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Arctic communities perceive climate impacts on access as a critical challenge to availability of subsistence resources

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Abstract Amplified climate change in the Arctic has altered interactions between rural communities and local wild resources. Shifting interactions warrant analysis because they can influence cultural practices and food security of northern societies. We collaborated with four indigenous communities in Alaska and conducted semi-directed interviews with 71 experienced harvesters to identify local perceptions of climate-driven trends in the environment, and describe the effects of those trends on the availability (i.e., abundance, distribution, accessibility) of subsistence resources. We then linked local perceptions with scientific climate projections to forecast how availability of subsistence resources may change in the future. Hunters identified 47 important relationships between climate-driven changes in the environment and availability of subsistence resources. Of those relationships, 60, 28, and 13 % focused on changes in harvester access, resource distribution, and resource abundance, respectively. Our forecast model indicated a net reduction in the availability of subsistence resources over the next 30 years. The reduction was caused primarily by climate-related challenges in access, rather than changes in abundance or distribution of resources. Our study

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demonstrates how giving insufficient attention to harvester access may produce misleading conclusions when assessing the impacts of climate change on future subsistence opportunities.

1 Introduction

The Arctic is experiencing rapid socio-economic and ecological changes, many of which relate to climate change (Ford et al. 2012; Hinzman et al. 2005; IPCC 2013). Evaluating relationships among climate change, ecological impacts, and the well-being of northern communities is therefore critical in assessing current and future societal challenges and opportunities. Climate impacts on ecosystems are particularly important for northern indigenous peoples with mixed cash-subsistence economies because of peoples' deep reliance on local wild resources (BurnSilver et al. 2016a; Nuttall et al. 2005). A proliferation of research has highlighted the tight linkages among Arctic community vulnerability, the harvest of local resources, and climate change from global to local perspectives (ACIA 2005; McDowell et al. 2016). We collaborated with residents of four indigenous communities in interior and coastal regions of Alaska to compare local perceptions and scientific models of climate change. We also explored local perceptions of the relationships among climate-driven changes in environmental variables and key components contributing to availability of local wild resources. Our evaluation of multiple regions in Alaska fostered analysis of climate impacts on a diverse set of local resources in forest, tundra, freshwater, and marine biomes.

Increasingly, attention has been given to local and traditional ecological knowledge (TEK) of climate and wild resources because of the unique and intimate connection of indigenous peoples have with Arctic landscapes (Lovecraft and Eicken 2011). We define TEK as the knowledge and insights acquired through oral history, extensive experience, and observations of an area or a species accumulated over generations (Huntington et al. 2005). TEK, however, has not always been recognized or respected by people outside of indigenous communities. Use and application of TEK by scientists in the Arctic expanded rapidly over the last few decades as researchers gained awareness of the knowledge, careful observation, and refined skill required by indigenous communities to be self-reliant and thrive in a harsh and dynamic environment (Huntington et al. 2005). TEK provides holistic insights of the natural world at spatial and temporal scales that are not easily addressed by disciplinary or compartmentalized scientific approaches (Berkes 2012; Kofinas et al. 2016). For example, TEK can help downscale coarse models and assess the assumptions used to construct models (IPCC 2013; Laidler 2006; Riedlinger and Berkes 2001). Integrating TEK into research processes can also help scientists to both identify pressing research questions and better understand societal implications of findings.

A key to sustaining the economic and cultural well-being of indigenous communities in the Arctic is maintenance of robust customary and traditional use (i.e., subsistence) practices (Lambden et al. 2007; Loring and Gerlach 2009, 2015; Smith et al. 2009). This requires continued *availability* of subsistence resources, the noncommercial and renewable products including wild foods, fiber, and fuel (e.g., firewood) directly harvested by and shared among residents of rural areas. Brinkman et al. (2013) considered a subsistence resource to be *available* to those relying on it if three minimum criteria are met: 1) the population size of the resource is sufficient to sustain an annual harvest (abundance), 2) harvesters can safely and reliably get to harvest areas (harvester access), and 3) the resource is present in accessible areas during the harvest season (seasonal distribution). Other definitions of availability address food security and ecosystem services to capture the amount, type, and quality of food a community has at its disposal, along with physical and logistical influences over procurement (see Loring and Gerlach 2015 for a review). During community collaborations, we applied Brinkman et al.'s (2013) three-component availability framework, and conveyed abundance as population size, seasonal distribution as the location of the species during traditional harvest times, and access as the physical ability for a person to travel to harvest area during traditional harvest times. Our framework fostered a direct investigation of harvester perceptions on how biophysical changes at the landscape scale influence each component of availability.

The first objective of our research was to identify local perceptions of ways that climate-driven environmental trends impact subsistence resources within our availability framework. Our second objective was to link local perceptions of availability with scientific climate-model projections to forecast how availability of subsistence resources may change in the future. Our approach is novel in that limited research has simultaneously assessed the association among multiple components of resource availability (abundance, access, distribution) for an array of harvested species based on climate-driven changes in the environment. Also, our availability framework facilitated a comparison of the sensitivity of each component of availability to climate-driven environmental trends from a local perspective. Many social, cultural, economic, and ecological factors can affect the persistence of subsistence practices and need to be integrated to provide a holistic understanding of changing subsistence opportunities in Arctic communities (BurnSilver et al. 2016a; Loring and Gerlach 2015; Moerlein and Carothers 2012). This study enhanced knowledge of the social challenges and opportunities associated with changes in biophysical variables related to climate, which will help fill ecological gaps in understanding to promote more holistic evaluations.

2 Study area

We evaluated impacts of climate-related environmental changes on availability of subsistence resources in four indigenous Arctic communities; two Gwitch'in Athabascan Indian communities in Interior Alaska (Venetie [population ≈ 200] and Fort Yukon [population ≈ 600]), and two Iñupiat communities on the coast of Northern Alaska (Wainwright [population ≈ 550] and Kaktovik [population ≈ 290]) (Fig. 1). Residents depend on subsistence resources for food, and harvest activities are closely connected to local culture and livelihood (Brinkman et al. 2014; BurnSilver et al. 2016b). These communities cannot be accessed by road. Instead, small aircraft and limited boat service during ice-free summer months are used. Small networks of roads (<10 km) exist within communities. Subsistence harvest areas surrounding communities are mainly accessed by boat, snowmobile, or all-terrain vehicle (ATV).

Venetie and Fort Yukon are located within the Yukon River drainage of the boreal forest. The boreal forest of Alaska is bounded by the Brooks (north) and Alaska (south) mountain ranges and is considered relatively vulnerable to abrupt climate-driven environmental climate (Chapin et al. 2006). In Interior Alaska, warming has contributed to increasing wildfire frequency and severity and thawing of discontinuous permafrost (Rupp et al. 2007). The environment around Venetie and Fort Yukon is characterized by flat topography, a mix of predominantly coniferous (*Picea glauca, Picea mariana*) and locally-abundant deciduous (*Betula* spp., *Populus* spp., *Salix* spp.) trees and shrubs, and numerous bogs, streams, sloughs, and lakes. Mean temperatures in the coldest and warmest months are −29 °C (January) and 17 °C (July), respectively. The region is semi-arid, with mean annual precipitation of

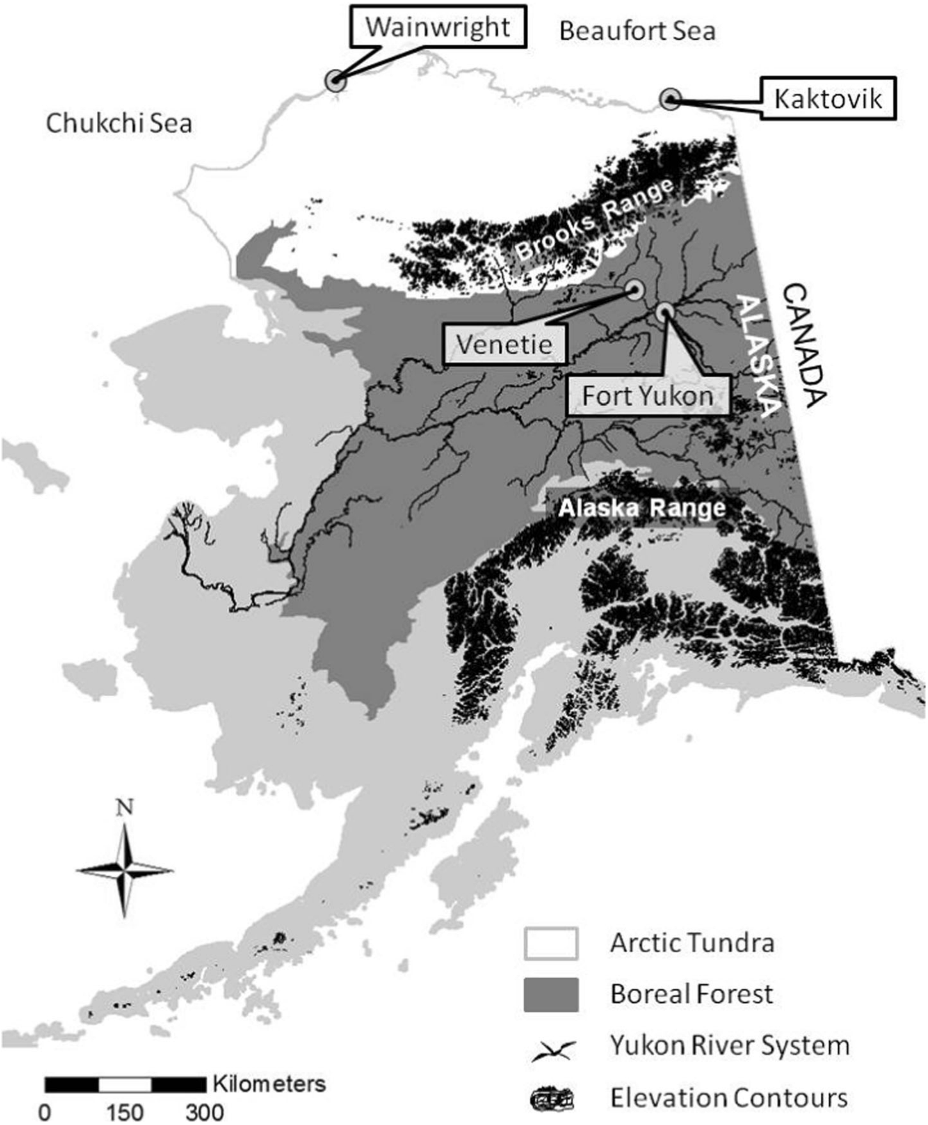

Fig. 1 Location of four indigenous communities participating in research on the impact of climate change on subsistence resources

approximately 17 cm, with mean snowfall of 115 cm (Brabets et al. 2000). In Interior Alaska communities, approximately 29 % of total calories come from subsistence foods, and harvest averages 145 kg per person (Fall 2012). Moose (*Alces alces*), caribou (*Rangifer tarandus*), salmon (king [*Oncorhynchus tshawytscha*], chum [*O. keta*]) and several species of waterfowl (e.g., white-fronted [*Anser albifrons*] and Canada [*Branta canadensis*] geese, long-tailed duck [*Clangula hyemalis*]) are the primary subsistence foods; however, many other species supplement harvest for food or are trapped for fur (Van Lanen et al. 2012).

Wainwright and Kaktovik are located on the coast of the Chukchi and Beaufort Seas, respectively, of the Arctic Ocean (Fig. 1). The terrestrial landscape around the two communities is flat, treeless, and consists of Arctic tundra with relatively low biodiversity and many shallow lakes on underlying permafrost. Arctic tundra consists of low shrubs, sedges, mosses, grasses, and lichens. Mean annual precipitation is 15 cm with mean snowfall of 73 cm. Regional mean temperatures in the coldest and warmest months are −28 °C (February) and 8 °C (July), respectively. Historically, the marine landscape has been covered with sea ice for roughly 9 months of the year, with open water along the coasts from late June through early October. People harvest a mix of terrestrial, freshwater, and marine resources, which primarily include, but are not limited to, bowhead whale (*Balaena mysticetus*), bearded seal (*Erignathus barbatus*), beluga whale (*Delphinapterus leucas*), caribou, Dall sheep (*Ovis dalli*) (Kaktovik only), waterfowl (e.g., white-fronted geese, black brant [*B. bernicla*], eiders [*Somateria spp.*], long-tailed duck), and fish (e.g., rainbow smelt [*Osmerus mordax*], whitefish [*Coregonus spp.*], arctic grayling [*Thymallus arcticus*]). Approximately 39 % of total calories come from subsistence foods, and harvest averages 199 kg per person (Fall 2012). The diversity of subsistence resources and significant nutrient contribution (189 % of the protein requirements in rural Alaska; Fall 2012) highlight the need to incorporate local knowledge to provide the context required to describe the complex harvest system.

3 Methods

3.1 Documenting local knowledge

Our research occurred in communities where we had ongoing and long-term collaborations. These collaborations were predicated on the idea of communities as integral partners in the research process in which knowledge co-generation was a primary goal (Kofinas et al. 2016). To ensure that our research addressed local issues and was community-driven, collaborations were formed with local organizations (e.g., tribal councils, village corporations) to design and implement our approach. For example, communities actively posed questions about climate impacts on subsistence activities prior to implementing our research. Tribal councils and local advisory committees chose research participants, and participants selected the resources that were evaluated and best represented their community's harvest system. In each community, our collaboration followed a semi-directed process (Huntington 1998), and open-ended questions guided face-to-face interviews with one to four harvesters at a time. In semi-directed interviews, researchers presented general questions to initiate discussion around topics of interest, but participants steered the discussion, determined the order topics were discussed, and made connections between topics that researchers might not anticipate. Participants were active and/or experienced harvesters with in-depth understanding of harvest patterns, subsistence populations, and landscape change who were particularly dependent on the resources we discussed. We digitally recorded and transcribed interviews. Both males and females of ages between mid-20s and mid-90s with hunting, fishing, and trapping specializations participated. The majority of participants were male and from older generations (>40 years old). Research was approved by the University of Alaska Fairbanks Institutional Review Board (#09-51), and we protected participant anonymity. Prior to any attempt at publication of our study, we reported results back to each community. Interview participants reviewed reports and assisted with interpretation of findings. After addressing and incorporating comments, final reports were delivered back to communities, and Tribal entities (Councils, Village Corporations) provided formal approval to share results with the public.

Each harvester participated in three interviews. Initial interviews served to collect local perceptions of: 1) important subsistence resources for the community, 2) what environmental factors affect each component of availability (i.e., abundance, seasonal distribution, and access) for each resource, and 3) past and current and availability of each resource. For example, local harvesters described how environmental factors increased or decreased population size of important resources (abundance), increased or decreased the presence of the resource in their harvest area during harvest times (seasonal distribution), and facilitated or challenged standard methods to physically get to harvest areas during harvest times (access). A second round of interviews began with more in-depth discussions of changes in climate-related environmental variables (e.g., temperature, wildfire, sea ice) have changed since the 1960s around each community and whether participants think changes are anomalies or trends that may continue over the next few decades. After harvesters shared their perceptions of climate-driven changes, we presented scientifically-derived and spatially-explicit maps (2 km resolution) illustrating mean temperature, precipitation, hydrology, vegetation composition, wildfire, wind, and sea ice for three time periods: 1960–1990, 2001–2010, 2030–2039 (Table 1). Climate projections were derived from a composite (i.e., mean output) of the five best-performing General Circulation Models (GCMs) for Alaska using the A1B (mid-range) emission scenario (SNAP 2013; Table 1). Other environmental projections were drawn from recent and well-cited studies. Participants were asked if they agreed, disagreed, or were unsure of the direction of environmental change represented in each science projection. Because of uncertainty with the extent of projected change, we asked participants to focus on the direction of the trend, rather than the specific magnitude of change.

Final interviews focused on identifying the relative importance of specific relationships between climate-related environmental trends and the availability of each subsistence resource during the peak times of harvest for that resource. Researchers compiled matrices of all identified relationships (environmental trend x resource x availability component) as participants provided them, and then asked participants to rank each relationship as inconsequential or important relative to the others based on prevalence and impact on their subsistence system. Inconsequential relationships were those that harvesters felt exerted an unknown or negligible impact on their subsistence system. Important relationships were those with obvious positive or negative impacts on subsistence opportunities. Researchers and participants agreed to exclude inconsequential relationships from further evaluation to focus on a subset of important issues. Participants described the extent of climate impact on important relationships using a positive and negative categorical ranking system (low impact = + or −, medium impact = ++ or −−, high impact = +++ or −−−). Researchers conducted a content analysis on interview transcriptions using ATLAS.ti qualitative data analysis software to determine hunters' perceptions of the relative influence of environmental change on availability when ranking was evenly split between categories (e.g., + and ++). We used this software to automatically select text segments associated with relationships to help weight codes and output ordinal categories matching our ranking system.

3.2 Forecasting change in availability of subsistence resources

Our research team forecasted future change in availability of subsistence resources by linking positive and negative relationships with local perceptions of future trends in each environmental variable (Table 1). Ranks (e.g., +, +++) were accounted for to allow the most important relationships to have a greater influence on the forecast model compared with less important

Table 1 The trend direction and source of scientific projections in climate-driven environmental variables and harvesters' perceptions of validity. Those that harvesters agreed with were used to model changes in the availability of subsistence resources over the next three decades (between 2000–2009 and 2030–2039) caused by projected changes in the climate for northern Alaska, USA

Variable	Description	Trend documented with science	Source	Harvesters' Perception
Temperature	Mean monthly and annual air temperature	Increased air temperatures	SNAP 2013	Agree
Forest Composition (Post wildfire succession)	Change in major forest types simulated using the computer program Boreal ALFRESCO (Alaska Frame Based Ecosystem Code), a stochastic state and transition model.	Increase in deciduous forest Decrease in coniferous forest	Rupp et al. 2007	Agree
Wildfire	Simulated using Boreal ALFRESCO	Increased frequency Increased severity Increased area burned	Rupp et al. 2007	Agree
Precipitation	Mean monthly and annual precipitation.	More precipitation	SNAP 2013	Disagree (less precipitation)
Hydrology (i.e., landscape aridity)	Calculated by subtracting potential evapotranspiration from precipitation.	Dryer environment	SNAP 2013	Agree
Sea ice	Regional representation of monthly sea ice coverage and thickness.	Decreased extent and thickness	IPCC 2013	Agree
Wind	Regional representation of change in mean wind speed.	Increased wind speeds	Hinzman et al. 2005; Hansen et al. 2013	Agree

relationships. The ranks were summed and averaged for each component of availability (abundance, access, distribution), for each subsistence resource, and for each community to provide forecasts (positive, negative, no anticipated change) of climate-driven change in availability over the next human generation (≈30 years). For example, if harvesters perceived that warming temperatures over the last 30 years have had a positive impact on abundance, and they perceived that temperatures would continue to increase over the next 30 years, then our forecast model would reflect an increase in abundance of that resource in the future. Both researchers and participants acknowledged that assuming a linear continuation of the relationship was a simplified rule that didn't fully capture the short-term variability of weather and harvest opportunities. However, the simplified approach was supported by the general trajectories of climate models (IPCC 2013) and by local perceptions of 30-year trends. To bound the complexity of our model, we assumed that each component of availability (i.e., access, abundance, distribution) had the same weight (i.e., influence) when calculating availability (at the resource and community scale), and we did not address potential adaptations (e.g., novel and innovative access strategies) by harvesters.

Additionally, we forecasted availability of subsistence resources without considering harvester access. We did this because: 1) resource managers often rely solely on abundance and distribution of resources, rather than harvester access, to predict harvest opportunities and set harvest regulations (Brinkman et al. 2013; Lancia et al. 2005); and 2) scientific investigations on the relationships between subsistence resources and climate change have often concentrated on the biological components (abundance and distribution) of the availability framework (Laidre et al. 2008; Parmesan 2006; Sharma et al. 2009; Vors and Boyce 2009). While researchers and harvesters acknowledge that certain subsistence resources may be more or less important during certain years or to certain households within the community, harvesters requested that each resource be considered as having an equal influence on the overall well-being of their subsistence system.

4 Results

4.1 Important environmental factors and availability components

Harvesters in coastal and interior communities chose to evaluate the availability of twelve and seven subsistence resources, respectively (Table 2, Appendix 1). Interior-community interviews reported that climate-driven changes in temperature, hydrology, and characteristics of the wildfire regime were impacting availability of subsistence resources (Table 1). Coastal communities reported that warming temperature, decreasing sea ice, and windier conditions were impacting resource availability (Table 1). Harvesters identified and described 47 important relationships between climate-driven changes in the environment and availability components that were worth consideration in the model or had an obvious positive or negative influence (Table 2, Appendix 2). Of those relationships, 60, 28, and 13 % focused on changes in harvester access, resource distribution, and resource abundance, respectively (Appendix 2).

4.2 Local perceptions compared with scientific projections

Excluding precipitation, harvester perceptions and science-model projections were in agreement on past and future trends across all environmental variables (Table 1). Participants in both

Table 2 Descriptive data on interviews with subsistence harvesters in the communities of Fort Yukon, Venetie, Wainwright, and Kaktovik Alaska, USA, indicating the number of harvesters interviewed (participants), number of subsistence resources evaluated (resources), number of climate-driven environmental variables impacting availability (variables), and the number of significant relationships identified between environmental variables and each component of availability (access, distribution, abundance)

Variables	Fort Yukon	Venetie	Wainwright	Kaktovik	All
Participants	22	20	17	12	71
Resources	3	4	6	6	19
Variables	3	3	3	3	12
Access	3	6	9	10	28
Distribution	3	6	1	3	13
Abundance	1	4	0	1	6
Availability[a]	7	16	10	14	47

[a] Combines access, distribution, and abundance relationships

coastal and interior communities thought projections showing a trend of increased precipitation were inaccurate because landscapes around their communities are drying and they expected this trend to continue. Disagreement on precipitation trends had no effect on the forecast model because no important relationships were identified between precipitation changes and resource availability (Appendix 2).

4.3 Forecasting future availability in subsistence resources

For all communities, resource availability was forecasted to decline or remain constant over the next 30 years. While no individual resource was expected to become more available to any community in the study, some components of availability were forecasted to improve for some individual resources (Table 3). Declining availability of most subsistence resources was primarily driven by environmental change challenging harvester access to subsistence resources. Approximately 93 % ($n = 28$) of access relationships identified by harvesters were negative (Appendix 2). The negative access relationships were primarily due to environmental changes that physically obstructed travel (e.g., fallen trees after a wildfire) or created unsafe travel conditions (e.g., unstable river or sea ice), particularly in coastal communities (Appendix 2). Perceived impacts of climate-driven changes in the environment on distribution and abundance of subsistence resources were less clear. Of six important relationships identified for abundance, 50 % were positive and 50 % were negative (Appendix 2). These relationships resulted in an increasing trend in the abundance of moose in Venetie and Fort Yukon, and a decreasing trend in abundance for caribou in Venetie and Kaktovik (Table 3, Appendix 2). Of thirteen relationships identified for the distribution component of availability, seven were positive and six were negative (Appendix 2). These relationships resulted in a negative trend for three resources, a positive trend for three resources, and no change for one resource.

Our forecast model output was markedly different when excluding the access component of availability (Table 3). When access was not considered, the availability of 74 % of resources was *not* anticipated to change because of environmental trends. Overall, availability was forecasted to have a slight net increase (3 increase, 2 decline, 14 unchanged) because of climate change when access was ignored. Availability of caribou and fish were forecasted to

Table 3 Climate-driven forecasts in changes in availability (with and without accounting for access) of key subsistence resources between the decades 2000–2009 and 2030–2039 based on perceived relationships identified by harvesters in the Alaskan communities of Fort Yukon, Venetie, Wainwright, and Kaktovik

Community	Individual resource	Availability component[a]	Change[b]	Availability[c]	Availability without *access*
Fort Yukon	Moose	Abundance	+	−	0
		Access	−		
		Distribution	−		
	Waterfowl	Access	−	−	0
	Fish	Distribution	−	−	−
		Access	−		
Venetie	Moose	Abundance	+	0	+
		Access	−		
		Distribution	0		
	Caribou	Abundance	−	−	−
		Access	−		
		Distribution	−		
	Waterfowl	Access	−	−	0
	Fish	No important relationships identified		0	0
Wainwright	Bowhead whale	Access	−	−	0
	Caribou	Access	−	0	+
		Distribution	+		
	Bearded seal	Access	−	−	0
	Waterfowl	No important relationships identified		0	0
	Beluga whale	No important relationships identified		0	0
	Fish	No important relationships identified		0	0
Kaktovik	Bowhead whale	Access	−	−	0
	Caribou	Abundance	−	−	0
		Access	−		
		Distribution	+		
	Dall's sheep	Access	−	−	0
	Waterfowl	No important relationships identified		0	0
	Bearded seal	Access	−	0	+
		Distribution	+		
	Fish	No important relationships identified		0	0

[a] If an availability component is not listed for a resource, then no important relationships were identified

[b] "–" = decline, "+" = increase, "0" = no important relationships or no net change when averaging relationships

[c] Average of "abundance", "access", and "distribution" scores for an individual resource

decline in Venetie and Fort Yukon, respectively. Moose, caribou, and bearded seal were forecasted to increase in Venetie, Wainwright, and Kaktovik, respectively.

5 Discussion

5.1 Importance of access

Compared with impacts on resource abundance and distribution, harvesters perceived that climate change has a disproportionally large impact on accessibility of subsistence resources. Perceptions that harvester access is challenged by climate-driven changes to rivers, land, sea ice, and open ocean corroborates earlier TEK studies (Chapin et al. 2008; Kofinas et al. 2010; Loring et al. 2011; McNeeley and Shulski 2011; Nelson et al. 2008; Rattenbury et al. 2009). The climate change-access association is important because there appears to be a mismatch between what local harvesters think is most vulnerable to climate change and what fish and wildlife management agencies focus most of their attention on. Studies on the relationships between subsistence resources and climate change typically concentrate on animal abundance and distribution (Hansen et al. 2011; Laidre et al. 2008; Parmesan 2006; Sharma et al. 2009; Vors and Boyce 2009), rather than harvesters' ability to access the resource. The disproportionate focus on population dynamics is likely because resource-management agencies mainly rely on population estimates as indicators of program success, and fluctuating population sizes stimulate changes in harvest regulations (Lancia et al. 2005; Brinkman et al. 2013).

We speculate that harvester access was the primary topic of discussion during interviews for several reasons. First, abundance and distribution of resources may have been secondary because most subsistence resource populations in community harvest areas were healthy and abundant during our study. For example, the bowhead whale population harvested from by Wainwright and Kaktovik has increased exponentially for decades (Givens et al. 2013) and harvesters noted they were using the same migration routes. Many of the barren-ground caribou herds in Alaska were near record highs when interviews were conducted (Lenart 2009). As animal population size increases, positive associations between abundance and harvest opportunities may weaken and other factors (e.g., access) may be better predictors of opportunities (Van Deelen and Etter 2003; Brinkman et al. 2013). Second, it was evident that harvesters had more control over decisions relating to access compared with large-scale changes in population dynamics and seasonal distribution of subsistence resources. For example, harvesters decide on the mode of access (e.g., boat, snowmobile) and the route they take to get to their harvest area. Individual harvesters are responsible for finding access to resources, whereas abundance and distribution are actively regulated and monitored by government agencies. Lastly, harvester access may have been the dominant topic because of the strong association between access and safety. Unfamiliar and unpredictable changes in the environment have meant that TEK, which has previously provided reliable cues that aid safe travel to hunting grounds across dangerous landscapes, may be less dependable now. Stronger and more erratic winds across open water (Hansen et al. 2013), unusual and unpredictable ice conditions on rivers, lakes, and sea (Jones 2014; Krupnik et al. 2010; Moerlein and Carothers 2012), and irregular freeze up and breakup (McNeeley and Shulski 2011) have been linked to injuries and deaths of arctic residents while hunting or fishing (Laidler et al. 2009).

5.2 Agreement between local perceptions and scientific projections

All communities we collaborated with agreed that climate-driven changes in the environment were occurring rapidly. This finding was not surprising considering the strong impacts of climate change on Arctic communities (Bronen and Chapin 2013; Hinzman et al. 2005), and the extensive engagement of communities in evaluating and responding to associated societal consequences (Krupnik et al. 2010; Lovecraft and Eicken 2011). Participants unanimously agreed on directions (increase or decrease) of change for nearly all variables that were considered.

Scientific projections of precipitation was one notable exception where participants disagreed with science models. Harvesters perceived that their subsistence areas were receiving less precipitation and that this trend may continue. Similar to other research incorporating local knowledge, harvesters supported their statements by noting shallower rivers and drying lakes (Moerlein and Carothers 2012). Disagreement between harvesters and science may be related to differences in parameters used to assess precipitation. Science uses weather stations to measure precipitation in units of rain or snow. Harvesters use environmental indicators. For example, during interviews on precipitation with interior community participants, harvesters' expressed less precipitation by stating that “lakes aren't holding water”, “river channel is getting shallow”, “fires are occurring where you wouldn't expect”, and “there seems to be a drying trend”. Therefore, metrics on which harvester perceptions are based for precipitation align more closely with scientific projections of landscape aridity (precipitation minus evapotranspiration) (Hinzman et al. 2005). If evapotranspiration exceeds precipitation, landscapes dry, more frequent and severe fires will occur and water levels will drop, consistent with harvester observations. Harvesters' disagreement with precipitation projections illustrates how researchers must be explicit about methods and assumptions of scientific data they share with communities, and the need to be aware of situations when researchers and local collaborators are saying the same thing, but imply something different.

5.3 Community response

Our research did not focus on local response or adaptation to the perceived net decline in subsistence resource availability, or on the influence of future innovations (e.g., new modes of access). However, other Arctic research (Berkes and Jolly 2001; Kofinas et al. 2010, 2016) revealed that indigenous communities have successfully sustained harvest practices by exhibiting flexibility in strategies, keys to overcoming novel challenges and unpredictable environmental conditions. We also witnessed this. For example, while interviews were being conducted, harvesters in Wainwright were exploring different harvest times and modes of access, which led to the first fall whale harvest in recorded history during 2010 (Suydam et al. 2011). Hunter success was facilitated by a transition from small boats to a larger vessel that can venture further from shore and navigate rougher seas. In Venetie, harvesters switched boat motors (long-shaft propellers to jet) allowing travel in increasingly shallow and unpredictable rivers. Larger boats and jet motors both consume more gasoline than smaller boats and propeller motors, respectively. Like these, many of the adaptions that harvesters shared with us and reported in other studies represent tradeoffs, such as more cash to purchase, ship, and fuel equipment that facilitates access (Brinkman et al. 2014).

5.4 Future research

Our analyses highlighted a small but important subset of climate-related changes linked to access in four indigenous communities. Although we focused on the effects of environmental factors, we recognize that several social and economic factors also interact to influence hunting patterns and resource availability. Under some circumstances, socioeconomic factors may be more influential than environmental factors in determining availability of subsistence resources (Brinkman et al.

2014; BurnSilver et al. 2016b; Loring and Gerlach 2015; Moerlein and Carothers 2012). During every interview, harvesters noted that high fuel costs were challenging their ability to practice a subsistence livelihood. In Interior Alaska, harvesters reported significant reductions in both the distance they travelled for subsistence and the number of subsistence trips they take because of high gasoline prices (Brinkman et al. 2014). Forecasts linking biophysical with socioeconomic conditions would foster holistic insights into subsistence system dynamics.

Although we asked harvesters about the impact of each separate environmental variable, we recognize that they interact. For example, the wildfire projections we used are influenced by temperature projections (Rupp et al. 2007). Many harvesters noted this and discussed the connections and interactions among the environmental variables. Venetie harvesters noted how relationships among air temperature, snow depth, wind condition, and time since fire need to be considered simultaneously to understand and explain distribution of caribou populations and access to caribou hunting areas. We speculate that development of models incorporating temporally- and spatially-explicit interactions among changing environmental variables may provide more accurate representations and estimations of hunters' perceptions of climate impacts on subsistence resource availability. Model projections of additional environmental variables are also warranted. We were unable to find and incorporate projections on river levels, water temperature, river-channel change, and river-ice breakup, all of which were variables identified by harvesters as influencing salmon availability. Forecasting and downscaling have already been identified as a critical challenge in global sustainability research (ICSU 2010), and our interviews with harvesters emphasize the need for projections at temporal and spatial resolutions meaningful at a local level.

Lastly, communities benefitted from our collaboration through enhanced local awareness of climate science and thorough documentation of important impacts to subsistence harvest practices. Our findings have been used by collaborating communities to advocate for policy changes that may assist with local adaptation to climate-related challenges. Although this study provided valuable insights, many unknowns remain with regard to the extent of climate-driven implications for subsistence communities at high latitudes. Research is inconclusive on whether subsistence needs will be met as communities respond and adapt to climate-related challenges. Research on the efficacy, spread, and limitations of rural innovations (especially for access) may help discern the potential for communities sustain harvest opportunities in the face of disturbance. Empirical investigations that systematically locate, quantify the prevalence of, and describe biophysical characteristics and mechanisms of disturbances altering access to subsistence resources are required to address critical knowledge gaps and to gauge the societal consequences of climate impacts on subsistence practices.

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