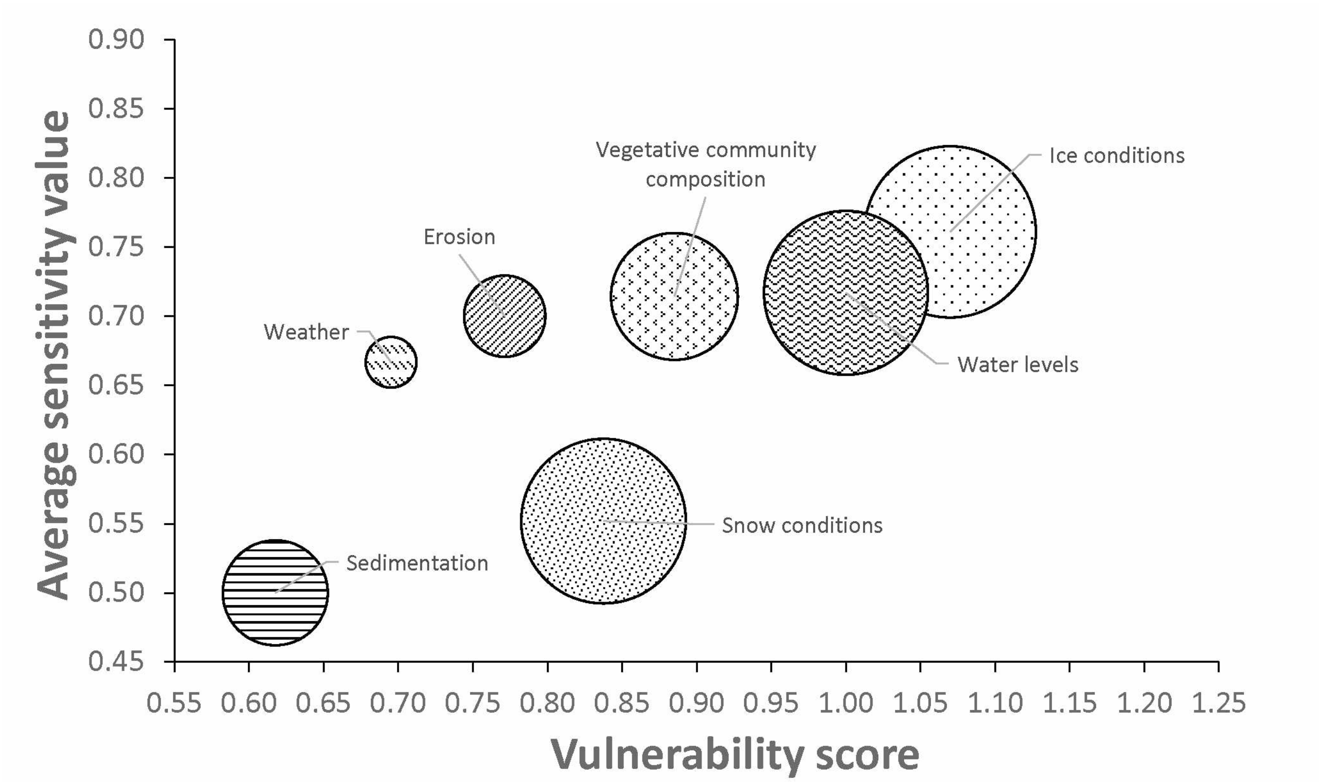
4b.
All communities



Condition	Average Likelihood (Li)	Average Sensitivity (S)	Vulnerability (V)†	Number of Observations	Margin of Error‡	V Value Range§
Ice Conditions	0.34	0.79	1.13	124	8.0%	1.04-1.12[a]
Erosion	0.30	0.78	1.08	63	23.2%	0.83-1.33[ab]
Water Levels	0.28	0.72	1.01	98	15.7%	0.85-1.17[ab]
Snow Conditions	0.28	0.71	1.00	108	20.0%	0.80-1.20[ab]
Vegetative Community Composition	0.15	0.74	0.90	53	4.2%	0.86-0.94[b]
Sedimentation	0.12	0.71	0.83	16	28.4%	0.59-1.07[abc]
Weather	0.06	0.65	0.71	17	8.2%	0.65-0.77[c]

† Vulnerability values may differ from those expected by adding Li and S values in graph due to rounding errors.
‡ Values at 95% confidence level.
§ V value ranges with different superscripts ([a,b]) denote significant differences (α=.05) from each other.

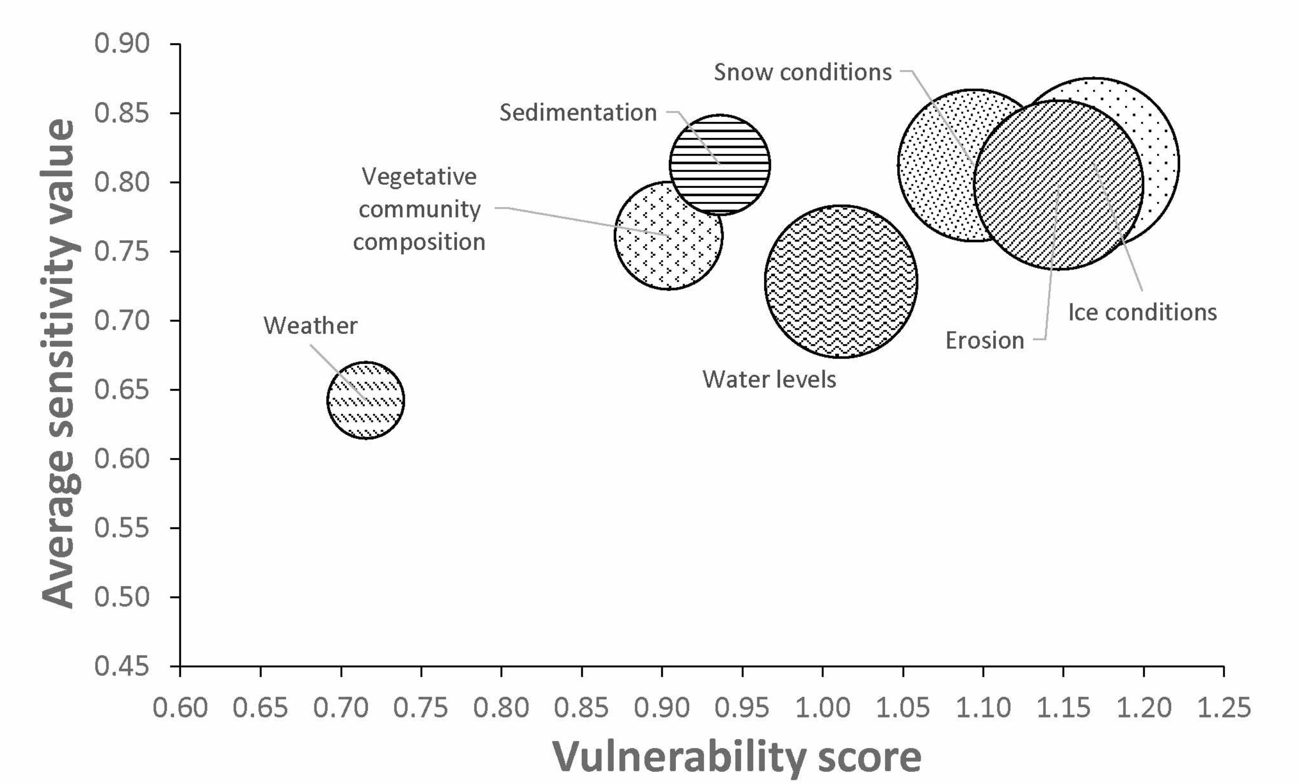
4c.
Road-connected communities



Condition	Average Likelihood (Li)	Average Sensitivity (S)	Vulnerability (V)†	Number of Observations	Margin of Error‡	V Value Range§
Ice Conditions	0.31	0.76	1.07	39	19.1%	0.87-1.27[a]
Water Levels	0.28	0.72	1.00	36	19.4%	0.89-1.19[a]
Vegetative Community Composition	0.17	0.71	0.89	15	9.3%	0.81-0.97[a]
Snow Conditions	0.29	0.55	0.84	40	61.6%	0.32-1.36[a]
Erosion	0.07	0.70	0.77	5	N/A	N/A
Weather	0.03	0.67	0.70	2	N/A	N/A
Sedimentation	0.12	0.50	0.62	2	N/A	N/A

† Vulnerability values may differ from those expected by adding Li and S values in graph due to rounding errors.
‡ Values at 95% confidence level.
§ V value ranges with different superscripts ([a,b]) denote significant differences (α=.05) from each other.

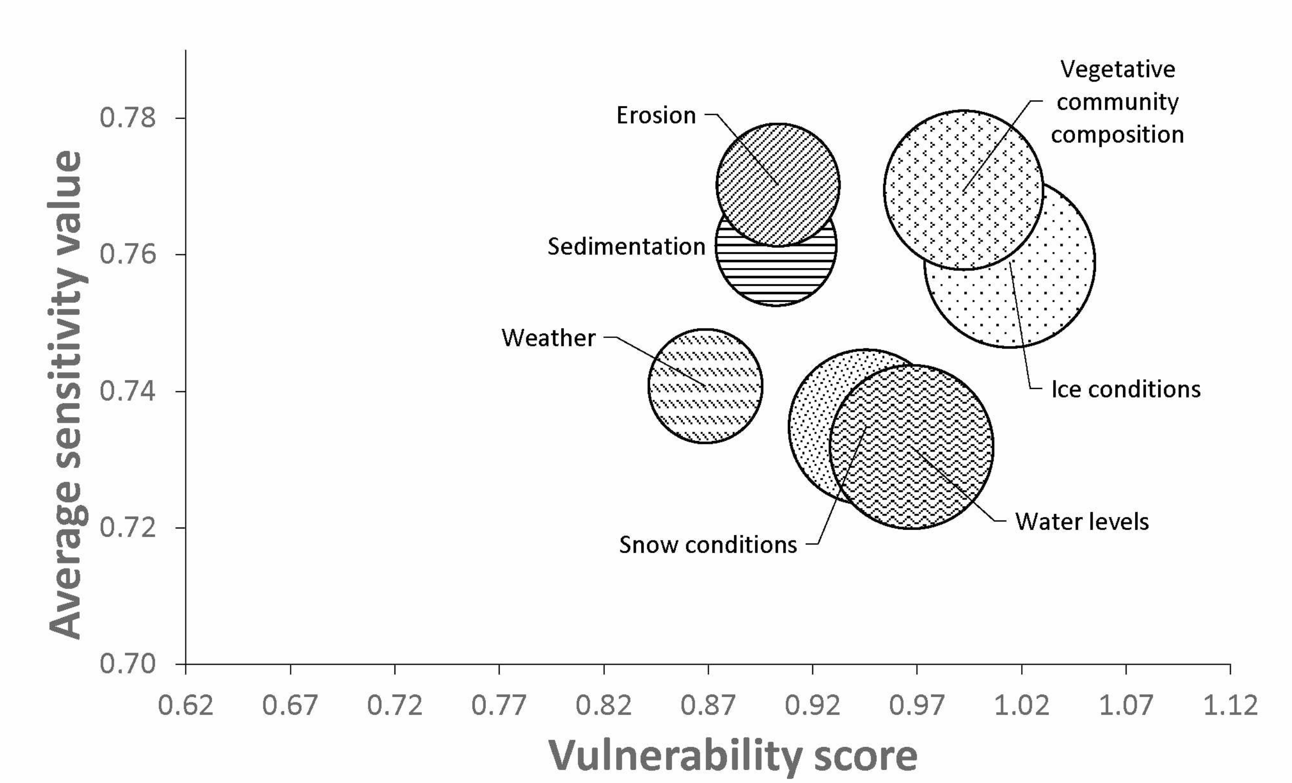
4d.
Remote communities



Condition	Average Likelihood (Li)	Average Sensitivity (S)	Vulnerability (V)†	Number of Observations	Margin of Error‡	V Value Range§
Ice Conditions	0.36	0.81	1.17	85	4.2%	1.12-1.22[a]
Erosion	0.35	0.80	1.15	58	23.4%	0.88-1.42[ab]
Snow Conditions	0.28	0.81	1.09	68	8.1%	1.00-1.18[a]
Water Levels	0.28	0.73	1.01	62	23.9%	0.77-1.25[abc]
Sedimentation	0.12	0.81	0.94	14	20.4%	0.75-1.13[abc]
Vegetative Community Composition	0.14	0.76	0.90	38	5.2%	0.85-0.95[b]
Weather	0.07	0.64	0.72	15	13.8%	0.62-0.82[c]

† Vulnerability values may differ from those expected by adding Li and S values in graph due to rounding errors.
‡ Values at 95% confidence level.
§ V value ranges with different superscripts ([a,b]) denote significant differences (α=.05) from each other.

5a.
All individuals

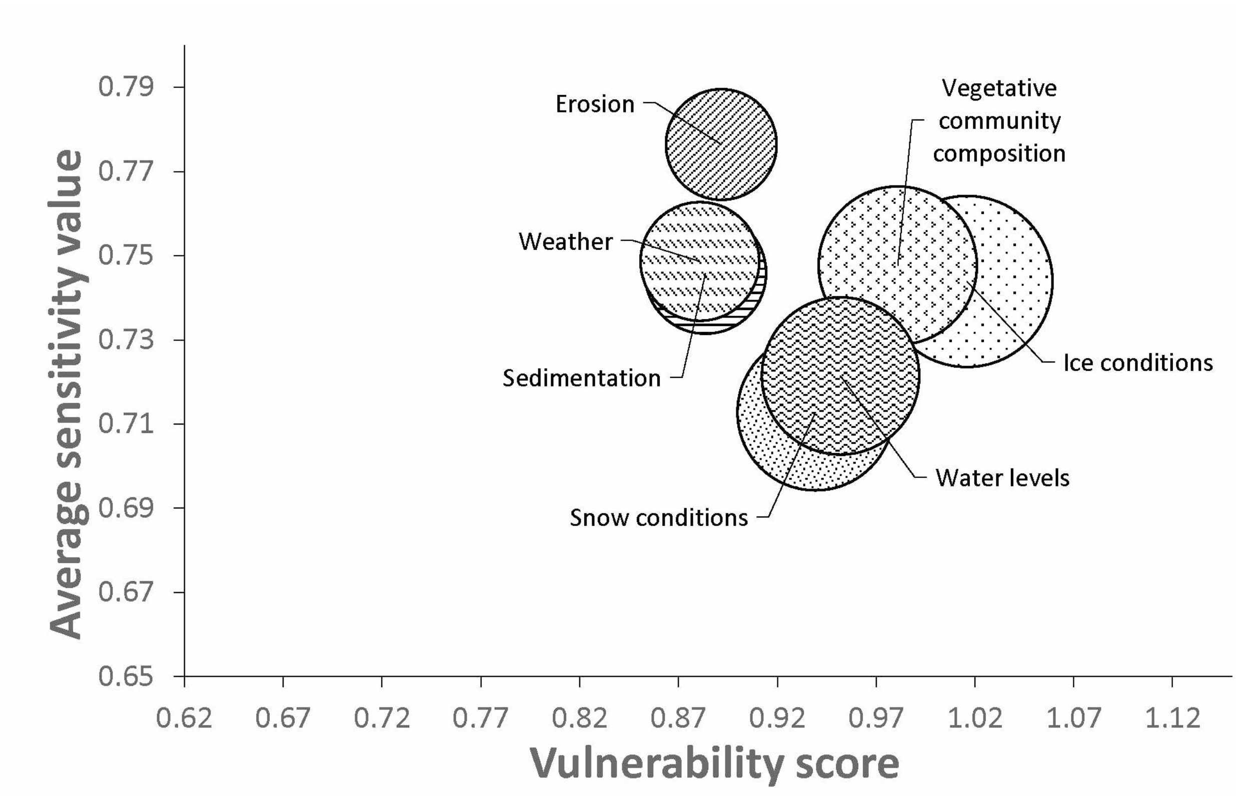


Condition	Average Likelihood (Li)	Average Sensitivity (S)	Vulnerability (V)†	Number of Observations	Margin of Error‡	V Value Range§
Ice Conditions	0.26	0.76	1.01	66	7.8%	0.93-1.09[a]
Vegetative Community Composition	0.22	0.77	0.99	57	7.1%	0.92-1.06[ab]
Water Levels	0.24	0.73	0.97	62	9.3%	0.88-1.06[ab]
Snow Conditions	0.21	0.73	0.95	50	5.5%	0.90-1.00[ab]
Sedimentation	0.13	0.76	0.90	22	9.1%	0.82-0.98[ab]
Erosion	0.13	0.77	0.90	20	4.1%	0.86-0.94[ab]
Weather	0.12	0.74	0.87	17	6.3%	0.82-0.92[b]

Figure 5. Graph and associated mean values for vulnerability analysis of interview data among 22 individuals (5a) 8 communities (5b), 2 road-connected communities (5c) and 6 remote communities (5d). Bubble size is indicative of the decimal total for the number of observations in a category (N), sensitivity values (S) are depicted on the Y axis, and vulnerability values (V) are shown by the X axis.

† Vulnerability values may differ from those expected by adding Li and S values in graph due to rounding errors.
‡ Values at 95% confidence level.
§ V value ranges with different superscripts ([a,b]) denote significant differences (α=.05) from each other.

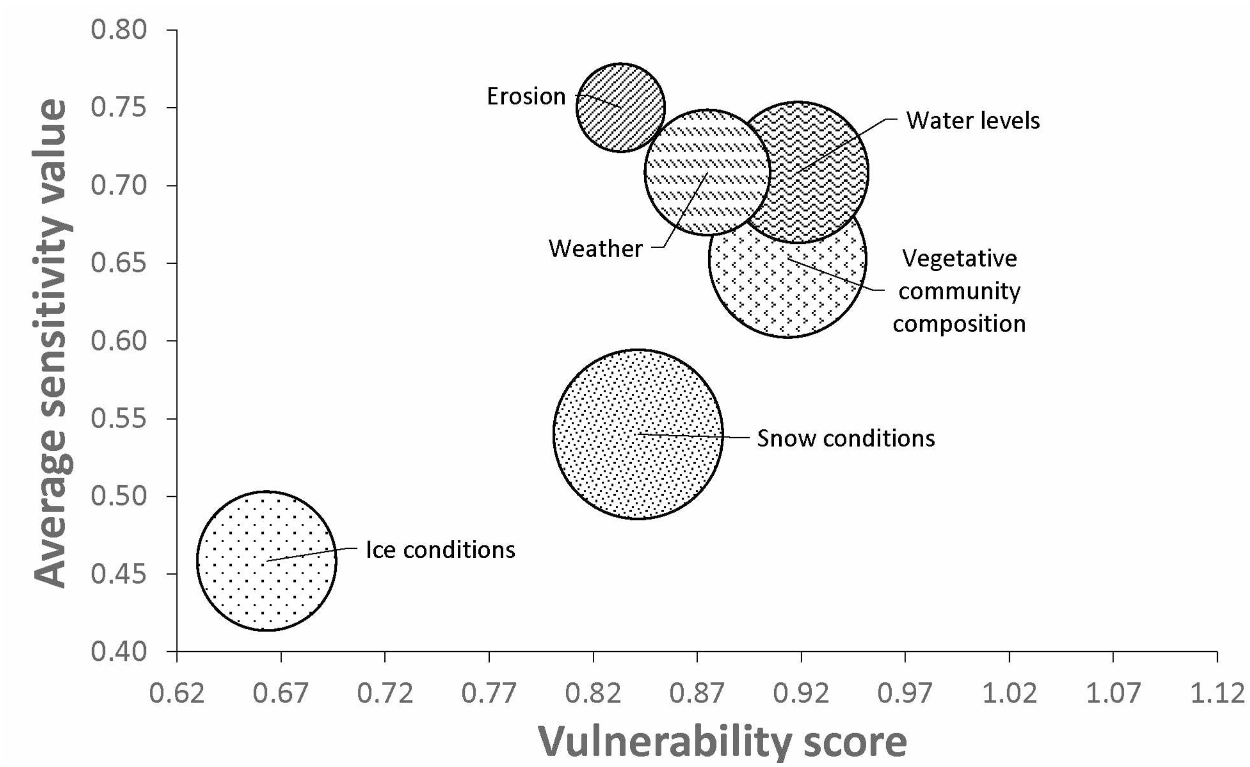
5b.
All communities



Condition	Average Likelihood (Li)	Average Sensitivity (S)	Vulnerability (V)†	Number of Observations	Margin of Error‡	V Value Range§
Ice Conditions	0.27	0.74	1.02	66	14.5%	0.87-1.17[a]
Vegetative Community Composition	0.23	0.75	0.98	57	7.7%	0.90-1.16[a]
Water Levels	0.23	0.72	0.95	62	10.4%	0.85-1.05[a]
Snow Conditions	0.23	0.71	0.94	50	5.1%	0.66-0.76[b]
Erosion	0.12	0.78	0.89	20	3.3%	0.86-0.92[a]
Sedimentation	0.14	0.75	0.88	22	11.6%	0.78-0.98[a]
Weather	0.13	0.75	0.88	17	7.3%	0.82-0.94[a]

† Vulnerability values may differ from those expected by adding Li and S values in graph due to rounding errors.
‡ Values at 95% confidence level.
§ V value ranges with different superscripts ([a,b]) denote significant differences (α=.05) from each other.

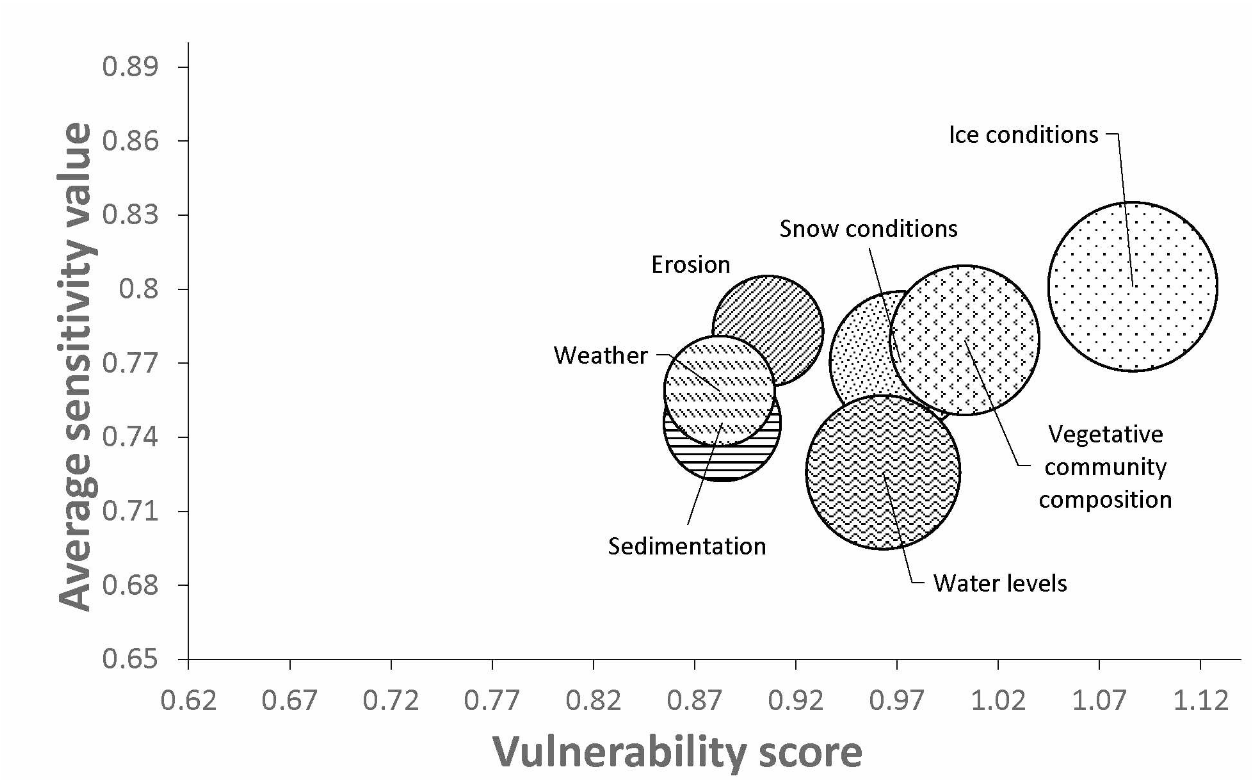
5c.
Road-connected communities



Condition	Average Likelihood (Li)	Average Sensitivity (S)	Vulnerability (V)[†]	Number of Observations	Margin of Error[‡]	V Value Range[§]
Water Levels	0.21	0.71	0.92	11	26.3%	0.68-1.16[a]
Vegetative Community Composition	0.26	0.65	0.91	14	6.6%	0.85-0.97[a]
Weather	0.17	0.71	0.88	4	N/A	N/A
Snow Conditions	0.30	0.54	0.84	16	5.0%	0.80-0.88[a]
Erosion	0.08	0.75	0.83	2	N/A	N/A
Ice Conditions	0.20	0.46	0.66	6	N/A	N/A
Sedimentation				0	N/A	N/A

† Vulnerability values may differ from those expected by adding Li and S values in graph due to rounding errors.
‡ Values at 95% confidence level.
§ V value ranges with different superscripts ([a,b]) denote significant differences (α=.05) from each other.

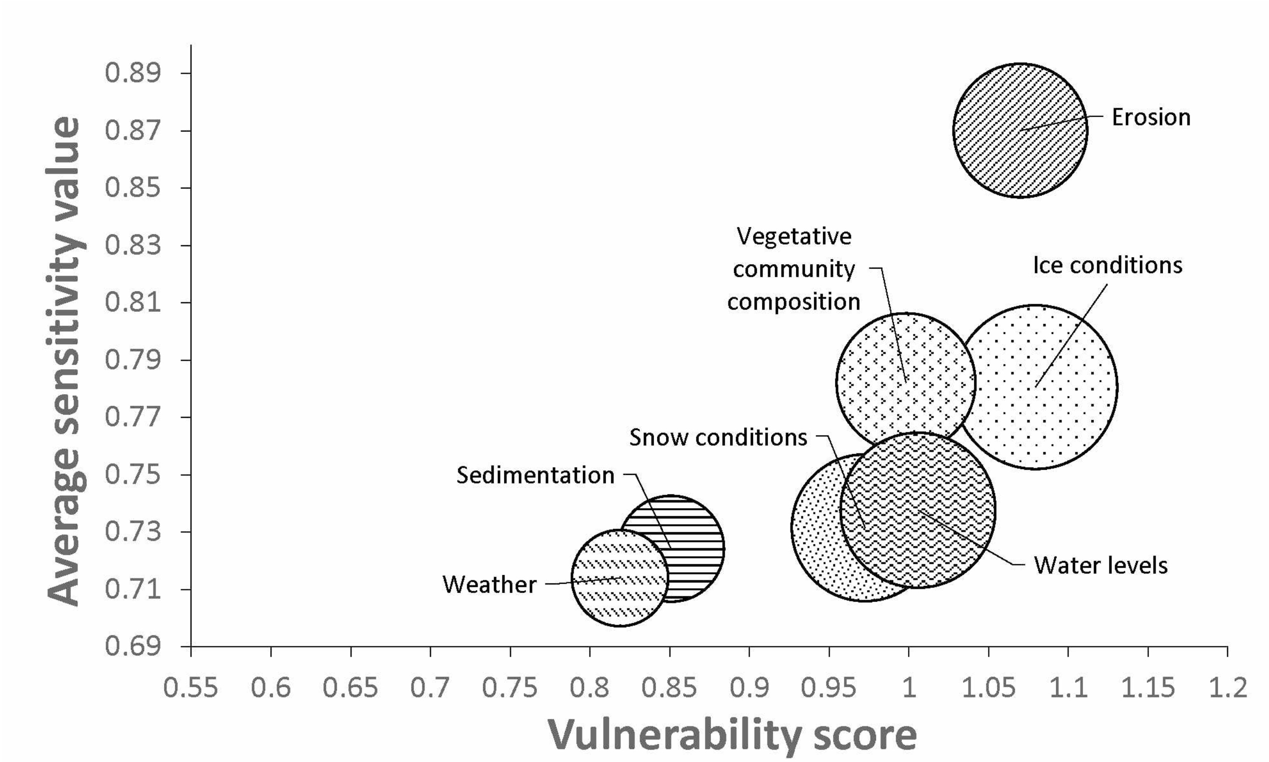
5d.
Remote communities



Condition	Average Likelihood (Li)	Average Sensitivity (S)	Vulnerability (V)†	Number of Observations	Margin of Error‡	V Value Range§
Ice Conditions	0.29	0.80	1.09	60	5.6%	1.03-1.15[a]
Vegetative Community Composition	0.22	0.78	1.00	43	9.3%	0.91-1.09[abc]
Snow Conditions	0.20	0.77	0.97	34	3.1%	0.94-1.00[b]
Water Levels	0.24	0.73	0.96	51	12.2%	0.84-1.08[abc]
Erosion	0.12	0.78	0.91	18	1.9%	0.89-0.93[c]
Sedimentation	0.14	0.75	0.88	22	11.6%	0.78-0.98[bc]
Weather	0.12	0.76	0.88	13	9.8%	0.79-0.97[bc]

† Vulnerability values may differ from those expected by adding Li and S values in graph due to rounding errors.
‡ Values at 95% confidence level.
§ V value ranges with different superscripts ([a,b]) denote significant differences (α=.05) from each other.

6a.
All individuals

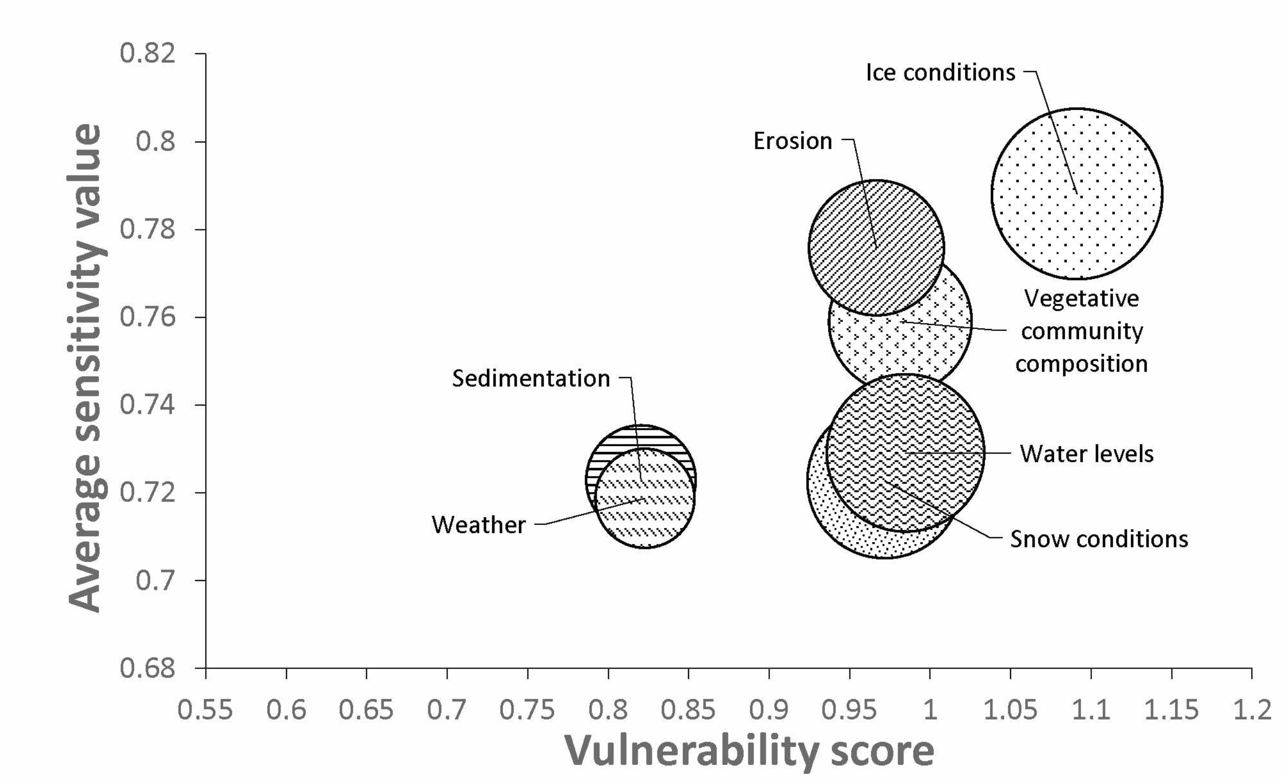


Condition	Average Likelihood (Li)	Average Sensitivity (S)	Vulnerability (V)†	Number of Observations	Margin of Error‡	V Value Range§
Ice Conditions	0.30	0.78	1.08	190	7.1%	1.00-1.16[a]
Erosion	0.20	0.87	1.07	83	12.4%	0.94-1.20[a]
Water Levels	0.27	0.74	1.01	160	8.6%	0.92-1.10[ab]
Vegetative Community Composition	0.22	0.78	1.00	110	7.1%	0.93-1.07[ab]
Snow Conditions	0.24	0.73	0.97	158	6.9%	0.90-1.04[ab]
Sedimentation	0.13	0.72	0.85	38	9.0%	0.77-0.93[bc]
Weather	0.11	0.71	0.82	34	6.8%	0.76-0.88[c]

Figure 6. Graph and associated mean values for vulnerability analysis of combined GPS and interview data at the individual (6a) community (6b), road-connected (6c) and remote (6d) levels. Bubble size is indicative of the decimal total for the number of observations in a category (N), sensitivity values (S) are depicted on the Y axis, and vulnerability values (V) are shown by the X axis.

† Vulnerability values may differ from those expected by adding Li and S values in graph due to rounding errors.
‡ Values at 95% confidence level.
§ V value ranges with different superscripts ([a,b]) denote significant differences (α=.05) from each other.

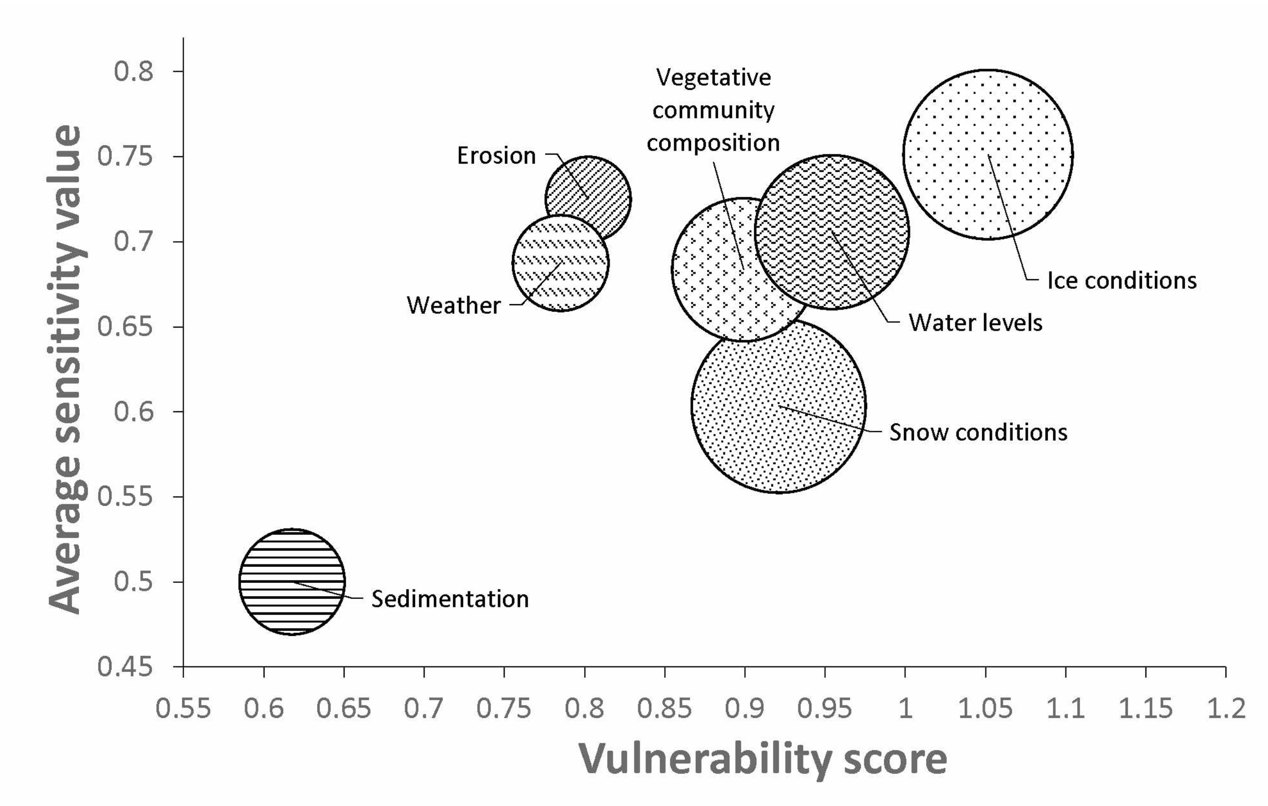
6b.
All communities



Condition	Average Likelihood (Li)	Average Sensitivity (S)	Vulnerability (V)†	Number of Observations	Margin of Error‡	V Value Range§
Ice Conditions	0.30	0.79	1.10	190	7.3%	1.02-1.18[a]
Water Levels	0.26	0.73	0.98	160	9.9%	0.88-1.08[abc]
Vegetative Community Composition	0.21	0.76	0.98	110	8.5%	0.9-1.06[ab]
Snow Conditions	0.25	0.72	0.97	158	11.7%	0.86-1.08[abc]
Erosion	0.19	0.78	0.97	83	15.0%	0.83-1.11[abc]
Sedimentation	0.13	0.72	0.82	38	16.8%	0.68-0.96[bc]
Weather	0.10	0.72	0.82	34	9.0%	0.75-0.89[c]

† Vulnerability values may differ from those expected by adding Li and S values in graph due to rounding errors.
‡ Values at 95% confidence level.
§ V value ranges with different superscripts ([a,b]) denote significant differences (α=.05) from each other.

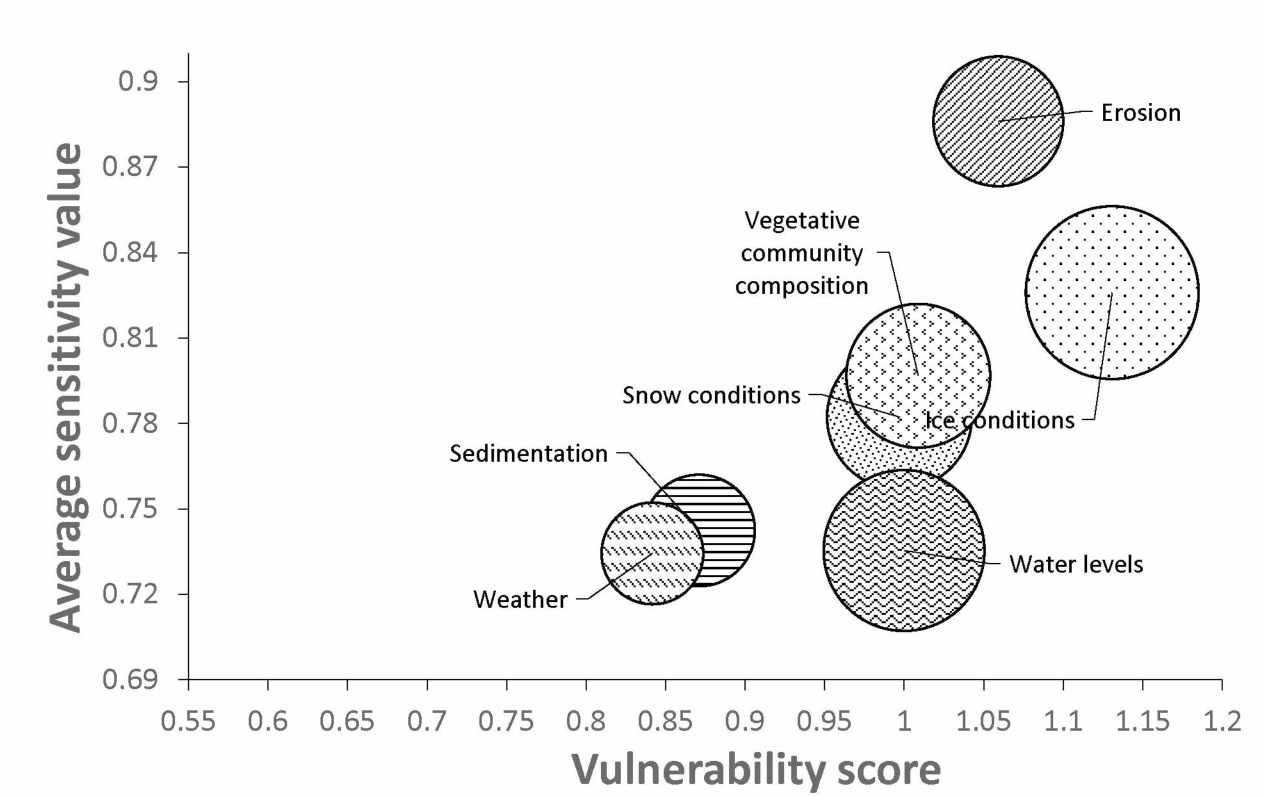
6c.
Road-connected communities



Condition	Average Likelihood (Li)	Average Sensitivity (S)	Vulnerability (V)†	Number of Observations	Margin of Error‡	V Value Range§
Ice Conditions	0.30	0.75	1.05	45	21.1%	0.83-1.27[ab]
Water Levels	0.25	0.71	0.95	47	17.1%	0.79-1.11[ab]
Snow Conditions	0.32	0.60	0.92	56	41.0%	0.54-1.3[ab]
Vegetative Community Composition	0.22	0.68	0.90	29	1.2%	0.89-0.91[a]
Erosion	0.08	0.73	0.80	7	7.6%	0.74-0.86[b]
Weather	0.10	0.69	0.79	6	22.4%	0.61-0.97[ab]
Sedimentation	0.12	0.50	0.62	2	N/A	N/A

† Vulnerability values may differ from those expected by adding Li and S values in graph due to rounding errors.
‡ Values at 95% confidence level.
§ V value ranges with different superscripts ([a,b]) denote significant differences (α=.05) from each other.

6d.
Remote communities



Condition	Average Likelihood (Li)	Average Sensitivity (S)	Vulnerability (V)[†]	Number of Observations	Margin of Error[‡]	V Value Range[§]
Ice Conditions	0.31	0.83	1.13	145	6.1%	1.06-1.2[a]
Erosion	0.17	0.89	1.06	76	16.2%	0.89-1.23[abc]
Vegetative Community Composition	0.21	0.80	1.01	81	10.3%	0.91-1.11[abc]
Snow Conditions	0.21	0.78	1.00	102	3.2%	0.97-1.03[b]
Water Levels	0.26	0.74	1.00	113	13.1%	0.87-1.13[abc]
Sedimentation	0.13	0.74	0.87	36	14.2%	0.75-0.99[bc]
Weather	0.11	0.73	0.84	28	10.1%	0.76-0.92[c]

† Vulnerability values may differ from those expected by adding Li and S values in graph due to rounding errors.
‡ Values at 95% confidence level.
§ V value ranges with different superscripts ([a,b]) denote significant differences (α=.05) from each other.

Table 1. Normalized values for sensitivity (S) categories and the descriptions used to classify the S component of each observation of an environmental condition.

Sensitivity	Description
1.00	Stops activity, forces serious sacrifices, prevents needs being met. Strong negative effect on safety.
0.83	Involves challenges including increased time, energy, and financial expenditures. Reduced harvest opportunity, negative effect on safety.
0.67	Activity performed, some forced change of plans or strategy. Minimal loss in opportunity, slight negative effect on safety.
0.50	No net effect on opportunity or safety.
0.33	Activity performed with more ease than normal. Slight gain in opportunity, slight positive effect on safety.
0.17	Creates additional opportunity, including decreased time, energy, and financial expenditures. Increased harvest opportunity, positive effect on safety.
0.00	Greatly enhances activity, enables abnormally efficient travel and access, and enhances ability to meet needs. Strong positive effect on safety.

Table 2. Example of how final vulnerability value was calculated for a single condition (ice conditions) documented by a single harvester. The final vulnerability value for a condition (0.97) was determined by adding the decimal value for the proportion of observations for a single condition (0.16) out of the total number of observations documented by a harvester to the corresponding sensitivity value (0.81, weighted average of all sensitivity values reported for observations within that condition) to determine an overall vulnerability value for each condition for each harvester.

Condition	Sensitivity Category	Number of Observations	Decimal of Total	Sensitivity Value	Vulnerability Value
Ice Conditions	0.00	0	0.00	0.00	0.00
	0.17	0	0.00	0.00	0.00
	0.33	0	0.00	0.00	0.00
	0.50	0	0.00	0.00	0.00
	0.67	5	0.04	3.33	3.37
	0.83	15	0.11	12.50	12.61
	1.00	2	0.01	2.00	2.01
Totals		22.00	**0.16**	**0.81**	**0.97**

Table 3. Numbers of harvesters and GPS/interview observations documented for each collaborating community.

Community	Number of Harvesters		Number of Observations	
	GPS	Interviews	GPS	Interviews
Holy Cross	2	2	25	35
Grayling	1	3	5	42
Nulato	2	6	21	66
Lake Minchumina	2	2	256	34
Beaver	3	3	20	43
Venetie	3	3	13	21
Healy	1	0	9	0
Delta Junction	1	1	17	24
Tok	3	2	113	29
Totals:	18	22	479	294

Appendix 1:

NASA Mapping Project
Documenting conditions related to travel & access to wild resources

Name:______________________________________ Date:_____________________

Photo ID:____________________________________

What is pictured?

____

____

How do these conditions influence travel or access to resources?

____

____

Trip purpose?

- Hunting
- Fishing
- Trapping
- Gathering (wood, berries)
- Village travel
- Camp
- Other_____________ __________________ __________________ ______________

How frequently have you observed this travel condition?

- Observed weekly
- Observed monthly
- Observed seasonally
- Observed yearly
- Observed every few years
- Observed every few decades
- Never observed before
- Not applicable

What year did you first notice this change? ________________________________

To what extent does this condition affect travel safety?

- Strong affect
- Moderate affect
- Weak affect
- No affect

How common is this condition occurring in other places around your community?

- This change is common, I see it everywhere.
- I have seen this change in some other areas.
- I haven't seen this change anywhere else.

Conclusion

Negative impacts of climate change on access to subsistence resources have become an increasing concern for many rural Alaskans. In response to these concerns, I collaborated with rural residents in nine communities in Interior Alaska to document environmental conditions affecting access to subsistence resources. For a period of 12 months, subsistence resource harvesters documented environmental changes they encountered that influenced their access to hunting, fishing, trapping, and gathering areas. I also interviewed both the participating harvesters and other community members to gather information concerning environmental change and access. I ranked the conditions documented to determine which posed the greatest threats to access to subsistence resources as a whole. In addition, I investigated the role that connectivity to road networks played in vulnerability of resource access to changing conditions. I found that changes in ice conditions, erosion, vegetative community composition, and water levels most negatively affected subsistence resource access across all communities.

Previous research has illustrated the impacts of these conditions on access to ecosystem services individually (Hinzman et al. 2005, McNeely et al 2011, Moerlein and Carothers 2012, Carothers et al. 2014, Brinkman et al. 2016), but my research was the first to evaluate their impacts relative to each other. Literature suggests that subsistence resource access is influenced by road accessibility (Magdanz et al. 2016), and my results concur with those findings. This could be due to a variety of factors, including increased competition for resources by non-locals (Wolfe and Walker 1987), easier access to less-costly commercial goods (Brinkman et al. 2014), or greater opportunities for wage employment (Kruse 1991). Communities that were accessible by road were less vulnerable to all conditions when compared to remote communities. Road-connected communities were most vulnerable to changes in vegetative community composition and water levels, whereas for remote communities abnormal ice conditions and erosion were particularly detrimental. Possible explanations for these relationships include differing modes of transportation. This information can be used by agencies to help inform management decisions concerning key subsistence resources, which could include regulatory rulings directing the management of key fish and wildlife populations while making allowances to accommodate challenges subsistence harvesters may encounter.

In addition to contributing to academic literature, the information collected by collaborators from rural communities is being actively incorporated into publicly accessible formats. One of the goals of my research was to disseminate findings among collaborating communities in the format(s) they predetermined to be most useful to them. They expressed interest in both overlaying information layers depicting specific environmental changes on high-resolution area maps, and in sharing information among communities to exchange ideas on strategies used to adapt to changing environmental conditions. The Local Ecological Observer (LEO) network, as well as the MapVentures project of the Scenarios Network for Alaska and Arctic Planning (SNAP) network are using information from my research to address parallel questions regarding ecosystem service accessibility and environmental change. These collaborations and others provide avenues for information generated by communities to be shared with a wider audience. They also increase the level of networking among individuals and communities that may have similar resource access constraints, and facilitate the exchange of ideas for adaptive solutions.

My research synthesizes a wide array of information into concise findings that can be used to guide future research. Investigating relationships among environmental conditions and subsistence resource types (i.e. hunting, fishing, trapping, etc.) could provide more fine-scale information to inform specific resource management decisions. Parallel studies that focus on the potential causes of environmental conditions affecting access could inform models that give spatial and temporal predictions of the risks that certain locations will face specific environmental change in the future. Finally, my research provided limited insight into the ability of rural Alaskans to adapt to challenges they encounter in accessing subsistence resources. Academics, agencies, and communities would mutually benefit from further collaborative efforts to understand the cascading consequences of climate-induced environmental changes on the culture, health, and well-being of rural Alaskans.

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Appendix 2: Institutional Review Board protocol approval letter

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Institutional Review Board
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September 17, 2015

To:	Todd Brinkman, PhD Principal Investigator
From:	University of Alaska Fairbanks IRB
Re:	[700936-4] Biophysical Characteristics and Mechanisms of Environmental Disturbances Influencing Human Access to Ecosystem Services in Boreal Alaska

Thank you for submitting the Amendment/Modification referenced below. The submission was handled by Administrative Review.

Title:	Biophysical Characteristics and Mechanisms of Environmental Disturbances Influencing Human Access to Ecosystem Services in Boreal Alaska
Received:	September 16, 2015
Expedited Category:	*6 and 7*
Action:	APPROVED
Effective Date:	September 17, 2015
Expiration Date:	January 27, 2016

Final review completed by the administrator because the requested modifications were minor.

This action is included on the October 7, 2015 IRB Agenda.

No changes may be made to this project without the prior review and approval of the IRB. This includes, but is not limited to, changes in research scope, research tools, consent documents, personnel, or record storage location.

Appendix 3: Institutional Review Board protocol closure/final report

UNIVERSITY OF ALASKA FAIRBANKS

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Institutional Review Board

909 N Koyukuk Dr. Suite 212, P.O. Box 757270, Fairbanks, Alaska 99775-7270

January 23, 2018

To:	Todd Brinkman, PhD Principal Investigator
From:	University of Alaska Fairbanks IRB
Re:	[700936-7] Biophysical Characteristics and Mechanisms of Environmental Disturbances Influencing Human Access to Ecosystem Services in Boreal Alaska

Thank you for submitting the Closure/Final Report referenced below. The submission was handled by Expedited Review under the requirements of 45 CFR 46.110, which identifies the categories of research eligible for expedited review.

Title:	Biophysical Characteristics and Mechanisms of Environmental Disturbances Influencing Human Access to Ecosystem Services in Boreal Alaska
Received:	January 15, 2018
Expedited Category:	7
Action:	APPROVED
Effective Date:	January 23, 2018
Expiration Date:	January 27, 2019

This action is included on the February 7, 2018 IRB Agenda.

No changes may be made to this project without the prior review and approval of the IRB. This includes, but is not limited to, changes in research scope, research tools, consent documents, personnel, or record storage location.