Zhou, J., G. P. Kofinas, K. Kielland, R. B. Boone, L. Prugh, and K. D. Tape. 2022. Climate change, moose, and subsistence harvest: social-ecological assessment of Nuiqsut, Alaska. Ecology and Society 27(3):29. https://doi.org/10.5751/ES-13175-270329

Research

Climate change, moose, and subsistence harvest: social-ecological assessment of Nuiqsut, Alaska

Jiake Zhou[1,2], Gary P. Kofinas[3], Knut Kielland[1,3], Randall B. Boone[4], Laura Prugh[5] and Ken D. Tape[6]

ABSTRACT. Assessing the impact of a rapidly warming climate on subsistence-based livelihoods in the Arctic is critical for building resilience for rural communities. We used a social-ecological system (SES) framework to evaluate the possible range of changes in moose abundance, distribution, and harvesting for Nuiqsut, a small native community in northern Alaska. Our results indicate that within the area used for hunting by the village, moose (*Alces alces*) abundance has been highly variable despite recent increases in tall shrubs, which provide forage and cover for moose. Projections for moose abundance also indicate continued fluctuation in the future. Our analysis shows that future increases in moose distribution under a warming climate will not be in river systems accessible to hunters by boat. Hunter access (i.e., river navigability) also may not increase under warming. The community of Nuiqsut thus offers a case study of high exposure to an expansion of moose habitat and distribution under warming, but low sensitivity to this change because of constraints on harvesting. These outcomes are not evident when evaluating social and ecological components separately, illustrating the value of an SES approach. They also provide an example in which a rapid change in an arctic landscape and subsistence resource under climate warming may not translate into altered harvest opportunities.

Key Words: *adaptive capacity; Alaska; Arctic; climate change; community resilience; moose; Nuiqsut; subsistence*

INTRODUCTION

Rapid warming in the Arctic is driving transformative changes in socioeconomic and ecological conditions (Hinzman et al. 2005, Arctic Council 2016, Pürtner et al. 2019)—including changes in subsistence harvesting—that are nutritionally and culturally important to Arctic communities (Kruse 1991, Burnsilver et al. 2016, Fall 2016, Gerlach et al. 2017). For instance, climate-related changes in environmental conditions, such as water levels, ice, snow, erosion, and wind speed all impeded subsistence travel and harvesting capacity by rural Arctic communities (Berkes and Jolly 2002, Kofinas et al. 2010, Hansen et al. 2013*b*, Brown et al. 2018, Cold et al. 2020). Although the assessment of climate change impacts on subsistence harvest is essential for building resilience in Arctic communities (Chapin et al. 2004, McDowell et al. 2016), our understanding of future harvest availability for many subsistence species is limited.

Moose (*Alces alces*) have been expanding into arctic regions of Alaska mainly due to climate-warming-induced expansion of tall shrubs (Hall 1973, Tape et al. 2016*b*). As a result, moose hunting has become a new opportunity in several high-latitude communities where it is an additional subsistence resource (Titus et al. 2009, Kofinas et al. 2010). Each harvested moose provides about 244 kg of wild game meat (Alaska Department of Fish and Game (ADF&G) 2014), and in many communities, is considered a desirable wild food. As the Arctic is predicted to warm rapidly (Overland et al. 2014, Meredith et al. 2019), moose habitat is projected to increase by more than twofold in arctic Alaska, and moose are likely to expand into drainage areas closer to many Arctic communities (Zhou et al. 2020). It is unknown, however, whether this increase in habitat and moose distribution will provide greater harvest opportunities for North Slope Iñupiat communities of Alaska.

Our objective was to assess the impact of warming on moose harvest in the hunting areas of Nuiqsut residents, an Iñupiat community on Alaska's North Slope. We used a social-ecological system (SES) framework (Walker and Salt 2006, Chapin et al. 2009, Collins et al. 2011) to evaluate the implications of a warming climate on subsistence harvest of moose. We followed Berman and Kofinas (2004) and Brinkman et al. (2013) to define availability of a subsistence resource as a combination of resource abundance, resource distribution, and hunter accessibility. Based on interviews with active moose hunters of Nuiqsut, harvest simulations using an agent-based model (Huston et al. 1988), and model projections about expected changes in interacting social and ecological components of the system, we evaluated plausible changes in moose availability. We further evaluated whether moose can serve as a potential substitution in a case of major losses in other subsistence resources under arctic warming. As moose habitat in the study area is expected to expand rapidly with warming (Zhou et al. 2020), we hypothesize that warming will likely facilitate more moose in river tributaries close to Nuiqsut, which will increase harvest opportunities, and thereby, this may be a case in which climate warming benefits local communities.

Study Area

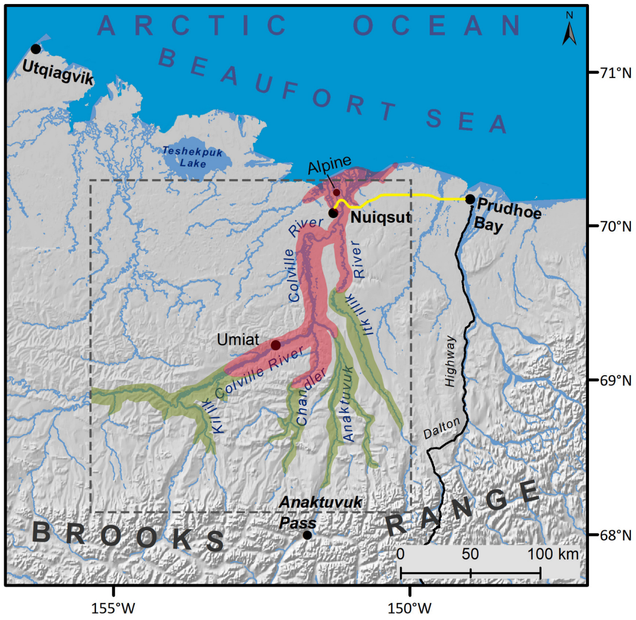
We evaluated the impact of climate change on future moose harvest by hunters of the Alaska North Slope community of Nuiqsut (Fig. 1). Nuiqsut, an Iñupiat village on the Colville River, is about 25 km from the coast of the Beaufort Sea and is accessible primarily by air. An ice road is operated in most years from January to April, running from Nuiqsut to Prudhoe Bay (approximately 100 km apart), where it connects to Dalton Highway. Nuiqsut is on the flat and treeless Arctic Coastal Plain, with a dominance of tundra tussocks, interspersed with numerous ponds, shallow lakes, and wetlands on underlying permafrost.

---

[1]Department of Biology and Wildlife, University of Alaska Fairbanks, Fairbanks, Alaska, USA, [2]College of Ecology, Lanzhou University, Lanzhou, Gansu, China, [3]Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, Alaska, USA, [4]Department of Ecosystem Science and Sustainability, Colorado State University, Fort Collins, Colorado, USA, [5]School of Environmental and Forest Sciences, University of Washington, Seattle, Washington, USA, [6]Geophysical Institute, University of Alaska Fairbanks, Fairbanks, Alaska, USA

The riparian corridors of streams and rivers in the study area host communities of plants dominated by tall shrubs such as feltleaf willow (*Salix alaxensis*) and Siberian alder (*Alnus viridis* ssp. *fruticosa*). In the riparian corridors, feltleaf willow was the tallest and most frequent shrub species. For example, Zhou et al. (2017) reported that feltleaf willow accounted for 46% of the recorded shrubs in the surveyed riparian corridors, whereas other tall shrub species were less than 12%. Patches of feltleaf willows in the riparian corridors are key habitat for moose (Mould 1977, Zhou et al. 2017). Both tall shrubs and moose are predominantly in river riparian corridors. Streams and rivers generally flow from the Brooks Range in the south to the Beaufort Sea in the north. Colville River is the longest (ca. 600 km) with the largest water volume in arctic Alaska. Moose hunting areas used by Nuiqsut harvesters are accessible by boat during August and September by traveling up the Colville River and its tributaries to tall riparian shrubs in the arctic foothills, where most moose occur (Zhou et al. 2017).

Fig. 1. Study area. The red denotes the Nuiqsut moose use area, approximated with hunter interviews and the estimation by Braund (2010). The green shows the accessible hunting areas with a scenario in which the river navigability was increased. The yellow line depicts the approximate location of the ice road. The dashed rectangle is the simulation area in the agent-based model. Umiat is an unincorporated community with only seasonal residents, serving as a camp and fuel stop for summer research activities and oil operations in the region.



Nuiqsut residents engage in a mixed subsistence-cash economy, where a majority of the residents participate in the subsistence economy (ADF&G 2014, Brubaker et al. 2014). The residents harvest a mix of terrestrial, freshwater, and marine species, including bowhead whale (*Balaena mysticetus*), white fish (*Coregonus* spp.), caribou (*Rangifer tarandus*), moose, seals (e.g., Bearded, *Erignathus barbatus* and Ribbon, *Phoca fasciata*), geese (e.g., White-fronted, *Anser albifrons*, and Canada, *Branta canadensis*), Arctic grayling (*Thymallus arcticus*), least cisco (*C. sardinella*), and burbot (*Lota lota*). The estimated per capita harvest by Nuiqsut residents in 2014 was 406 kg, where the majority was from bowhead whales, caribou, and fish (ADF&G 2014). Despite the high harvest amount, a survey report of Nuiqsut households found levels of food insecurity, with 38% not having enough healthy food and 53% sporadically experiencing insufficient food (Brubaker et al. 2014). Due to high transportation costs by air and lack of year-round road access, store-bought food in the village is expensive, highlighting the value of subsistence harvest, such as moose hunting, to food security.

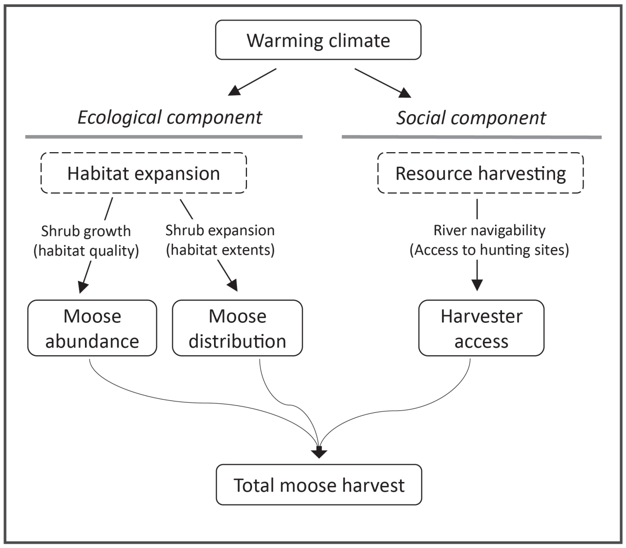
North Slope Borough (NSB) has the highest per capita income in Alaska because of cash received from taxation of oil facility infrastructure and transfer payments to residents. Under the Alaska Native Claims Settlement Act (ANCSA) in1971, Alaska Native regional corporations (e.g., Arctic Slope Regional Corporation (ASRC)) own subsurface rights, whereas local village corporations, such as Kuukpik Corporation, own the surface rights. The ASRC partially owns the Alpine oil field, 13 km north of Nuiqsut, and Kuukpik Corp. has a surface use agreement with ConocoPhillips, the Alpine oil field operator. North Slope Borough, Kuukpik Corp., and the Borough School District are the three major employers in Nuiqsut. Residents are also eligible to receive annual dividends from the Alaska Permanent Fund Dividend (PFD), ASRC, and Kuukpik Corp. Over the last decade, PFD annually provided $1,390 on average per person (https://pfd.alaska.gov/). Dividends from ASRC, for example, were approximately $7,000 in 2018 for each of 261 residents with 100 shares (http://www.north-slope.org/). Nuiqsut residents with 100 shares from Kuukpik Corp. could annually receive from $12,000 to $20,000. However, the unemployment rate is high (e.g., 23% in 2017, U.S. Census 2017 American Community Survey (ACS) 5-year Survey), and many residents own less than 100 shares of ASRC or Kuukpik Corp. stock, and some have no shares at all. Over 70% of current residents who were born after 1971 (i.e., ANCSA) can own shares only via inheritance and gifts from original shareholders or, in rare cases, issuance of new shares with approval from the existing shareholders. With increasingly more residents born after 1971, the number of residents with 100 shares is likely to decrease over time into the future. A sustainable harvest of wild foods is therefore critical to the resilience of Nuiqsut community for coping with rapid changes in the environment under future warming. Given their size, moose can provide a substantial amount of wild food (ADF&G 2014), which may enable many households with low cash income to cope with the extremely high cost of commercial food and low food security in this arctic village (Brubaker et al. 2014).

METHODS

Conceptual Model

We simulated the shrub–moose–hunter system with an agent-based model (ABM) as a social-ecological system, and assessed a plausible range of future changes in each of the key components under warming. The shrub–moose–hunter system incorporated a suite of social and ecological components (Fig. 2). The ecological component included the warming-induced expansion of tall shrub habitats, which presumably would influence moose distribution and, to some extent, moose abundance. The analysis focused on changes in key variables of moose distribution and density. The social component considered access to moose harvest areas. The analysis of access focused on changes in navigability of the rivers (i.e., access to hunting areas). Although better equipment (e.g., jet vs. propeller boats) augments accessibility and reduces time needed for travel, river navigability was assumed to be mainly affected by climate-induced hydrological changes, such as river water levels.

Fig. 2. Social-ecological system framework for assessing climate change impact on moose harvest opportunities.



Our conceptual diagram (Fig. 2) does not depict all the variables that influence moose harvest by Nuiqsut residents. For the social component, for example, the complexity of factors controlling moose harvest also includes harvesters' time for hunting, hunter expertise, the number of hunters, hunting regulations, hunting gear, and employment and other sources generating additional cash (Kruse 1991, Berman and Kofinas 2004). Rather, our conceptual diagram and model describe the main pathways through which we assumed climate change could affect key variables controlling moose harvest availability.

Collection of Empirical Data

To parametrize the model representation of the behaviors of moose harvesters and the hunting environment, we worked with the Kuukpik Subsistence Oversight Panel (KSOP) to identify and interview active moose hunters of Nuiqsut. We completed semi-structured interviews with 12 active moose harvesters in 2014. All participants were male, aged between 31 and 74, most with decades of moose hunting experience. To aid the documentation of geolocations by hunters, we used a large touch screen displaying digital maps of the region. Important georeferenced points and lines, such as hunting grounds and travel routes, were digitized on the GIS-enabled touch screen. Interview data were used to (1) set the geographic location and scope of the simulation environment and (2) parameterize and calibrate hunting routes, mode, distance, duration, and site selection in the simulation model. We digitally recorded interviews with both audio and video. Number of hunters used in the simulation model were obtained from historical data collected by the ADF&G. Our research involving human subjects was approved by the Institute Review Board at University of Alaska Fairbanks (IRB #391916). Throughout the study, we conducted numerous meetings and workshops with KSOP, the public, and the Kuukpik Corp. (the village corporation of Nuiqsut) to present and gain approval of the research plan, to give progress reports, and at the end, to share findings and receive additional feedback.

To assess the range of changes in moose abundance, we used moose aerial survey data from ADF&G during 1991–2016 (n = 26 yr) in the Game Management Unit 26A, located primarily in riparian systems of the Colville, Chandler, Anaktuvuk, Killik, and Itkillik rivers. To estimate future moose population dynamics, we used the moose counts as time series data in an auto regressive integrated moving average (ARIMA) model that seeks patterns in the data (Box et al. 2015). The model accuracy was assessed by mean absolute percentage error (MAPE). To estimate future projections in moose habitat in the study area, we adopted model outputs from Zhou et al. (2020) under A2 warming scenario of the Intergovernmental Panel on Climate Change (IPCC; Nakicenovic and Swart 2000), a business-as-usual scenario where no significant cut in global carbon emission is considered. To assess plausible changes in river navigability, we assumed water level (river discharge) was correlated with precipitation in our study area (McClelland et al. 2014). We used available data regarding monthly mean discharge rate during 2002–2021 (n = 20 yr) from the U.S. Geological Survey (USGS; https://www.usgs.gov/) and projections of future precipitation from the Scenarios Network for Alaska and Arctic Planning (SNAP), hosted at University of Alaska Fairbanks (https://www.snap.uaf.edu).

The Simulation Model

To simulate changes in moose harvest under climate warming, we built a spatially specific agent- (or individual-) based model (ABM) in the NetLogo environment (Wilensky 1999; NetLogo (https://ccl.northwestern.edu/netlogo/)). The ABM focuses on local interactions of agents with their environment to identify emergent general patterns (Huston et al. 1988, Bonabeau 2002). The simulation environment (2,016 × 2,010 km) of the Nuiqsut moose hunting area (Fig. 1) is characterized by suitable moose habitat along major rivers: Colville, Anaktuvuk, Chandler, Killik, and Itkillik rivers. The suitable habitat for this simulation was based on the tall-shrub habitat for moose estimated by our previous paper (Zhou et al. 2020), which was developed in a Maxent Model based on variables of climate and landscape structures in our study area. Each cell within the spatially specific environment has a value from 0 (non-habitat) to 1 (the best habitat for moose) of habitat suitability, calculated by the Maxent Model (Zhou et al. 2020). Individual moose are distributed on the simulation landscape in relation to habitat suitability. It is assumed that moose initially sense the habitat quality of their environment and then randomly move around within the suitable habitat. This is a density-dependent model and where moose avoid forming large groups at a single site. Although some moose in the south of Brooks Range are migratory (Joly et al. 2015), we assumed no long-distance migration in our study area.

Hunters use navigable waterways to travel from Nuiqsut to moose hunting grounds upriver (south). In interviews, moose hunters reported that they typically have access to areas within 5 km from each side of the rivers for harvesting. To simplify the simulation model, we assumed no differences in riverbank height (i.e., accessibility) on both sides of the rivers. Based on their input, we assumed that the accessibility value decreases linearly from the highest at the riverbank to the lowest at the distance of 5 km from the riverbank. If hunters encounter moose within this range, they then will hunt the moose with a probability of success, which is set during the model calibration process based on validation data from observed moose harvest. If the group harvested no moose at the selected sites, it will either continue to search in the nearby area or travel further upstream to search for moose, with a maximum of 10 d per each hunting trip. On the 10th d of hunting, hunters return to Nuiqsut even if they are unsuccessful. However, hunters can make multiple hunting trips within the duration of hunting season, from 1 August to 15 September each year. One time-step of the model corresponds to 1 d. Simulations are run for the hunting duration in each simulation year.

To consider a range of future changes in moose harvest, we used four scenarios (Table 1). The baseline scenario (H_0M_0) was based on the most recent population sizes of moose (*n* = 280) and hunters (*n* = 12) in the harvest area. The baseline scenario was calibrated with empirical data by comparing the model output of harvest amount to available historical data. We also ran scenarios with only increased moose abundance (H_0M_+), only increased number of hunters (H_+M_0), and increased hunters and moose (H_+M_+). The values for the increased scenarios were the historic maximum observed values of hunters and moose in the study area (Table 1). From the baseline, the number of hunters were increased by 233% to the historic maximum level (40 hunters). Moose were increased from a baseline density of nine moose per 1,000 km² on average to the historic maximum of 52 moose per 1,000 km² on average, with 448% increase in moose abundance. Additionally, to assess the impact of navigability (access) on moose harvest, we ran the same four scenarios with levels of current and increased navigability in the river systems. The accessible hunting area within the moose habitat was increased by 267% when hunters were allowed to travel further upstream.

Table 1. Scenario matrix in the simulation model. The number of hunters and moose is increased from current (H_0, M_0) to historical maximums (H_+, M_+) in the simulation.

		Moose abundance	
		M_0 = 280	M_+ = 1535
Number of Hunters	H_0 = 12	H_0M_0	H_0M_+
	H_+ = 40	H_+M_0	H_+M_+

To observe the model output, we recorded the number of moose harvested in each simulation year. We assumed the edible meat mass of a moose to be 244 kg (ADF&G 2014) and converted the number of harvested moose into the mass of moose harvested for Nuiqsut. The average annual total harvest over the 50 simulation years was compared with different simulation scenarios.

Scenarios of Losses in Harvested Ecosystem Services

A diversified source of accessible subsistence resources contributes to the general resilience of Arctic communities by offering choices for Indigenous communities to switch harvested species in the event of shortfalls in any specific resources (Berkes and Jolly 2002, Hansen et al. 2013*a*). The harvest intensity of a resource, therefore, depends on demand, modulated in part by availability of other subsistence resources. To assess if moose is a potential alternative resource for compensating any shortfalls in other subsistence resources, we used a simple approach to evaluate the degree of dependency of Nuiqsut on particular resources, and calculated how much moose harvest is required for substitution if that resource is lost due to a catastrophic shock to the system (e.g., Kofinas et al. 2016). We ran six scenarios, and in each scenario, we assumed the total loss of a specific resource (i.e., edible meat mass in kilograms), such as whales or caribou (Table 2). We calculated the "hypothetical loss" of each resource as a percentage (i.e., "proportional loss"), and presented it in moose equivalent amount (i.e., "moose unit," the number of moose required to replenish the same amount of meat lost in other subsistence species). For this scenario analysis, we used a comprehensive harvest data set available for 1984, 1993, and 2014 from ADF&G's Community Subsistence Information System (CSIS; http://www.adfg.alaska.gov/sb/CSIS/). This scenario analysis allowed us to consider the extent to which moose would potentially fill subsistence shortfalls with climate warming.

Table 2. Scenarios of hypothetical shortfalls in major subsistence resources expressed in the equivalent number of moose. "Total inflow" is the estimated total amount of all harvested resources that go into the Nuiqsut community. "Hypothetical loss" is the amount of shortfalls in specific resources under a hypothetical scenario, which is expressed as a percentage of the total harvested resources under "Proportional loss" and as the equivalent number of moose in "moose unit."

Year	Total inflow (kg)	Hypothetical loss (kg)	Proportional loss	In moose units
Scenario # 1 Assuming total loss in whales				
1985	72,591	3,383	5%	14
1993	121,480	34,884	29%	143
2014	168,733	67,171	40%	275
Scenario # 2 Assuming total loss in caribou				
1985	72,591	27,225	38%	112
1993	121,480	37,271	31%	153
2014	168,733	47,715	28%	196
*Scenario # 3 Assuming total loss in salmon (*Salmos salar*)*				
1985	72,591	620	0.9%	3
1993	121,480	458	0.4%	2
2014	168,733	1,764	1.0%	7
Scenario # 4 Assuming total loss in non-Salmon fish				
1985	72,591	31,408	43%	129
1993	121,480	40,588	33%	166
2014	168,733	38,604	23%	158
Scenario # 5 Assuming total loss in seals				
1985	72,591	2,010	3%	8
1993	121,480	3,769	3%	15
2014	168,733	9,652	6%	40
Scenario # 6 Assuming total loss in birds and eggs				
1985	72,591	3,645	5%	15
1993	121,480	1,962	2%	8
2014	168,733	2,203	1%	9

RESULTS

Simulation Model Results

Over the 50 simulation years, an increase in moose abundance (H_0M_+), hunter numbers (H_+M_0), or both (H_+M_+) yields increased total harvest of 165%, 80%, and 443%, respectively (Fig. 3). However, increased navigable access to the drainage systems leads to limited gains in total harvest (Fig. 3). When hunting access is increased by allowing hunters to travel further upstream, for example, the total harvest amount is increased by only 17% (i.e., 151 kg) in the H_0M_0 scenario.

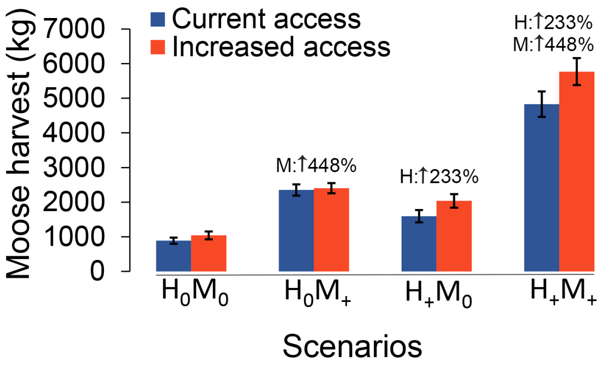


Fig. 3. Simulated harvests with changes in the number of hunters, hunting access, and moose distribution and abundance. Increasing access has limited impact on moose harvest. Y-axis shows the moose harvest amount (kg). X-axis shows four scenarios with current (blue) and increased (orange) river navigable access. "H_0M_0" is the baseline scenario with the recent number of hunters (H) and moose (M). In the "H_0M_+" scenario, only moose abundance is increased to the historical maximum. "H_+M_0" is the scenario with only the number of hunters increased to the historical maximum. In the "H_+M_+" scenario, both hunter number and moose abundance are increased to their historical maximums. The percentage increases in H and M were shown on top of the bars.

Projected Moose Distribution, Abundance, and Harvest Access

Moose habitat is predicted to more than double by year 2099 in arctic Alaska (Zhou et al. 2020). However, juxtaposing the spatial patterns of moose distribution and the navigable river systems reveals that the expected gains in the spatial extent of moose habitat under climate warming will likely occur in predominantly riparian areas along rivers and streams that are not navigable for Nuiqsut residents (Fig. 4). Within the accessible hunting drainage systems, no significant increases in the spatial extent of tall-shrub habitats are expected, where tall shrubs are not likely to expand from riparian areas onto the non-riparian tundra areas (Tape et al. 2012, Zhou et al. 2020).

Based on past patterns of moose population dynamics within the hunting area, the ARIMA model (accuracy = 78%) predicted an increase to 374 (±76) moose on average in 2030, albeit with wide confidence intervals (Fig. 5). Nonetheless, the ARIMA model prediction and the projected increase in moose habitat under future warming (Zhou et al. 2020) both indicate that moose abundance will likely increase in the near future, but with high uncertainty.

For harvest access, we found no clear trends in river discharge (as an indicator for water level) in August and September during 2002–2020 (Fig. 6A1, A2). Colville River discharge patterns indicate that boat access to inland moose hunting areas has not increased during 2002–2014, which was confirmed by moose hunters interviewed for this study in 2014. Over the 7 yr after our 2014 interviews, river discharge continuously showed no clear trends (Fig. 6A1, A2). For long-term trends in the future given the observed relations between discharge and precipitation (Fig. 6A, B), however, no significant increase in precipitation is predicted in the months of August and September when moose hunting occurs (SNAP n.d.) (Fig. 6C).

Scenarios of Losses in Subsistence Resources

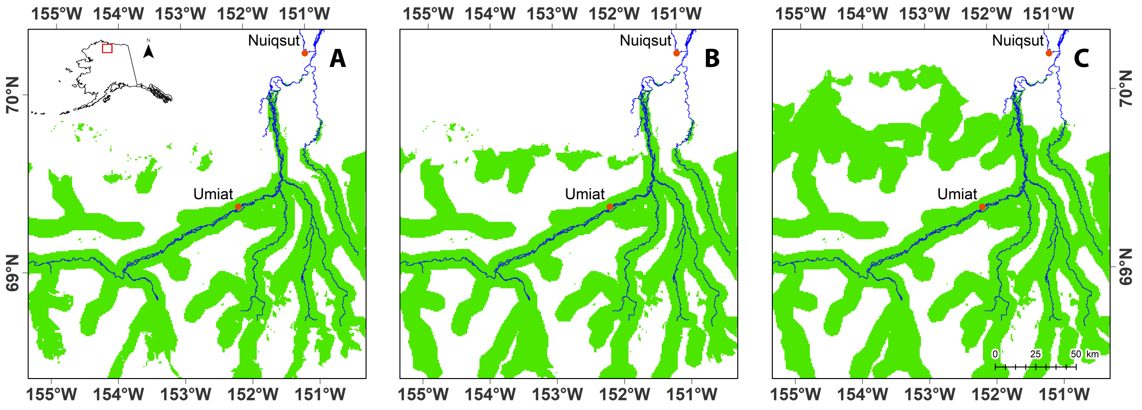
Nuiqsut is primarily a whaling and caribou hunting community as reflected in harvest data showing a high dependence on whales (e.g., 40% of total inflow in 2014), caribou (28% of total inflow in 2014), and fish (24% of total inflow in 2014). Table 2 shows the amount of moose harvest required for compensating any hypothetical losses in these major subsistence resources. In Scenario #1, for example, if any catastrophic disruptions resulted in a total loss of whale harvest (67,171 kg) in 2014, Nuiqsut would require 275 additional moose to maintain the same level of subsistence inflow to the community (Table 2). For a total loss in caribou harvest, Nuiqsut would require 196 additional moose. The current level of harvest inflow to Nuiqsut is less than five moose per year. Our simulation model also shows that with the scenario of historical maximum levels of 1,535 moose and 40 hunters with increased navigability, the harvest system can only provide a total harvest of about 24 (± 2) moose per year on average. Even with the expected habitat expansion for moose under arctic warming, moose harvest in the near future will not likely meet the potential demand in case of hypothetical losses.

DISCUSSION

The accelerating warming in the Arctic may impact the distribution and abundance of subsistence resources, as well as access to the resource by local harvesters. Using a social-ecological system (SES) framework (Chapin et al. 2009), we have evaluated the impact of warming-induced expansion of tall shrubs on future moose harvest for Nuiqsut in Alaska's high Arctic. Adequately describing the full set of variables influencing the complexity of moose harvest availability is beyond the scope of this paper. However, given the plausible range of changes considered in our analysis, we projected that arctic warming, mediated via changes in tall-shrub habitat, is unlikely to increase subsistence moose harvest. Hence, the case of projected changes in moose harvesting in Nuiqsut serves as an example in which rapid landscape change and resultant expansion in resource distribution do not translate into increased harvest.

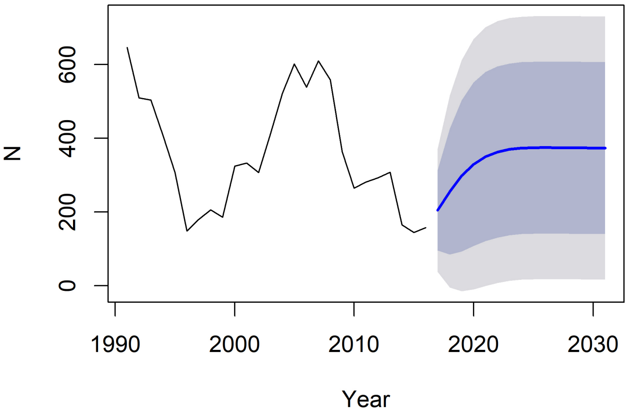
Our findings reveal that the expected rapid expansion in moose habitat in our study area (Zhou et al. 2020) will likely occur predominantly in the arctic drainage systems that are mostly inaccessible to hunters by boat. Without increases in moose distribution in currently accessible areas and with no additional gains in harvest access to areas expected to have expanding moose habitats, the primary control on harvest by Nuiqsut residents, therefore, appears to be moose abundance, for which there is a high uncertainty in the trends in the future. Furthermore, even if harvest access is increased by traveling further upstream, the

Fig. 4. Expansion patterns of moose habitat. The green area depicts moose habitat under IPCC A2 warming scenario in 2020s (A), 2050s (B), and 2090s (C), adopted from Zhou et al. (2020). The blue lines represent the major waterways potentially used by moose hunters. The red dots show the locations of Nuiqsut and Umiat. Moose hunters from Nuiqsut can currently reach Umiat on the Colville River and similar distances in other major drainage areas.



additional return in harvest may be limited. Currently, hunters already have access to the best habitats where most moose occur. The riparian corridors higher up in the Brooks Range are suboptimal habitats with lower abundance of tall shrubs (Zhou et al. 2017). Increased access to these poor habitat areas leads to diminishing returns in harvest amount per unit effort.

Fig. 5. Prediction of moose in the study area. The blue line represents the mean moose number estimated by an ARIMA model. The gray and light blue areas show the 95% and 80% confidence intervals, respectively.

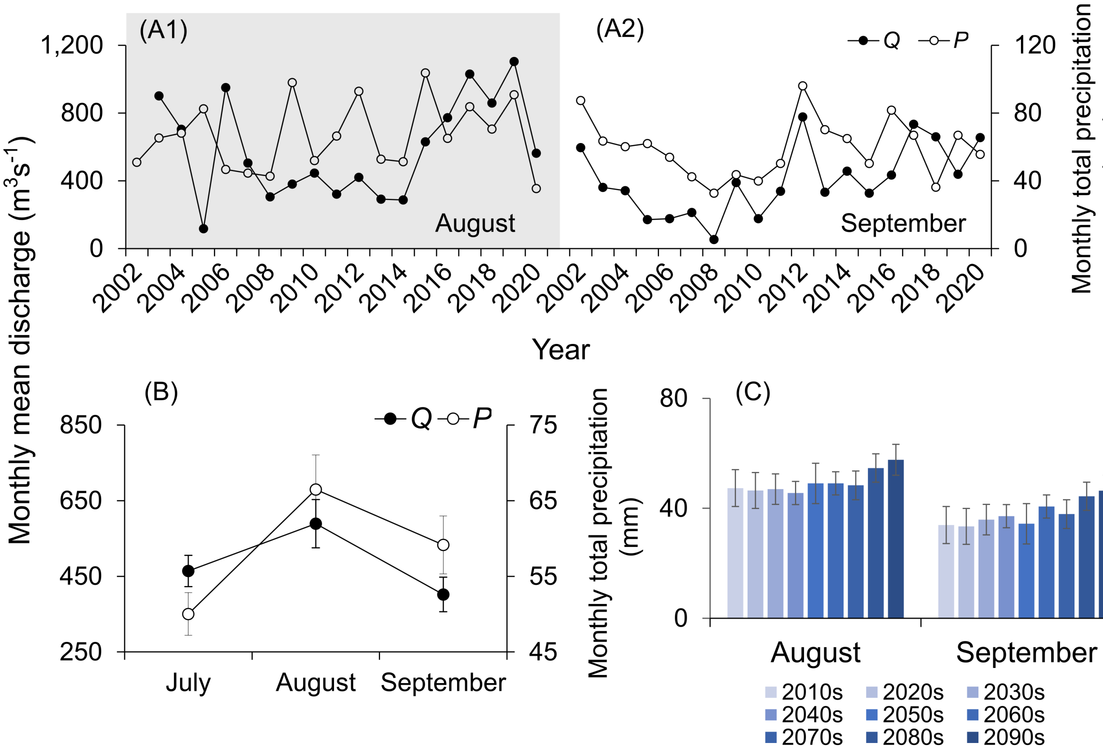


We recognize that climate change is not the only factor that exerts direct controls on moose abundance. The moose population in our study area has fluctuated since 1970, and even declined in recent years, despite the recent shrub expansion (Klimstra and Dagget 2020). Non-climatic variables can strongly influence moose abundance, such as predation (Peterson et al. 1984, Gasaway et al. 1992, McLaren and Peterson 1994, Messier 1994), disease (Forbes et al. 1996, Nymo et al. 2016), parasitism (Jones et al. 2019), malnutrition (Kubota et al. 1970, O'Hara et al. 2001, Wam et al. 2018), density-dependent effects (Seaton et al. 2011), and resource competition possibly by snowshoe hares (*Lepus americanus*; Dodds 1960, Belovsky 1984, Zhou et al. 2017).

The aforementioned factors may also influence moose abundance synergistically with warming (Weiskopf et al. 2019). For instance, climate warming may also affect predation and resource competition. Local warming may influence brown bear (*Ursus arctos*) fitness in the study area via altering local resource availability (Hilderbrand et al. 2019), which in turn plausibly changes predation on moose. Warming-induced shrub expansion may also affect resource competition by facilitating range expansion into the Arctic by other shrub-dependent species (Tape et al. 2016*a*, Zhou et al. 2017). The most influential variable on future harvest (i.e., moose abundance) (Fig. 3) is therefore also the least predictable using climate projections. Future studies that identify primary drivers of changes in moose population in this rapidly changing region are thus critical for understanding and managing moose abundance and harvest opportunities.

The application of a SES framework highlights the importance of analyzing spatial patterns of resource distribution and harvest access for assessing climate change impacts on harvest availability (Brinkman et al. 2013, Brown et al. 2015), which is consistent with concerns expressed by Alaska Native communities (Berman and Kofinas 2004, Arctic Council 2016, Brinkman et al. 2016, Christie et al. 2018, Meredith et al. 2019). Without considering the social component of hunting access, assessment of climate change impacts on subsistence resources can be misleading and confounding (Gerlach et al. 2017). Hunters from Nuiqsut exclusively use the Colville River and its tributaries for autumn moose hunting, which controls where and when hunters have access. Without enhanced navigable routes and assuming no significant change in gear, hunters cannot access other drainage systems where warming-induced habitat expansion for moose will likely occur (Zhou et al. 2020). Our simulation results further highlight the significance of where on the landscape hunters have access (Berman and Kofinas 2004, Johnson et al. 2016). For

Fig. 6. Colville River discharge and precipitation during the hunting season. (A) Trends in the observed monthly mean discharge (Q) and estimated monthly total precipitation (P) in (A1) August and (A2) September during 2002–2020. (B) Mean Q and P with standard errors (error bars) for July, August, and September during 2002–2021. (C) Predicted decadal mean precipitation with standard errors (error bars) in August and September under PICC A2 warming scenario. Q (m^3s^{-1}) was measured at Umiat USGS station (https://www.usgs.gov/), and P (mm) was estimated in the basin area of Colville River above Umiat, based on data from SNAP (https://www.snap.uaf.edu).



example, hunters currently travel 233 km on average for a moose hunting trip, with a reported expenditure of 231 L of gasoline per trip (= $305). Traveling to poor habitat at further distances is costly (Brinkman et al. 2014) and has diminishing returns in harvest.

Our analysis, however, suggests that boat access will not likely increase during the hunting season in the near future given the historical patterns of river water levels and future projections of precipitation in the watershed. River basins in the moose hunting area lack substantial glaciers, and watershed runoff is therefore not likely to increase with warming (McClelland et al. 2014, Rawlins et al. 2019). The expected delay in freeze-up (Magnuson et al. 2000) would presumably prolong boat access, but during the interviews, hunters said that river levels were often too low for boating by the end of August and early September. Data from the USGS Gauge support their observations. Other unknown factors, such as changes in river channeling and erosion, may also affect navigability at certain sites (Walker and Hudson 2003, Payne et al. 2018, Stephani et al. 2020), but data describing long-term trends across large areas of the North Slope are not available.

Adopting alternative modes of gaining access, such as snowmobiles, all-terrain vehicles, or new forms of overland travel, and changes in regulations (e.g., spring hunting) may enable Nuiqsut moose hunters to capitalize on increased moose distribution in drainage areas that are relatively close to the village, particularly to the west of Colville drainages (Fig. 4C). However, the future trajectory of moose abundance under warming in the Nuiqsut hunting area is far from certain. Arctic warming is also making the tundra travel more dangerous and unreliable (Brubaker et al. 2014, Ford et al. 2019, Meredith et al. 2019).

The moose harvest in Nuiqsut also directly depends on the number of hunters participating each year (Fig. 3). The historical patterns of moose hunters showed a steady decline (Append. 1: Fig. A1.1A). If we assume the village population influences the total number of hunters participating in moose harvest, then the Nuiqsut population remains stable and based on the in- and out-migration patterns, there is no indication for an increase in hunters (Append. 1: Fig. A1.1B). These patterns indicate that the number of moose hunters will not likely increase in the near future. On the other hand, the motivation to hunt moose and the number of hunters may increase if demand for moose increases in scenarios in which the availability of other key subsistence species significantly decreases.

Due to the constrained access to river systems by boat, we showed that future warming on the North Slope will not likely allow moose to compensate for any possible major losses in other subsistence resources in a rapidly changing Arctic (Hinzman et al. 2005, Kittel et al. 2011, Meredith et al. 2019). The amount of moose harvest that the subsistence system can provide to Nuiqsut is vastly inadequate for meeting the potential shortfalls. Our scenario analysis of possible shortfalls in resources, however, did not consider how intercommunity sharing of subsistence foods may compensate for potential short-term shortfalls in subsistence harvest, as is evidenced elsewhere on the North Slope (Kofinas et al. 2016). Sharing of food, gear, and labor are intrinsic components of Iñupiat culture, and a critical source of resilience and adaptive capacity (Wenzel 2000, Berkes and Jolly 2002, Ford et al. 2006, Baggio et al. 2016, Burnsilver et al. 2016, Fawcett et al. 2018). In Nuiqsut, the ADF&G's CSIS report (ADF&G 2014) estimated that 91.4% of community households gave away harvested foods, and 96.6% received harvested resources in 2014.

In the past, expanding moose populations provided an important source of subsistence food in the northern communities (Wolfe and Walker 1987, Titus et al. 2009, Kofinas et al. 2010). To reduce vulnerability in subsistence food security with a warming climate in the future, managers should focus on increasing moose harvest opportunities in accessible areas to increase the reliability of moose as a subsistence food source for the Nuiqsut community, particularly when shortages and uncertainties arise in other subsistence species (Brinkman et al. 2007, Kofinas et al. 2010, 2016).

As noted, the response of moose abundance to future warming will not be linear. The complexity of biotic and abiotic factors influencing moose abundance under warming inevitably introduces high uncertainty in projecting moose population trends in our study area. To reduce uncertainty in assessing moose abundance trends and to increase hunting opportunities, managers could take some immediate actions to increase our understanding of moose population dynamics under the expected future warming in the study area. First, managers should increase efforts to monitor and evaluate potential resource competition by snowshoe hares and its impact on moose abundance (Tape et al. 2016*a*, Zhou et al. 2017). Second, there is an urgent need to conduct surveys on predators such as wolves (*Canis lupus*) and brown bears and to assess their predation impact on moose abundance (Klimstra and Dagget 2020). Finally, surveying on the quality and quantity of shrub forage in the moose habitat is necessary to assess the relationship between forage resource and moose density under future warming.

Another means of increasing hunting capacity and access is the increase in cash income. In the context of moose hunting, cash is needed to buy gear (boats, tents, rifles, freezers) and gas, which are essential to subsistence moose production. As noted, oil revenue is the main source of cash input to the community, the future trends of which are influenced by policy decisions and market fluctuation beyond the control of North Slope communities. Additionally, because it potentially reduces the stock value and voting power of existing shareholders, issuance of new shares is often less likely to occur. However, Kuukpik Corp. recently voted to issue 50 new shares to direct descendants of original shareholders. With younger residents with increased shares, harvest capacity by Nuiqsut may increase (Kruse 1991).

Although a SES framework may be idiosyncratic and ad hoc when used to address context-specific problems, the general approach is essential for assessing harvest resilience under climate warming (Chapin et al. 2009). We demonstrated that using a SES framework for assessing climate change impacts on subsistence harvest led to a different conclusion than would have arisen by evaluating changes in social and ecosystem components separately (Chapin et al. 2006, Liu et al. 2007). When considering how both social and ecological factors influence harvest opportunity, our analyses show that the community of Nuiqsut is likely to experience a case of high exposure to an expansion of moose habitat and distribution under warming, but low sensitivity to this change because these ecological changes are unlikely to translate into greater harvest of moose. These findings highlight the importance of employing integrated and interdisciplinary approaches for providing a holistic understanding (Berman and Kofinas 2004, Berman et al. 2004, Kruse et al. 2004, Chapin et al. 2009, Euskirchen et al. 2020) when assessing future impact of climate change on ecosystem services (Meredith et al. 2019).

Responses to this article can be read online at:
https://www.ecologyandsociety.org/issues/responses.php/13175

Acknowledgments:

We thank the community of Nuiqsut and KSOP, particularly moose hunters for sharing their critical knowledge and making this study possible. We also thank Naomi O'Neal for her essential help on conducting the hunter interviews. Financial support during the study includes the Liz Claiborne and Art Ortenberg Foundation, UAF dissertation completion fellowship, UAF Jessie O'Bryan McIntosh Scholarship, Alaska EPSCoR NSF award #OIA-1757348, and the state of Alaska, National Socio-Environmental Synthesis Center (SESYNC), ARCUS, and National Climate Adaptation Science Center. Alaska EPSCoR NSF award # OIA-1208927 and NSF Award # 1263854 to G.P.K, and NSF award #1833056 to K.D.T.

Data Availability:

The data/code that support the findings of this study are openly available in "figshare" at https://doi.org/10.6084/m9.figshare.14443694 https://doi.org/10.6084/m9.figshare.14443373 https://doi.org/10.6084/m9.figshare.14443376 https://doi.org/10.6084/m9.figshare.14443505. Ethical approval for this research study was granted by University of Alaska Fairbanks Institute Review Board (#391916).

LITERATURE CITED

Alaska Department of Fish and Game (ADF&G). 2014. Alaska Department of Fish and Game's community subsistence information system. Alaska Department of Fish and Game, Anchorage, Alaska, USA. URL: http://www.adfg.alaska.gov/sb/CSIS/

Arctic Council. 2016. Arctic resilience report. Page 1-218 in M. Carson and G. Peterson, editors. Stockholm Environment Institute and Stockholm Resilience Centre, Stockholm, Sweden.

Baggio, J. A., S. B. BurnSilver, A. Arenas, J. S. Magdanz, G. P. Kofinas, and M. De Domenico. 2016. Multiplex social ecological network analysis reveals how social changes affect community robustness more than resource depletion. Proceedings of the National Academy of Sciences 113(48):13708-13713. https://doi.org/10.1073/pnas.1604401113

Belovsky, G. E. 1984. Moose and snowshoe hare competition and a mechanistic explanation from foraging theory. Oecologia 61 (2):150-159. https://doi.org/10.1007/BF00396753

Berkes, F., and D. Jolly. 2002. Adapting to climate change: social-ecological resilience in a Canadian western Arctic community. Ecology and Society 5(2): 18. https://doi.org/10.5751/ES-00342-050218

Berman, M., and G. Kofinas. 2004. Hunting for models: grounded and rational choice approaches to analyzing climate effects on subsistence hunting in an Arctic community. Ecological Economics 49(1):31-46. https://doi.org/10.1016/j.ecolecon.2003.12.005

Berman, M., C. Nicolson, G. Kofinas, J. O. E. Tetlichi, and S. Martin. 2004. Adaptation and sustainability in a small Arctic community: results of an agent-based simulation model. Arctic 57(4):401-414. https://doi.org/10.14430/arctic517

Bonabeau, E. 2002. Agent-based modeling: methods and techniques for simulating human systems. Proceedings of the National Academy of Sciences 99(3):7280-7287. https://doi.org/10.1073/pnas.082080899

Box, G. E. P., G. M. Jenkins, G. C. Reinsel, and G. M. Ljung. 2015. Time series analysis: forecasting and control. Fifth edition. Wiley, Hoboken, New Jersey, USA.

Braund, S. R. 2010. Subsistence mapping of Nuiqsut, Kaktovik, and Barrow. Report prepared for the Minerals Management Service Alaska OCS Region, U.S. Department of Interior. Stephen R Braund and Associates, Anchorage, Alaska, USA.

Brinkman, T. J., W. D. Hansen, F. S. Chapin, G. Kofinas, S. BurnSilver, and T. S. Rupp. 2016. Arctic communities perceive climate impacts on access as a critical challenge to availability of subsistence resources. Climatic Change 139(3-4):413-427. https://doi.org/10.1007/s10584-016-1819-6

Brinkman, T. J., G. Kofinas, W. D. Hansen, F. S. Chapin, III, and S. Rupp. 2013. A new framework to manage hunting: why we should shift focus from abundance to availability. The Wildlife Professional 7(3):38-43.

Brinkman, T., J. Kelly, M. Vandyke, A. Firmin, and A. Springsteen. 2014. Impact of fuel costs on high-latitude subsistence activities. Ecology and Society 19(4): 18. https://doi.org/10.5751/ES-06861-190418

Brinkman, T., G. Kofinas, F. S. Chapin, and D. Person. 2007. Influence of hunter adaptability on resilience of subsistence hunting systems. Journal of Ecological Anthropology 11 (1):58-63. https://doi.org/10.5038/2162-4593.11.1.4

Brown, C. L., K. A. Seaton, T. J. Brinkman, E. S. Euskirchen, and K. Kielland. 2015. Applications of resilience theory in management of a moose-hunter system in Alaska. Ecology and Society 20(1): 16. https://doi.org/10.5751/ES-07202-200116

Brown, D. R. N., T. J. Brinkman, D. L. Verbyla, C. L. Brown, H. S. Cold, and T. N. Hollingsworth. 2018. Changing river ice seasonality and impacts on interior Alaskan communities. Weather, Climate, and Society 10(4):625-640. https://doi.org/10.1175/WCAS-D-17-0101.1

Brubaker, M., J. Bell, H. Dingman, M. Itta, and K. Kasak. 2014. Climate change in Nuiqsut , Alaska, strategies for community health. Alaska Native Tribal Health Consortium (ANTHC), Anchorage, Alaska, USA. URL: https://anthc.org/wp-content/uploads/2016/01/CCH_AR_072014_Climate-Change-in-Nuiqsut.pdf

Burnsilver, S., J. Magdanz, R. Stotts, M. Berman, and G. Kofinas. 2016. Are mixed economies persistent or transitional? Evidence using social networks from Arctic Alaska. American Anthropologist 118(1):121-129. https://doi.org/10.1111/aman.12447

Chapin, F. S., M. Hoel, S. R. Carpenter, J. Lubchenco, B. Walker, T. V Callaghan, C. Folke, S. A. Levin, K.-G. Mäler, C. Nilsson, S. Barrett, F. Berkes, A.-S. Crépin, K. Danell, T. Rosswall, D. Starrett, A. Xepapadeas, and S. A. Zimov. 2006. Building resilience and adaptation to manage Arctic change. AMBIO 35 (4):198-202. https://doi.org/10.1579/0044-7447(2006)35[198:BRAATM]2.0.CO;2

Chapin, F. S., G. P. Kofinas, and C. Folke, editors. 2009. Principles of ecosystem stewardship: resilience-based natural resource management in a changing world. Springer-Verlag, New York, New York, USA. https://doi.org/10.1007/978-0-387-73033-2

Chapin, F. S., G. Peterson, F. Berkes, T. V. Callaghan, P. Angelstam, M. Apps, C. Beier, Y. Bergeron, A.-S. Crepin, K. Danell, T. Elmqvist, C. Folke, B. Forbes, N. Fresco, G. Juday, J. Niemela, A. Shvidenko, and G. Whiteman. 2004. Resilience and vulnerability of northern regions to social and environmental change. AMBIO 33(6):344-349. https://doi.org/10.1579/0044-7447-33.6.344

Christie, K. S., T. E. Hollmen, H. P. Huntington, and J. R. Lovvorn. 2018. Structured decision analysis informed by traditional ecological knowledge as a tool to strengthen subsistence systems in a changing Arctic. Ecology and Society 23 (4): 42. https://doi.org/10.5751/ES-10596-230442

Cold, H. S., T. J. Brinkman, C. L. Brown, T. N. Hollingsworth, D. R. N. Brown, and K. M. Heeringa. 2020. Assessing vulnerability of subsistence travel to effects of environmental change in Interior Alaska. Ecology and Society 25(1): 20. https://doi.org/10.5751/ES-11426-250120

Collins, S. L., S. R. Carpenter, S. M. Swinton, D. E. Orenstein, D. L. Childers, T. L. Gragson, N. B. Grimm, J. M. Grove, S. L. Harlan, J. P. Kaye, A. K. Knapp, G. P. Kofinas, J. J. Magnuson, W. H. McDowell, J. M. Melack, L. A. Ogden, G. P. Robertson, M. D. Smith, and A. C. Whitmer. 2011. An integrated conceptual framework for long-term social-ecological research. Frontiers in Ecology and the Environment 9(6):351-357. https://doi.org/10.1890/100068

Dodds, D. G. 1960. Food competition and range relationships of moose and snowshoe hare in Newfoundland. The Journal of Mammalogy 24(1):52-60. https://doi.org/10.2307/3797356

Euskirchen, E. S., K. Timm, A. L. Breen, S. Gray, T. S. Rupp, P. Martin, J. H. Reynolds, A. Sesser, K. Murphy, J. S. Littell, A. Bennett, W. R. Bolton, T. Carman, H. Genet, B. Griffith, T. Kurkowski, M. J. Lara, S. Marchenko, D. Nicolsky, S. Panda, V. Romanovsky, R. Rutter, C. L. Tucker, and A. D. McGuire. 2020. Co-producing knowledge: the integrated ecosystem model for resource management in Arctic Alaska. Frontiers in Ecology and the Environment 18(8):447-455. https://doi.org/10.1002/fee.2176

Fall, J. A. 2016. Regional patterns of fish and wildlife harvests in contemporary Alaska. Arctic 69(1):47-64. https://doi.org/10.14430/arctic4547

Fawcett, D., T. Pearce, R. Notaina, J. D. Ford, and P. Collings. 2018. Inuit adaptability to changing environmental conditions over an 11-year period in Ulukhaktok , Northwest Territories. Polar Record 54(2):119-132. https://doi.org/10.1017/S003224741800027X

Forbes, L. B., S. V. Tessaro, and W. Lees. 1996. Experimental studies on *Brucella abortus* in Moose (*Alces alces*). Journal of Wildlife Diseases 32(1):94-104. https://doi.org/10.7589/0090-3558-32.1.94

Ford, J. D., D. Clark, T. Pearce, L. Berrang-Ford, L. Copland, J. Dawson, M. New, and S. L. Harper. 2019. Changing access to ice, land and water in Arctic communities. Nature Climate Change 9 (4):335-339. https://doi.org/10.1038/s41558-019-0435-7

Ford, J. D., B. Smit, and J. Wandel. 2006. Vulnerability to climate change in the Arctic: a case study from Arctic Bay, Canada. Global Environmental Change 16(2):145-160. https://doi.org/10.1016/j.gloenvcha.2005.11.007

Gasaway, W. C., R. D. Boertje, D. V. Grangaard, G. David, R. O. Stephenson, and D. G. Larsen. 1992. The role of predation in limiting moose at low density in Alaska and Yukon and implications for conservation. Wildlife Monographs 120:3-59.

Gerlach, S. C., P. A. Loring, G. Kofinas, and H. Penn. 2017. Resilience to rapid change in Bering, Beaufort, and Chukchi Sea communities. Pages 153-171 in L. D. Hinzman, P. Outridge, A. Klepikov, J. E. Walsh, M. Ananicheva, T. Armstrong, J. Bengtson, G. Flato, S. C. Gerlach, H. P. Huntington, G. Kofinas, P. Loring, A. L. Lovecraft, L. Eerkes-Medrano, E. Nikitina, B. L. Preston, S. F. Trainor, J. Gamble, and L. Thorsteinson, editors. Adaptation actions for a changing Arctic: perspectives from the Bering/Chukchi/Beaufort Region. Technical report, Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. https://doi.org/10.2172/1435018

Hall, E. S. Jr. 1973. Archaeological and recent evidence for expansion of moose range in northern Alaska. Journal of Mammology 54(1):294-295. https://doi.org/10.2307/1378902

Hansen, W. D., T. J. Brinkman, F. S. Chapin, and C. Brown. 2013a. Meeting indigenous subsistence needs: the case for prey switching in rural Alaska. Human Dimensions of Wildlife 18(2):109-123. https://doi.org/10.1080/10871209.2012.719172

Hansen, W. D., T. J. Brinkman, M. Leonawicz, F. S. Chapin, and G. P. Kofinas. 2013b. Changing daily wind speeds on Alaska's North Slope: implications for rural hunting opportunities. Arctic 66(4):448-458. https://doi.org/10.14430/arctic4331

Hilderbrand, G. V., K. Joly, M. S. Sorum, M. D. Cameron, and D. D. Gustine. 2019. Brown bear (*Ursus arctos*) body size, condition, and productivity in the Arctic, 1977–2016. Polar Biology 42(6):1125-1130. https://doi.org/10.1007/s00300-019-02501-8

Hinzman, L. D., N. D. Bettez, W. R. Bolton, F. S. Chapin, M. B. Dyurgerov, C. L. Fastie, B. Griffith, R. D. Hollister, A. Hope, H. P. Huntington, A. M. Jensen, G. J. Jia, T. Jorgenson, D. L. Kane, D. R. Klein, G. Kofinas, A. H. Lynch, A. H. Lloyd, A. D. McGuire, F. E. Nelson, W. C. Oechel, T. E. Osterkamp, C. H. Racine, V. E. Romanovsky, R. S. Stone, D. A. Stow, M. Sturm, C. E. Tweedie, G. L. Vourlitis, M. D. Walker, D. A. Walker, P. J. Webber, J. M. Welker, K. S. Winker, and K. Yoshikawa. 2005. Evidence and implications of recent climate change in northern Alaska and other Arctic regions. Climatic Change 72(3):251-298. https://doi.org/10.1007/s10584-005-5352-2

Huston, M., D. DeAngelis, and W. Post. 1988. New computer models unify ecological theory. Bioscience 38(10):682-691. https://doi.org/10.2307/1310870

Johnson, I., T. Brinkman, K. Britton, J. Kelly, K. Hundertmark, B. Lake, and D. Verbyla. 2016. Quantifying rural hunter access in Alaska. Human Dimensions of Wildlife 21(3):240-253. https://doi.org/10.1080/10871209.2016.1137109

Joly, K., T. Craig, M. S. Sorum, J. S. Mcmillan, and M. A. Spindler. 2015. Moose movement patterns in the Upper Koyukuk River drainage, Northcenteral Alaska. Alces 51:87-96.

Jones, H., P. Pekins, L. Kantar, I. Sidor, D. Ellingwood, A. Lichtenwalner, and M. O'neal. 2019. Mortality assessment of moose (*Alces alces*) calves during successive years of winter tick (*Dermacentor albipictus*) epizootics in New Hampshire and Maine (USA). Canadian Journal of Zoology 97(1):22-30. https://doi.org/10.1139/cjz-2018-0140

Kittel, T. G. F., B. B. Baker, J. V. Higgins, and J. C. Haney. 2011. Climate vulnerability of ecosystems and landscapes on Alaska's North Slope. Regional Environmental Change 11(SUPPL. 1):249-264. https://doi.org/10.1007/s10113-010-0180-y

Klimstra, R., and C. T. Dagget. 2020. Moose management report and plan, Game Management Unit 26A: report period 1 July 2010–30 June 2015, and plan period 1 July 2015–30 June 2020. Species Management Report and Plan ADF&G/DWC/SMR&P-2020-9, Alaska Department of Fish and Game, Juneau, Alaska, USA.

Kofinas, G., S. B. Burnsilver, J. Magdanz, R. Stotts, and M. Okada. 2016. Subsistence sharing networks and cooperation: Kaktovik, Wainwright, and Venetie, Alaska. BOEM Report 2015-023DOI; AFES Report MP 2015-02. School of Natural Resources and Extension, University of Alaska Fairbanks, Alaska, USA.

Kofinas, G. P., F. S. Chapin, S. BurnSilver, J. I. Schmidt, N. L. Fresco, K. Kielland, S. Martin, A. Springsteen, and T. S. Rupp. 2010. Resilience of Athabascan subsistence systems to interior Alaska's changing climate. Canadian Journal of Forest Research 40(7):1347-1359. https://doi.org/10.1139/X10-108

Kruse, J. A. 1991. Alaska Inupiat subsistence and wage employment patterns: understanding individual choice. Human Organization 50(4):317-326. https://doi.org/10.17730/humo.50.4.c288gt2641286g71

Kruse, J. A., R. G. White, H. E. Epstein, B. Archie, M. Berman, S. R. Braund, F. S. Chapin, J. Charlie, C. J. Daniel, J. Eamer, N. Flanders, B. Griffith, S. Haley, L. Huskey, B. Joseph, D. R. Klein, G. P. Kofinas, S. M. Martin, S. M. Murphy, W. Nebesky, C. Nicolson, D. E. Russell, J. Tetlichi, A. Tussing, M. D. Walker, and O. R. Young. 2004. Modeling sustainability of Arctic communities: an interdisciplinary collaboration of researchers and local knowledge holders. Ecosystems 7(8):815-828. https://doi.org/10.1007/s10021-004-0008-z

Kubota, J., S. Rieger, and V. A. Lazar. 1970. Mineral composition of herbage browsed by moose in Alaska. The Journal of Wildlife Management 34(3):565-569. https://doi.org/10.2307/3798864

Liu, J., T. Dietz, S. R. Carpenter, M. Alberti, C. Folke, E. Moran, A. N. Pell, P. Deadman, T. Kratz, J. Lubchenco, E. Ostrom, Z. Ouyang, W. Provencher, C. L. Redman, S. H. Schneider, and W. W. Taylor. 2007. Complexity of coupled human and natural systems. Science 317(5844):1513-1516. https://doi.org/10.1126/science.1144004

Magnuson, J. J., D. M. Robertson, B. J. Benson, R. H. Wynne, D. M. Livingstone, T. Arai, R. A. Assel, R. G. Barry, V. Card, E. Kuusisto, N. G. Granin, T. D. Prowse, K. M. Stewart, and V. S. Vuglinski. 2000. historical trends in lake and river ice cover in the northern hemisphere. Science 289(5485):1743-1746. https://doi.org/10.1126/science.289.5485.1743

McClelland, J. W., A. Townsend-Small, R. M. Holmes, F. Pan, M. Stieglitz, M. Khosh, and B. J. Peterson. 2014. River export of nutrients and organic matter from the North Slope of Alaska to the Beaufort Sea. Water Resources Research 50(2):1823-1839. https://doi.org/10.1002/2013WR014722

McDowell, G., J. Ford, and J. Jones. 2016. Community-level climate change vulnerability research: trends, progress, and future directions. Environmental Research Letters 11(3):033001. https://doi.org/10.1088/1748-9326/11/3/033001

McLaren, B. E., and R. O. Peterson. 1994. Wolves, moose, and tree rings on Isle Royale. Science 266(5190):1555-1558. https://doi.org/10.1126/science.266.5190.1555

Meredith, M., M. Sommerkorn, S. Cassotta, C. Derksen, A. Ekaykin, A. Hollowed, P. Kofinas, A. Mackintosh, J. Melbourne-Thomas, M. M. C. Muelbert, G. Ottersen, H. Pritchard, and E. A. G. Schuur. 2019. Polar regions. Pages 203-320 in H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Oken, J. Petzold, B. Rama, and N. M. Weyer, editors. The ocean and cryosphere in a changing climate: a special report of the Intergovernmental Panel on Climate Change (IPCC). IPCC, Geneva, Switzerland.

Messier, F. 1994. Ungulate population models with predation: a case study with the North American moose. Ecology 75(2):478-488. https://doi.org/10.2307/1939551

Mould, E. D. 1977. Movement patterns of moose in the Colville River area, Alaska. Thesis, University of Alaska, Fairbanks, Alaska, USA.

Nakicenovic, N., and R. Swart, editors. 2000. Emissions scenarios. Special report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK.

Nymo, I. H., K. Beckmen, and J. Godfroid. 2016. Anti-*Brucella* antibodies in moose (*Alces alces gigas*), muskoxen (*Ovibos moschatus*), and Plains bison (*Bison bison bison*) in Alaska, USA. Journal of Wildlife Diseases 52(1):96-99. https://doi.org/10.7589/2015-04-100

O'Hara, T. M., G. Carroll, P. Barboza, K. Mueller, J. Blake, V. Woshner, and C. Willetto. 2001. Mineral and heavy metal status as related to a mortality event and poor recruitment in a moose population in Alaska. Journal of Wildlife Diseases 37(3):509-522. https://doi.org/10.7589/0090-3558-37.3.509

Overland, J. E., M. Wang, J. E. Walsh, and J. C. Stroeve. 2014. Future Arctic climate changes: adaptation and mitigation time scales. Earth's Future 2(2):68-74. https://doi.org/10.1002/2013EF000162

Payne, C., S. Panda, and A. Prakash. 2018. Remote sensing of river erosion on the Colville River, North Slope Alaska. Remote Sensing 10(3):397. https://doi.org/10.3390/rs10030397

Peterson, R. O., R. E. Page, and K. M. Dodge. 1984. Wolves, moose, and the allometry of population cycles. Science 224(4655):1350-1352. https://doi.org/10.1126/science.224.4655.1350

Pürtner, H.-O., D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegriía, M. Nicolai, A. Okem, J. Petzold, B. Rama, and N. M. Weyer, editors. 2019. The ocean and cryosphere in a changing climate: a special report of the Intergovernmental Panel on Climate Change (IPCC). IPCC, Geneva, Switzerland.

Rawlins, M. A., L. Cai, S. L. Stuefer, and D. Nicolsky. 2019. Changing characteristics of runoff and freshwater export from watersheds draining northern Alaska. The Cryosphere 13(12):3337-3352. https://doi.org/10.5194/tc-13-3337-2019

Scenarios Network for Alaska and Arctic Planning (SNAP). (n. d.) Decadal summaries of precipitation for Alaska in A2 warming scenario. SNAP, International Arctic Research Center, University of Alaska, Fairbanks, Alaska, USA. URL: https://www.snap.uaf.edu/data

Seaton, C. T., T. F. Paragi, R. D. Boertje, K. Kielland, S. DuBois, and C. L. Fleener. 2011. Browse biomass removal and nutritional condition of moose *Alces alces*. Wildlife Biology 17(1):55-66. https://doi.org/10.2981/10-010

Stephani, E., J. Drage, D. Miller, B. M. Jones, and M. Kanevskiy. 2020. Taliks, cryopegs, and permafrost dynamics related to channel migration, Colville River Delta , Alaska. Permafrost and Periglacial Processses 31(2):239-254. https://doi.org/10.1002/ppp.2046

Tape, K. D., K. Christie, G. Carroll, and J. A. O'Donnell. 2016a. Novel wildlife in the Arctic: the influence of changing riparian ecosystems and shrub habitat expansion on snowshoe hares. Global Change Biology 22(1):208-219. https://doi.org/10.1111/gcb.13058

Tape, K. D., D. D. Gustine, R. W. Ruess, L. G. Adams, and J. A. Clark. 2016b. Range expansion of moose in Arctic Alaska linked to warming and increased shrub habitat. PLoS One 11(4): e0152636. https://doi.org/10.1371/journal.pone.0152636

Tape, K. D., M. Hallinger, J. M. Welker, and R. W. Ruess. 2012. Landscape heterogeneity of shrub expansion in Arctic Alaska. Ecosystems 15(5):711-724. https://doi.org/10.1007/s10021-012-9540-4

Titus, K., T. L. Haynes, and T. F. Paragi. 2009. The importance of moose, caribou, deer and small game in the diets of Alaskans. Pages 137-143 in R. T. Watson, M. Fuller, M. Pokras, and W. G. Hunt, editors. Ingestion of lead from spent ammunition: implications for wildlife and humans. The Peregrine Fund, Boise, Idaho, USA. https://doi.org/10.4080/ilsa.2009.0312

Walker, B., and D. Salt. 2006. Resilience thinking: sustaining ecosystems and people in a changing world. Island Press, Washington, D.C., USA.

Walker, H. J., and P. F. Hudson. 2003. Hydrologic and geomorphic processes in the Colville River delta, Alaska. Geomorphology 56 (3-4):291-303. https://doi.org/10.1016/S0169-555X(03)00157-0

Wam, H. K., A. M. Felton, C. Stolter, L. Nybakken, and O. Hjeljord. 2018. Moose selecting for specific nutritional composition of birch places limits on food acceptability. Ecology and Evolution 8(2):1117-1130. https://doi.org/10.1002/ece3.3715

Weiskopf, S. R., O. E. Ledee, and L. M. Thompson. 2019. Climate change effects on deer and moose in the Midwest. The Journal of Wildlife Management 83(4):769-781. https://doi.org/10.1002/jwmg.21649

Wenzel, G. W. 2000. Sharing, money, and modern Inuit subsistence-obligation and reciprocity at Clyde River, Nunavut. Senri ethnological Studies 53:61-85.

Wilensky, U. 1999. NetLogo (and NetLogo user manual). Center for Connected Learning and Computer-based Modeling, Northwestern University, Evanston, Illinois, USA.

Wolfe, R. J., and R. J. Walker. 1987. Subsistence Economies in Alaska: productivity, geography, and development impacts. Arctic Anthropology 24(2):56-81.

Zhou, J., L. Prugh, K. D. Tape, G. Kofinas, and K. Kielland. 2017. The role of vegetation structure in controlling distributions of vertebrate herbivores in Arctic Alaska. Arctic, Antarctic, and Alpine Research 49(2):291-304. https://doi.org/10.1657/AAAR0016-058

Zhou, J., K. D. Tape, L. Prugh, G. Kofinas, G. Carroll, and K. Kielland. 2020. Enhanced shrub growth in the Arctic increases habitat connectivity for browsing herbivores. Global Change Biology 26(7):3809-3820. https://doi.org/10.1111/gcb.15104

Appendix 1. Supplemental information on trends in hunter numbers on North Slope of Alaska.

Figure A1.1. Historical number of North Slope resident hunters and Permanent Fund Dividend (PFD) applicants from Nuiqsut. (A) North Slope resident hunters. Open circle denotes total hunters and filled circle represents successful hunters from North Slope community. The data were adopted from ADF&G. (B) Number of successful applicants for Alaska's PFD with an address in Nuiqsut village, as a potential indicator for in- and out-migration. Source: data compiled by Nuiqsut Comprehensive Development Plan, available at http://www.north-slope.org.