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Co-production of knowledge reveals loss of Indigenous hunting opportunities in the face of accelerating Arctic climate change

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Abstract

Profound sea ice loss is rapidly transforming coupled social-ecological Arctic marine systems. However, explicit impacts to harvesting of traditional resources for coastal Indigenous communities remain largely unquantified, particularly where the primary research questions are posed by the Indigenous community as a result of emerging approaches such as knowledge co-production. Here, we directly link reduced sea ice coverage to decreasing harvesting opportunities for ugruk (bearded seal, *Erignathus barbatus*) as a component of a partnership among a multidisciplinary team of scientists, Indigenous Elder Advisory Council, and sovereign Indigenous tribe in northwest Alaska, USA. We collaboratively established research questions, coordinated data collection, and interpreted results to understand the causes and consequences of changing ugruk harvests for the community of Qikiqtaġruk (Kotzebue). The duration of spring ugruk hunts by the Qikiqtaġruŋmiut declined significantly during 2003–2019 due to a shift (∼3 weeks earlier) in the timing of regional sea ice breakup. Harvests now cease ∼26 d earlier than in the past decade. Using historical sea ice records, we further demonstrate that ice coverage in May now resembles conditions that were common in July during the mid-20th century. Overall, we show that climate change is constraining hunting opportunities for this traditional marine resource, although Qikiqtaġruŋmiut hunters have so far been able to offset a shortened season with changes in effort. Notwithstanding recent hunting success in unprecedentedly sparse ice conditions, accessibility to traditional resources remains a prominent concern for many Arctic communities. Management and policy decisions related to Arctic marine mammal resources, such as ugruk, are therefore also interwoven with food security, well-being, and culture of Indigenous communities. Hence, research that originates with Indigenous sovereignty over the entire research process, such as demonstrated here, has the potential to also lead to more inclusive, sustainable, and equitable outcomes in the face of rapid and accelerating Arctic change.

1. Introduction

The circumpolar Arctic is the ancestral home of Inuit people whose traditional way of life is linked to the marine ecosystem through multi-generational and holistic knowledge systems of environmental conditions (ICC-Alaska 2016, 2020, Rapinski *et al* 2018, Watt-Cloutier 2018). The Arctic is also experiencing some of the most profound environmental and ecosystem shifts associated with climate change on Earth

(Post *et al* 2019), threatening the very food security and sovereignty of the people most dependent upon intact sea ice ecosystems (Watt-Cloutier 2018). Marine mammals are fundamental to the transforming Arctic social-ecological seascape, serving multiple functional roles as nutritional, spiritual, and cultural resources (Jensen *et al* 2009) as well endemic and sentinel species uniquely adapted to sea ice environments (Laidre *et al* 2015). Although the responses and resilience of Arctic marine mammals to climate change vary among species and populations, changes in migration, health, population size, or distribution associated with sea ice loss underscore the sensitivity of these species to climate change (Moore and Reeves 2018).

The collective consequences of climate change are presumed to be negative for both Arctic marine mammals and the Indigenous people who hunt them (Hovelsrud *et al* 2008, Berner *et al* 2016). Climate-driven impacts to marine mammal populations broadly translate to changes in the quality and availability of traditional marine resources due to the reliance of many of these species on sea ice for critical life history stages and foraging, with potential implications to Inuit hunters of AK, Chukotka (Russia), Canada, and Greenland (ICC-Alaska 2016). Sea ice changes additionally impact access to traditional resources, since it is the platform upon which many harvesting activities as well as the animals rely (Krupnik and Jolly 2002, Hovelsrud and Smit 2010, Druckenmiller *et al* 2013). Substantial broad-scale transformations are already underway in many Arctic regions, revealing a cascading set of potential consequences for social-ecological systems and Indigenous hunters, such as shifts in hunting seasonality (Huntington *et al* 2020). In the Pacific Arctic, access to marine mammals, in addition to safety on sea ice, is widely perceived by Yup'ik and Iñupiaq communities of Inuit Alaska as the more immediate threat to subsistence harvesting, compared to biological changes in species distribution or abundance (Brinkman *et al* 2016, Huntington *et al* 2016). Ultimately, the loss of harvesting opportunities for traditional resources represents a critical threat to multifaceted and interrelated aspects of Indigenous food security and well-being (Hicks *et al* 2016, ICC-Alaska 2016, Breslow *et al* 2017) since Indigenous food security is holistic and can reflect dynamic relationships of ecological health, cultural preservation, and decision-making power (Heeringa *et al* 2019). In turn, food security is intimately linked through culture, history, and policy to recent movements to respect and assert Indigenous food sovereignty and resilience (Jäger *et al* 2019, ICC-Alaska 2020).

While changing environmental conditions, such as wind and weather patterns, have been shown to affect marine mammal hunting opportunities (Hansen *et al* 2013, Huntington *et al* 2013, Fox *et al* 2020), the ability to directly quantify climate-driven consequences for Arctic marine mammal Indigenous hunters has remained elusive (Huntington 2019). There are limited long-term records of Inuit harvest success in the scientific literature, and Indigenous Knowledge systems have typically not been valued on the same level as western science (Raymond-Yakoubian and Daniel 2018), even though weaving Indigenous and scientific perspectives can lead to new insights about marine mammals in particular and changing Arctic marine ecosystems in general (Moore and Hauser 2019). Increasingly, understanding and responding to transforming social-ecological Arctic systems requires engaging Indigenous communities as equitable partners in research relevant to the resources and environment upon which they rely and intimately know (Lynch and Brunner 2007, Johnson *et al* 2016, Robards *et al* 2018, Wheeler *et al* 2020).

Here, we present an example of a research program that provides a novel view into the direct impacts of Arctic climate change on Indigenous hunters, by taking a co-production of knowledge approach led by the Indigenous community itself. We quantify how sea ice loss has contributed to decreased access to a critical marine resource by Indigenous hunters by focusing on the spring hunting season for ugruk, or bearded seal (*Erignathus barbatus*), relative to sea ice changes in the Kotzebue Sound region of northwest Alaska in the Pacific Arctic during the past 17 years (figure 1). Ugruk are closely associated with broken ice in spring as they move into the Chukchi Sea, relying on ice floes as a platform for pupping, resting, and molting and many capitalizing on the rich foraging grounds in the shallow Kotzebue Sound (Cameron *et al* 2018). Qikiqtaġruŋmiut, the Iñupiaq people who have been living on the coast of Kotzebue Sound for thousands of years, rely on ugruk more than any other marine resource and harvest hundreds annually during the sea ice breakup period (Whiting 2006). The majority of the meat is cut into strips and dried, while the oil rendered from the blubber is a treasured condiment to be eaten throughout the year (figure 1). Overall, ugruk are a critical resource for the Qikiqtaġruŋmiut, embodying the local Iñupiaq harvesting practices and shared values (Green *et al* 2020).

What environmental factors affect the changing ugruk hunting season in Kotzebue Sound? This research question emerged from a collaborative partnership titled the Ikaaġvik Sikukun project ('ice bridge' in Iñupiaq) that adopted an Indigenous-led co-production of knowledge practice. Our knowledge co-production model elevates equity among partners as the overarching theme (Behe and Daniel 2018, Behe *et al* 2019), shifting the power dynamic to the local sovereign Tribal government from more scientist-driven or extractive approaches that have been practiced with Indigenous collaborators historically (David-Chavez and Gavin 2018, Latulippe and Klenk 2020). Partners included an Indigenous Elder

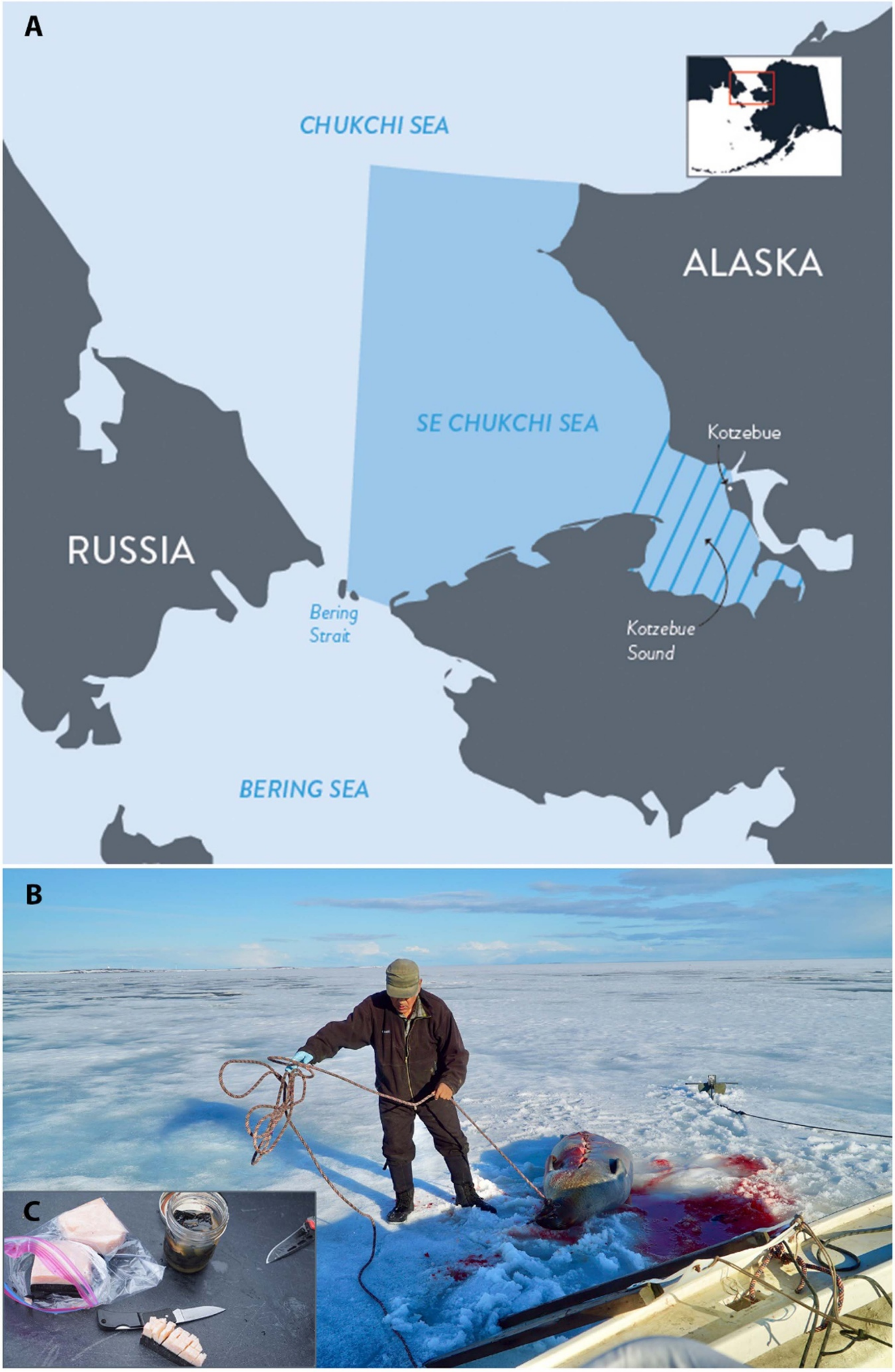

Figure 1. The Chukchi Sea and Kotzebue Sound study area of ugruk hunting by the Qikiqtaġruŋmiut people. (A) Map of the study area, including southeast Chukchi Sea, Kotzebue Sound region, and Iñupiaq community of Kotzebue (Qikiqtaġruk) in Northwest Arctic Alaska, USA. (B) Elder Advisor Roswell (Qalayauq) Schaeffer, Sr stands on an ice floe with a harvested ugruk on 13 May 2019, which was the earliest date he has ever harvested an ugruk. (C) Traditional marine foods consumed in Kotzebue, including dried ugruk strips stored in a jar of processed ugruk oil. Photos by Sarah Betcher, Farthest North Films.

Advisory Council, Indigenous Tribal Environmental Program, and multidisciplinary team of scientists. Through an iterative process centered on the Indigenous Knowledge of the Elder Advisory Council, we developed a research program to understand the environmental factors affecting the Qikiqtaġruŋmiut ugruk hunting season to: (a) quantify changes in the duration of the harvest season; (b) identify and examine changes in sea ice conditions that affect ugruk and ugruk hunters through a combination of local Indigenous Knowledge and remotely-sensed sea ice data; and (c) understand how hunters have responded to shifting harvest seasons and conditions.

2. Methods

2.1. Case study environmental and cultural context

Kotzebue Sound is a large, shallow embayment encompassing just over 90 000 km^2 and averaging 12–16 m in depth. Straddling the Arctic Circle, it is located in the Southeast corner of the Chukchi Sea just north of Bering Strait and is characterized as an estuarine body due to the significant freshwater input from four major rivers (the Noatak, Kobuk, Selawik and Buckland Rivers), in addition to many smaller streams of water that flow into it around its entire borderlands. Sea ice forms and melts seasonally in Kotzebue Sound, which until recently was typically occupied by continuous shorefast ice for up to 5 months of the year (Mahoney *et al* 2014). Being the only major estuarine embayment on the Alaska side north of the Bering Strait, Kotzebue Sound provides a unique feeding, breeding, and molting habitat for marine mammals.

The Native Village of Kotzebue is one of 229 Federally-recognized Tribes in AK, operating as the sovereign government of the Qikiqtaġruŋmiut who are the original inhabitants of the northeast area of Kotzebue Sound surrounding modern-day Kotzebue (Qikiqtaġruk). Recognizing their inherent sovereignty, the Native Village of Kotzebue governs and maintains jurisdiction over its ∼3000 citizens and focuses all activities on a set of Iñupiaq values centered on collaboration, respect, and sharing. The Tribe's Environmental Program recognizes, advocates for, facilitates and leads scientific inquiries to ensure that Tribal priorities and Indigenous Knowledge are equitably integrated into the discussions, decisions, and processes carried out by researchers and agencies in the region.

Marine mammals have always played a central role in the daily lives and yearly subsistence activities of the Qikiqtaġruŋmiut and much of their history and culture revolves around them (Whiting 2006, Green *et al* 2020). Human existence in this part of the world would have been extremely difficult, if not impossible, without the calories, nutrients, heat from burning rendered oil, and material goods that marine mammals provide (Jensen *et al* 2009). Even today with the connectivity to modern conveniences, goods, and services, marine mammals continue to play a critical cultural, spiritual, and nutritional role in the everyday lives of the Qikiqtaġruŋmiut (Whiting 2006).

2.2. Defining our co-production of knowledge approach

Recently growing in popularity, research co-produced among scientists and 'user' groups affected by climate change has taken many forms (Bremer and Meisch 2017) and often involves iterative, in-person, and joint assessment of research goals, methodology and desired products, and resulting scientific products (Beier *et al* 2017). Increasingly, Indigenous organizations are also exerting their own agency in collaborative research by asserting Indigenous sovereignty and jurisdiction to generate data that is rooted in Indigenous stewardship and worldviews (Wilson *et al* 2018), thereby raising equity as a guiding concept of co-production research with Indigenous people (Raymond-Yakoubian and Raymond-Yakoubian 2017, Behe and Daniel 2018, Behe *et al* 2019). To establish a research partnership among a local Indigenous Elder Advisory Council, the Tribal Environmental Program, and multidisciplinary team of scientists (i.e. physical and biological oceanographers, sea ice geophysicists, marine biologists, and an ethnographic filmmaker), we adopted an Indigenous-led co-production of knowledge practice (Behe and Daniel 2018, Behe *et al* 2019) tailored to the northwest Alaska coastal community of Kotzebue. Ultimately, our co-production process joined classically-trained scientists, Indigenous Knowledge holders, and the Tribal government in an effort to avoid extractive or prescriptive science (Latulippe and Klenk 2020) while also recognizing that the community itself is best positioned to determine their science needs (Lynch and Brunner 2007). Our co-production process was particularly centered on meaningful and active engagement according to Native Village of Kotzebue Council Tribal Resolution 16–70 (supplementary appendix 1 (available online at stacks.iop.org/ERL/16/095003/mmedia)), which permitted Tribal collaboration with scientists and emphasized Tribal self-determination to develop research responsive to the 'needs and desires of the Native Village of Kotzebue'. Tribal resolution 16–70 supported our project's effort to strengthen the 'capacity of the Tribe and its members to participate in field research, including integrating [I]ndigenous [K]nowledge into the research goals and findings'.

For this case study, co-production of Indigenous and scientific knowledge involved multiple and repeated meetings of the full transdisciplinary team in Kotzebue throughout 2017–2021, which was critical for building trust among our team, engaged communication and interpretation of our research products, and required that the full team (i.e. scientists and Tribal representatives) be accountable to the community. The Native Village of Kotzebue Tribal Council and Environmental Program identified four Qikiqtaġruŋmiut Elders to compose our Elder Advisory Council for the Ikaaġvik Sikukun project who embodied the values and knowledge needed to inform the subject matter (cryosphere and marine mammals) being investigated. Each member of our full team committed to collaboratively participating in the process of establishing research questions (years 1 and 2), coordinating data collection (years 2 and 3), interpretation (years 3 and 4) and communication of results (continuous throughout with the Native Village of Kotzebue, years 3–5 with the scientific community). We committed to the inclusion of our full team, including our Tribal Principal Investigator (A V P) and Elder Advisory Council (J G, C H, R J S, R S Sr), in the academic peer review process of our research products (e.g. Loseto *et al* 2020) as well as in scientific presentations. We also prioritized sharing research results back with the community of Kotzebue (e.g. in person, at the high school, and via bi-annual newsletters mailed to each post office boxholder), and specifically sharing results in Kotzebue before other academic arenas. Only the broad research area (i.e. understanding changes in the spring sea ice breakup period in Kotzebue Sound) was determined in advance, and all other details, including specific research questions and topics of study, were decided upon as part of the collaborative co-production process.

Understanding changes in the ugruk harvest period emerged as one out of six total overarching research questions focused on the spring breakup period. Three sources of information were combined in this analysis: (a) records of ugruk hunting activity during spring harvest periods from 2003 to 2019; (b) Indigenous Knowledge shared by our Elder Advisory Council about the sea ice conditions affecting ugruk and harvest activities; and (c) historical and satellite data of sea ice coverage.

2.3. Combining harvest records, Indigenous Knowledge, and sea ice data to understand changes in ugruk hunting periods

We developed a unique time-series of an Indigenous harvest period for an Arctic marine mammal species, specifically ugruk in this case. Starting in the summer of 2002, the Environmental Program Director (A V W) for the Native Village of Kotzebue began to make weekly observations of the local weather, traveling conditions, fish and wildlife activity, and the related hunting and fishing pursuits of the people of Kotzebue. This included noting when the spring ugruk hunting season commenced. The start date of the harvest period documented each year represented the initial effort to search for seals to harvest, which commences on the 1st day of every spring when boats are able to travel out into Kotzebue Sound from Kotzebue through the ice floes. The hunting season was recorded as concluded when the last ugruk of the year were taken or when people were no longer able to find ugruk. We calculated harvest duration as the difference in number of days between hunting season commencement and end date. Additional factors, such as weather, ocean, and sea ice conditions were also recorded each week as well as aspects of hunter effort to successfully harvest enough seals for local needs.

To understand Indigenous Knowledge of ugruk and the sea ice factors affecting ugruk harvests, we used iterative informal conversations and formal semi-directive interviews (Huntington 1998) with our Elder Advisory Council (J G, C H, R J S, R S Sr). Our discussions occurred in a diversity of settings and arrangements between scientists and Elders, including one on one conversations of the science team with a single Elder or small group meetings. Our meetings initially occurred at the Native Village of Kotzebue conference room, but follow-up meetings also included gatherings to share food and stories, conversations on the landfast sea ice during our field activities to address additional research questions (see Mahoney *et al* 2021, Witte *et al* 2021). The full team would meet daily over several multi-day or multi-week visits to Kotzebue each year, as well as maintain regular virtual meetings and email correspondence when not in person.

During our initial meetings, we co-established what suite of factors govern ugruk accessibility and availability during spring hunting. This included the period during which Kotzebue Sound is initially accessible by boat during ice breakup, as well as when ugruk are present (table S1). We then assembled time-series of break-up dates from sea ice satellite imagery as proxies for each of the factors identified by the Elder Advisory Council to inform our understanding of the environmental factors affecting changes in the ugruk hunting season.

2.4. Historical changes in sea ice cover

Our Elder Advisory Council relied on their local and Indigenous Knowledge to suggest that there had been rapid and accelerating loss of sea ice cover within the Kotzebue Sound region during the past >100 years of their and their recent ancestors' memory. The historical sea ice atlas (HSIA; http://seaiceatlas.snap.uaf.edu/) is the only dataset of which we are aware that is capable of quantifying sea ice conditions over a comparable period of time, and we used it to evaluate the long-term changes in seasonal sea ice coverage within the region. The HSIA is a gridded dataset of monthly average sea ice concentration data based on the Sea Ice Back to 1850 dataset (Walsh *et al* 2017). With a resolution of 0.25°, it provides a spatially complete record of fractional coverage of sea ice in the waters around AK going back to 1850. The dataset currently extends to December 2018. Here, we use data beginning in 1953, coinciding with the advent of routine charting of sea ice by the US Naval Oceanographic Office. After September 1979, the dataset is primarily based on daily data from passive microwave satellites. For each month and year, we calculated the average ice concentration for the grid cells lying within a polygon defining the southeastern Chukchi Sea (figure 1).

2.5. Identification of sea ice break-up dates from visible-band satellite imagery

Visible-band satellite imagery offer a straightforward means to observe the annual process by which sea ice in a region breaks-up and transitions to a state of open water (e.g. Dey *et al* 1979, Vincent and Marsden 2001, Fraser *et al* 2010, Kwok 2014). Due to the high reflectance contrast between ice and open water, any opening in the sea ice wider than the pixel size of an image can be routinely identified in a cloud-free image (Key *et al* 1993). Similarly, any ice floe larger than a pixel can also be detected. In this study, we used moderate resolution imaging spectrometer (MODIS) imagery with a pixel resolution of 250 m. Data sources with higher spatial resolution may have allowed for the detection of smaller openings and ice floes, but such imagery are not typically available on a daily basis.

MODIS data have been widely used for observing sea ice (e.g. Drüe and Heinemann 2004, Rösel *et al* 2012, Willmes and Heinemann 2015), but they were first introduced into this study by a member of our Elder Advisory Council (R J S), who uses the imagery to learn where there might be accessible sea ice for hunting bearded seals. Following this suggestion from our Elder Advisor, we acquired daily true color corrected reflectance imagery for the period from 2003–2019 through NASA's Global Imagery Browse Services in order to quantify the day of year (DOY) associated with four recognizable events during the annual break-up process that correspond to different stages in the ugruk hunting season (table S1, figure S1).

The 1st break-up event corresponds to the appearance of km-scale leads and openings that create conditions conducive for ugruk to enter Kotzebue Sound and is taken to be a proxy for when seals may first be available in Kotzebue Sound. A distinct circular feature often opens ahead of the channel opening that defines the 2nd break-up event, which is visible on MODIS images and can be used by hunters to anticipate and prepare for the hunt. The 2nd event is defined by the opening a roughly 600 m wide channel through the landfast ice in front of town, which allows hunters to launch their boats (see figure S1). The 3rd event is marked by an absence of ice in the region identified as the inner sound (figure S1), which signifies the end of a period when ugruk might be found relatively close to Kotzebue. Lastly, the 4th break-up event is marked by an absence of detectable ice anywhere in Kotzebue Sound. Seals that remain in Kotzebue Sound at this time would only be 'swimmers' and therefore not targeted by hunters.

The 250 m resolution of the MODIS imagery used in this study readily allows identification of all the features of the ice cover that define these four break-up events. Isolated floes smaller than 250 m may be missed in the MODIS imagery, but such floes do not represent an ideal hunting environment and the presence of such ice is unlikely to extend the hunting season. Hence, based on iterative discussions with members of our Elder Advisory Council, we are confident that MODIS imagery are appropriate for the purpose of identifying ice conditions relevant for ugruk hunting.

For each spring during the period 2003–2019, three independent observers (D D W H, A S, C R W) visually inspected each daily MODIS image to identify the DOY for each event, which were used as covariates in the statistical analysis described below. In the case of days when cloud cover obscured the image, each observer used the date of the 1st cloud-free image in which the criteria for each event were met. Pairwise Pearson correlation tests shows the dates of each event were significantly correlated among observers (figure S2). This demonstrated our method was not sensitive to observer subjectivity and so we used median dates for each proxy variable in all subsequent analyses.

2.6. Statistical analysis

We quantified trends in harvest duration (number of days from hunt start to end), hunt start date, and hunt end date over 2003–2019 using generalized linear models (GLMs). Harvest duration was modeled with a Poisson error structure, while GLMs of annual trends in the hunt start and end dates applied a gamma error structure. We also used GLMs to identify the proxy variables associated with each harvest response variable, applying the same error structures as used for trend quantification. We used stepwise model selection to establish final proxy variables that best explained each harvest response, based on the lowest Akaike's Information Criteria value (Zuur *et al* 2009) (table S2). In each case, statistical significance was assessed using a critical value of $P < 0.05$. All statistical analyses were conducted in base packages of R (R Core Development Team 2020), and final model fit and validation of assumptions were assessed by investigating patterns in residuals, *Q–Q* plots, and leverage of residuals.

3. Results

3.1. Tribal records: quantifying changes in harvest periods

Over the past 17 years, the duration of the spring ugruk hunting season for the Qikiqtaġruŋmiut significantly decreased at a rate of nearly a day per year (figure 2; $P = 0.001$). The start date of hunting

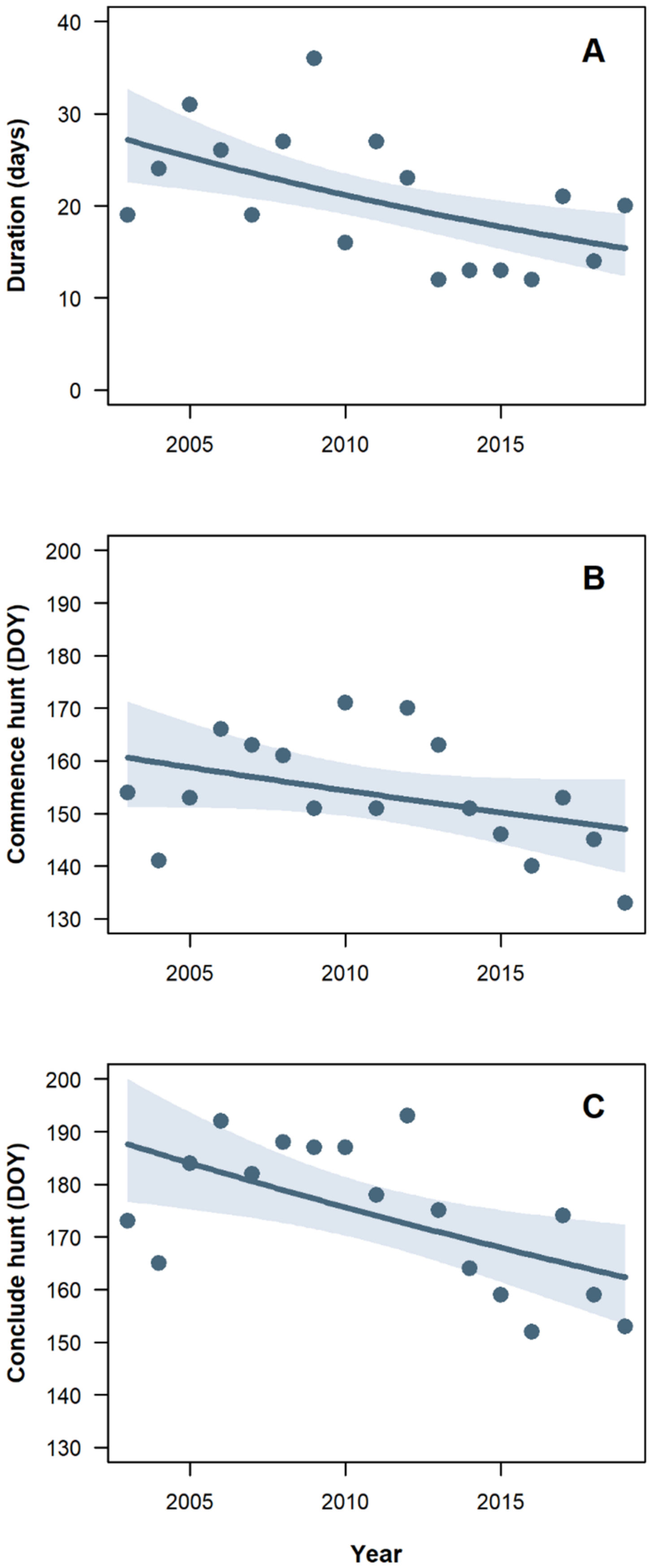

Figure 2. Observed and model fits of duration and timing of spring ugruk harvests during 2003–2019, based on (A) the number of elapsed days for hunting, (B) the DOY when hunting commenced, and (C) the DOY when hunting concluded each year. Start and end dates were recorded along with weekly descriptive observations of the local weather, traveling conditions, fish and wildlife activity and the related hunting and fishing pursuits of the Qikiqtaġruŋmiut. Shading corresponds to the 95% confidence intervals.

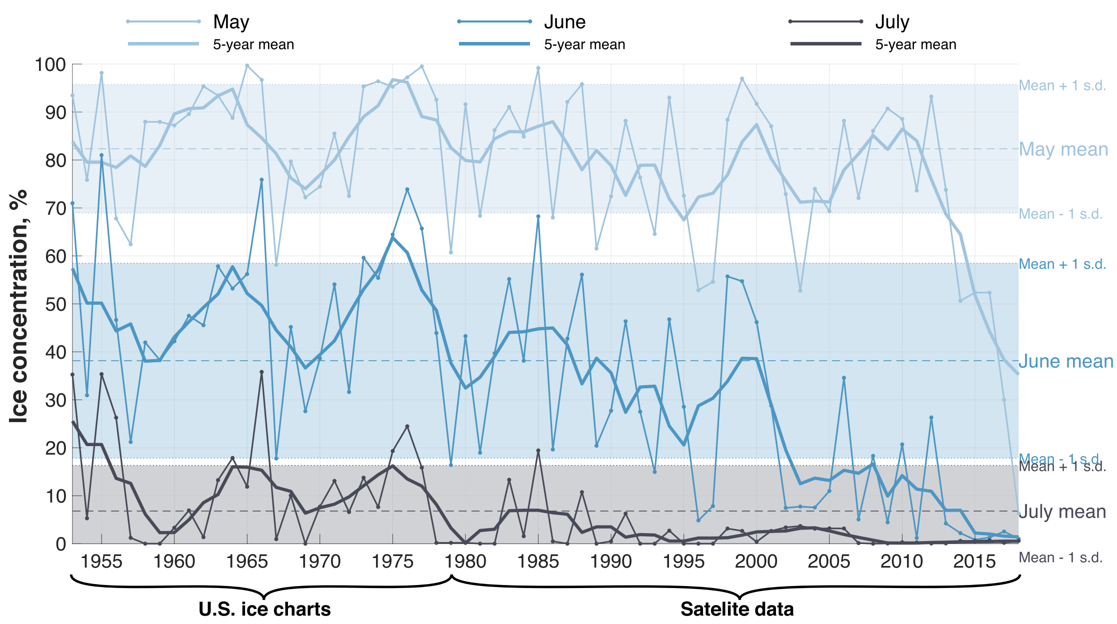

Figure 3. May–July monthly mean sea ice concentration, based on the southeast Chukchi Sea region (see figure 1). The shaded regions indicate one standard deviation around the mean ice concentration for the time period for each month. Historic data pre-1980 is based on US ice charts while 1980–2018 are based on satellite data (see section 2).

shifted earlier, but a significant trend was not detected ($P = 0.119$). In contrast, the end date has become significantly earlier ($P = 0.014$), revealing that the overall decrease in hunting duration is spurred by hunts that conclude earlier now than in the past. During 2003–2019, the harvest termination date now occurs ~1.6 d earlier per year, such that hunting ends ~26 d earlier.

3.2. Historical sea ice conditions

Throughout the latter half of the 20th century and early 21st century, the southeastern Chukchi Sea, including Kotzebue Sound, was reliably occupied by a near-continuous sea ice cover >85% from January to April (figure 3). Open water would typically begin encroaching northward through Bering Strait sometime during May, reducing the average concentration to as low as 65%, but broken ice would persist throughout June covering at least 15% of the ocean surface, but averaging >35%. However, starting around 2010 this pattern changed, with ice conditions during May and June in the last decade resembling those of June and July of earlier years. Indeed, the average ice concentration during May 2018 (the most recent year of data available, see section 2) dropped below 15% and into the realm of ice conditions typically associated with July.

3.3. Indigenous Knowledge: sea ice factors impacting harvest periods

The Elder Advisory Council identified several sea ice conditions that affect ugruk habitat and ugruk hunters during the spring harvest period in Kotzebue Sound (table S1). In particular, Indigenous Knowledge indicated that seals need open leads and the ice to start breaking up to be able to enter Kotzebue Sound as the Chukchi Sea ice pack also breaks up. The persistence of so-called 'white ice' floes during this time above prime feeding areas makes ideal habitat for the seals to feed, molt, and haul out. Hunters regard Kotzebue Sound as an important area for ugruk to build fat reserves before continuing their northward migration towards the northern Chukchi and Beaufort Seas. Sufficient ice floes were also critical for hunters who prefer hunting hauled out seals to minimize loss due to the rapid sinking of seals when shot in the water. Hunters also could not gain access to seals in Kotzebue Sound until they were able to launch small boats when the 'channel' opens in front of the village. Then proximity to broken ice floes determined accessibility of ugruk to hunters who hunt from small (<7 m) open vessels.

3.4. Combining data sources to understand how sea ice loss impacts harvest duration

Hunt duration, when compared to a set of proxies representing the social-ecological factors identified through the Indigenous Knowledge of our Elder Advisors, was influenced by a combination of access at both the beginning and end of annual harvest periods (table 1). Hunt duration was prolonged when the date boats could be launched occurred earlier, while hunts also lasted longer the later Kotzebue Sound cleared of ice (figure 4, table S2). The timing to commence hunts reflected both access (ability to launch boats) as well as availability (near proximity of broken ice), such that the start of hunts was delayed the later breakup occurred. Final model selection revealed that the end of the harvest period was most strongly influenced by the date that ice cleared from the entire Kotzebue

Table 1. Final GLM model results following model selection (see table S2) for ugruk harvest duration and the DOY when hunts commenced and concluded for the Qikiqtaġruŋmiut of Kotzebue Sound during 2003–2019.

Harvest response	Covariate	Estimate	se	*P* value
Hunt duration	DOY boats can launch	−0.035	0.010	0.0006
	DOY ice clears	0.036	0.008	<0.0001
Commence hunt DOY	DOY boats can launch	−0.00003	<0.001	0.0002
	DOY nearby ice clears	−0.00002	<0.001	0.0087
Conclude hunt DOY	DOY ice clears	−0.00002	<0.001	0.0187
	DOY nearby ice clears	−0.00002	<0.001	0.0529

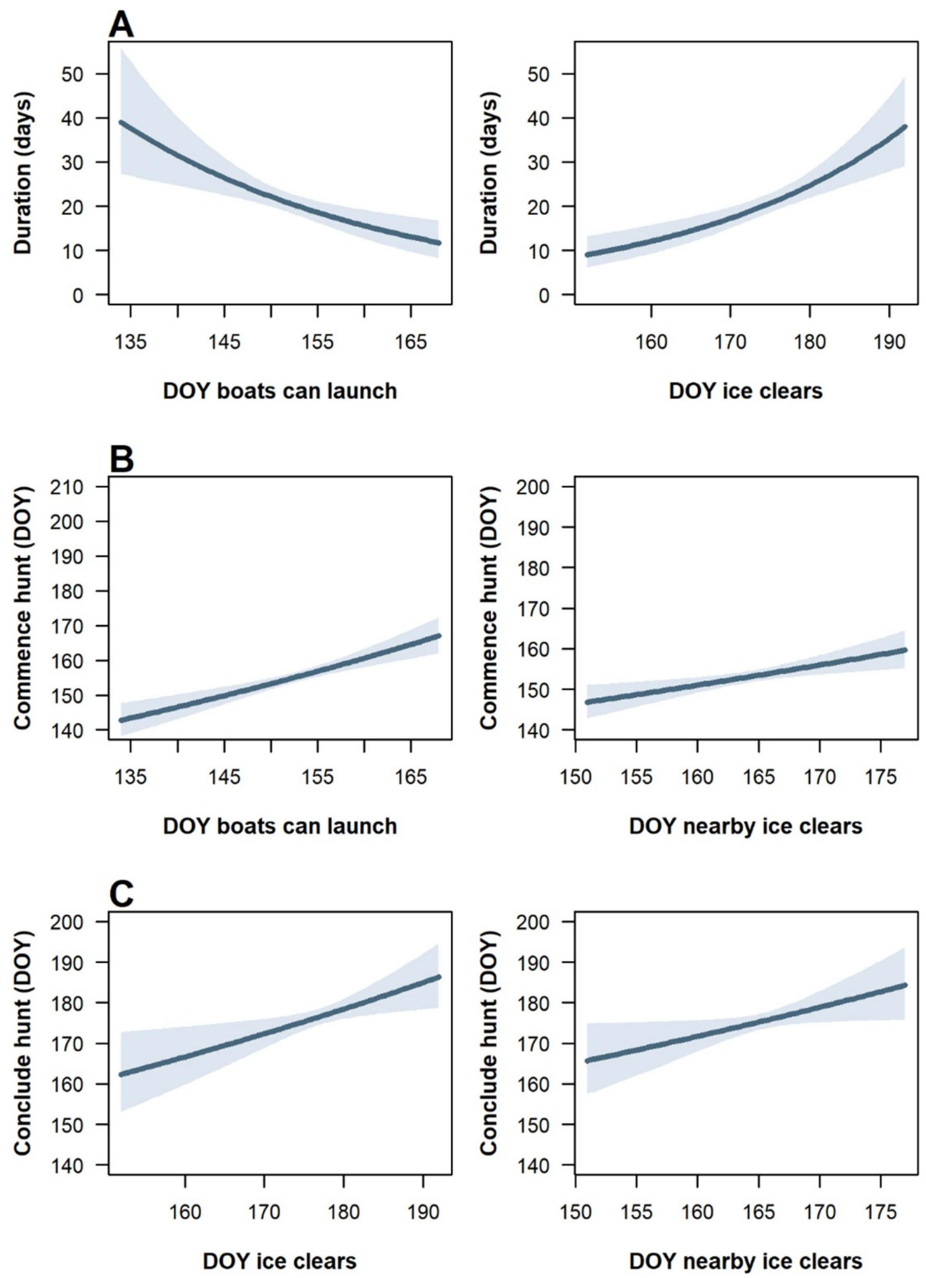

Figure 4. Sea ice factors affecting the phenology of annual ugruk harvests. Final model selection reveal that (A) hunt duration is explained by access at the beginning (i.e. DOY, that boats can launch) and end (i.e. DOY ice clears from Kotzebue Sound) of the breakup period. (B) The DOY when hunts commence is predicted by the DOY boats can launch and availability of nearby ice that is seal habitat (DOY nearby ice clears). (C) The DOY when hunts conclude is predicted by the DOY ice clears from Kotzebue Sound and availability of nearby ice that is seal habitat. Shading corresponds to 95% confidence intervals.

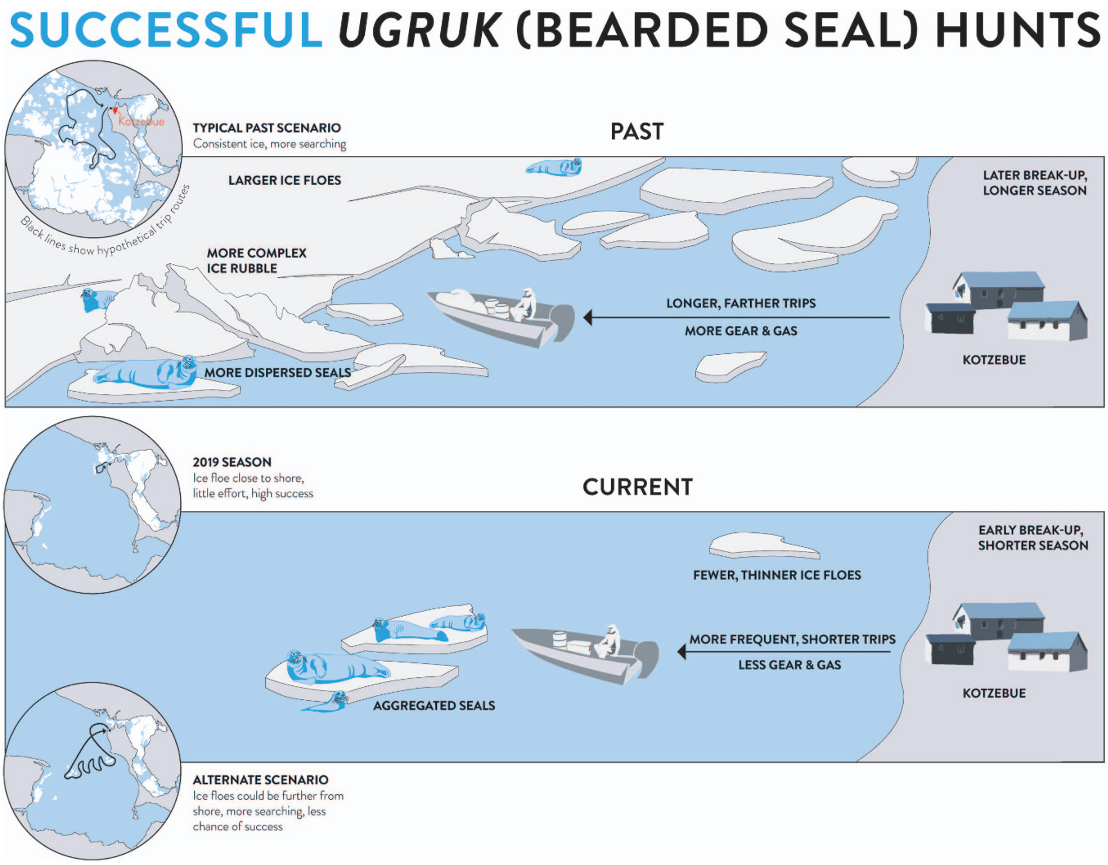

Figure 5. Social-ecological consequences of changing ugruk harvests. Conceptual diagram of the implications of changing ugruk hunting seasons, showing how hunters modify harvesting strategies as a result of differences in hunter effort, seal ecology, and ice habitat availability and complexity during past and the recent 2019 season, as well as potential alternate hunting scenarios under current conditions.

Sound (i.e. hunts ended later in years when ice persisted in Kotzebue Sound longer) although the date when nearby ice clear was also included in the final model.

Although Tribal records did not record hunter success in terms of the number of seals harvested, they provided an indication that Qikiqtaġruŋmiut hunters were able to get what they needed in years with condensed harvest periods; however, the context of harvesting effort and conditions varied over time (figure 5). Counterintuitively, 2019 was an example of a 'good' year for ugruk hunting, despite unprecedented lack of wintertime sea ice in Kotzebue Sound and neighboring Chukchi and Bering Seas (Stabeno and Bell 2019) and the earliest start of hunting on record (table S3). Although relatively few ice floes suitable for ugruk persisted in Kotzebue Sound, they remained in close proximity to town (<30 min motoring). Moreover, ugruk occupied those floes in high numbers, presumably since there was so little ice in the region that the seals densely aggregated on the scarcely available ice habitat. Additionally, a long stretch of unusually warm and sunny weather likely contributed to hunter success by encouraging seals to bask and therefore remain visible on top of the ice while also providing good visibility and sea conditions for hunters. Hunters reported an extremely high success rate per trip, and many boats made multiple trips in a day. In contrast, during earlier years, hunters often spent several days to complete a trip. In the past, Kotzebue Sound would be filled with broken ice separated by channels and leads that open and close, so seals were more dispersed among the available ice habitat. Navigating the dense ice pack was more challenging for hunters who would be prepared to camp within the ice pack or on nearby beaches while waiting for leads to open. Also, hunting seals on what were historically larger and more complex floes often required more effort to stalk a seal and then haul it back to the boat. Thus, hunters can so far modify harvesting strategies so the negative effects of a shortened hunting season and loss of sea ice habitat can be offset by ease of access to dense aggregations of seals if conditions are favorable.

4. Discussion

Overall, our analyses indicate that the ugruk harvesting season for Qikiqtaġruŋmiut hunters is being compressed by the shorter spring ice breakup period. Indeed, if we summarize across our time-series from 2003 to 2019, Kotzebue Sound now clears of sea ice ~22 d earlier (figure S3) and is the primary factor contributing to a shrinking ugruk hunting season.

Ultimately, the cessation of hunting is increasingly curtailed. This change presumably also shifts the timing and presence of ugruk in Kotzebue Sound because of their close association with broken ice, such that we conclude that hunting ugruk is essentially the same as hunting ice. The Qikiqtaġruŋmiut raise concerns for the potential loss of a major cultural and nutritional resource if the hunting season continues to be reduced.

Our analysis of the HSIA data provides a quantitative record of multi-decadal sea ice change in the southeastern Chukchi Sea and allows us to place the relatively recent changes affecting the ugruk hunting season in a longer-term context. For most of the 20th century, May was a month of reliably high ice concentration, June was a transitional season with the greatest year-to-year variability and sea ice persisted in measurable quantities into the month of July (figure 3). However, since around the time that Tribal records of the ugruk season began, average ice concentrations in June have dropped to within the range of values historically found in July. At the same time, average ice concentrations for July have remained below 5% throughout the 21st century and effectively dropped to zero in 2007. Ice concentrations during May show a comparable reduction, although they did not start to resemble those historically seen in June until 2013. Thus, there has been a roughly 1 month shift in the springtime ice regime in the southeastern Chukchi Sea that is comparable to the 22 d shift in the timing of ice-free conditions within Kotzebue Sound. However, the HSIA data suggest that changes affecting the tail end of the spring transition season started changing earlier than those affecting the beginning, leading to an overall shortening of the transition period. This serves to illustrate how the interaction between decadal-scale changes in different parts of a system at different times can lead to an increased variability at shorter timescales. In this case, the interannual variability of in the length of the ugruk season for Qikiqtaġruŋmiut hunters can be partly understood in terms of a trend toward earlier ice-free conditions that began around the turn of the 21st century and a trend toward earlier onset of break-up that began within the last 10 years.

This study is unique in actually quantifying the impacts of climate change on harvest timing for an Arctic Indigenous community by centering these analyses on research questions posed by and driven by Qikiqtaġruŋmiut Indigenous Knowledge, developing climatological records for the specific environmental cues used for their harvests, and pairing these with records kept by the Tribal government. Few co-production of knowledge projects have been carried out as this one has, with only the broad research area determined in advance, and all other details, including specific questions and topics of study, decided upon as part of the collaborative process while also retaining Indigenous Knowledge sovereignty (Raymond-Yakoubian and Raymond-Yakoubian 2017, Behe and Daniel 2018, Latulippe and Klenk 2020). Although we did not explicitly rely on Indigenous methodologies, such as talking circles or story-telling, that can focus food sovereignty research collaborations between Indigenous communities and scientists (Jäger *et al* 2019), our approach embraced the knowledge system and worldviews of the Qikiqtaġruŋmiut in support of their sovereignty of the bearded seal system in Kotzebue Sound. Several previous efforts have relied on global climate models to project or hypothesize impacts of factors like temperature or sea ice conditions on human behavior or well-being, yet too often models ignore or poorly resolve other variables that the Indigenous communities themselves say are important (Huntington 2019) or do not effectively consider the broader social-ecological context and complexity (Vogel and O'Brien 2006). Directly linking Indigenous Knowledge with environmental modeling can yield broad-scale social ecological insights as well as inform transdisciplinary and co-production research with Indigenous communities in the Arctic (Laidler *et al* 2011, Cooley *et al* 2020, Fox *et al* 2020). We found that the close collaboration of our multidisciplinary research team with the Indigenous Elders of the community was essential to developing models that could accurately capture the impacts of changing sea ice conditions on traditional harvests as well as informing our understanding of the relationship between ugruk and changing breakup conditions. By combining diverse information sources, such as Indigenous Knowledge and satellite imagery, we were able to explain the shrinking ugruk harvest season. Our approach exemplifies a bottom-up approach (Eicken *et al* 2021) that emphasizes equitable and intentional engagement of Indigenous Knowledge with scientists as well as the free, prior, and informed consent of the Tribe. As we demonstrate in this effort, bridging Indigenous and scientific understandings of marine mammal ecology and health can generate novel insights that may not otherwise be possible (Pfeifer 2018, Moore and Hauser 2019).

Recent efforts in the Canadian Arctic further illustrate that the level of skill by Inuit hunters and their individual risk tolerance to changing environmental conditions can play an outsized role in regard to accessing traditional resources, at least over a broad geographic scale of several communities (Ford *et al* 2019). For our case study of the ugruk hunt of the Qikiqtaġruŋmiut, the proximity to ice (and thus the availability of seals) is a determining factor of the hunt start date. Northern Kotzebue Sound is the region most accessible by small boats departing from Kotzebue, so hunters who are able to capitalize on seals that are close and available at the beginning of the hunting period experience less risk and fuel expenses than those who wait until later when the only remaining broken ice floes typically concentrate farther away in western portions of Kotzebue Sound. However, a shorter hunting season also has implications for hunters with regular forms of weekday employment within the community, since many of these hunters may only be able to hunt on the weekends. Thus, a side effect of a reduced hunting window means there are also fewer weekends available for workers to hunt, which could lead to tradeoffs in riskier behavior to access seals within the time available to hunt or the inability to hunt altogether in years when only one or two weekends fall within the hunting window. Community members also acknowledge declining participation by younger generations (Green *et al* 2020), as well as potential loss of cultural traditions due to rapid environmental change (Moerlein and Carothers 2012), and other more pressing contemporary social issues such as disparities in health, poverty, and education (Huntington *et al* 2019).

Our analysis does not consider the quality of ugruk available to Qikiqtaġruŋmiut hunters in terms of potential changes in the numbers, body condition, timing, or distribution of seals that may be associated with sea ice loss. The Beringia population of ugruk are considered 'threatened' under the US Endangered Species Act based on their association with rapidly declining sea ice habitats, despite relatively limited information on population numbers or trends (Conn *et al* 2014) and evidence that AK subsistence harvests are sustainable (Nelson *et al* 2019). Similarly, ugruk in recent decades had thicker blubber and no significant changes in pup growth or pregnancy rates compared to a historical period (Crawford *et al* 2015), suggesting that recent environmental changes have so far not significantly affected body condition metrics. Perhaps more pressing, however, is the recent emergence of several federally-declared 'unusual mortality events' involving ugruk and other ice seals that raise concerns regarding food safety and security, as well as ecosystem health more broadly (Moore and Gulland 2014).

Our analysis suggests that so far hunters have compensated for shorter seasons by modifying harvesting strategies so the negative effects of a shortened hunting season and loss of sea ice habitat can be offset by ease of access to dense aggregations of seals when conditions are favorable. However, it is possible that future weather and environmental conditions may create sparse remaining sea ice in Kotzebue Sound that is substantially farther from the community than experienced in 2019 (figure 5). Hunting success would be considerably lower over a brief season. Furthermore, as sea ice habitat continues to decline, it will take an increasingly improbable set of circumstances to offset the resulting loss of access to marine mammals.

5. Conclusion

The ugruk hunt in Kotzebue Sound is an example of a complex social-ecological system undergoing rapid environmental change, which we examined through a collaborative research process that valued and uplifted Indigenous Knowledge and Tribal sovereignty while specifically evaluating questions raised by the community itself. Indigenous Knowledge and sovereignty anchored our co-production of knowledge approach, as integral components from the outset in terms of choice of research question, methodological approach, data sources, and interpretation. By centering Indigenous Knowledge into the scientific approach of hypothesis-based inquiry, we have been able to design a study to investigate access and availability of a critical Arctic marine mammal resource, quantify hunter responses, and interpret climate-driven impacts, which are at times counterintuitive.

Notwithstanding recent hunting success in unprecedentedly sparse ice conditions, accessibility to traditional resources remains a prominent concern for Arctic communities that dovetails with a growing emphasis on Inuit food security and sovereignty. Management and policy decisions related to Arctic marine mammal resources, such as ugruk, are therefore also interwoven with health, well-being, and culture of Indigenous communities (ICC-Alaska 2016, Breslow *et al* 2017), which is directly linked to decision-making power for food security and sovereignty (Heeringa *et al* 2019, Jäger *et al* 2019, ICC-Alaska 2020). We demonstrate the power of bottom-up research with the free, informed, and prior consent (Eicken *et al* 2021) of the Qikiqtaġruŋmiut and simultaneously recognized their inherent capacity and self-determination to conduct research regarding their own knowledge systems, waters, and resources (Latulippe and Klenk 2020). Hence, research that originates with Indigenous Knowledge and accounts for local well-being, values, and capacity has the potential to also lead to more inclusive, sustainable, and equitable outcomes with transformative opportunities for ocean planning processes and Indigenous-led policy-making (Hicks *et al* 2016, David-Chavez and Gavin 2018, Raymond-Yakoubian and Daniel 2018, Wheeler *et al* 2020). Here, we have demonstrated a successful approach for such research that reveals how large-scale changes in sea ice are affecting access to a vital traditional resource.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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