



**Special Section:**

Rhythms of the Earth: Ecological Calendars and Anticipating the Anthropogenic Climate Crisis

**Key Points:**

- Biodiversity is the foundation of ecological calendars which are used to anticipate seasonal change
- Ecological calendars are an expression of food sovereignty and facilitate the goal of food security
- An empirical analysis of biodiversity responses to climate change is vital to render ecological calendars relevant in the climate crisis

**Supporting Information:**

Supporting Information may be found in the online version of this article.

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**Citation:**

Kassam, K.-A. S., & Bernardo, J. (2022). Role of biodiversity in ecological calendars and its implications for food sovereignty: Empirical assessment of the resilience of indicator species to anthropogenic climate change. *GeoHealth*, 6, e2022GH000614. <https://doi.org/10.1029/2022GH000614>

Received 25 JUN 2022  
Accepted 10 AUG 2022

# Role of Biodiversity in Ecological Calendars and Its Implications for Food Sovereignty: Empirical Assessment of the Resilience of Indicator Species to Anthropogenic Climate Change

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**Abstract** Ecological calendars are knowledge systems based on close observation of one's habitat to measure and give meaning to time, thereby providing anticipatory capacity for livelihood activities and contributing to food sovereignty. They rely upon seasonal indicators that integrate biophysical and ecological phenomena (e.g., first snowfall, last frost, blossoming of a tree species; seasonal appearance of an animal or plant) with locally grounded cultural meaning and value systems. These context-specific relationships have enabled Indigenous and rural societies to anticipate weather and other seasonal processes in their environment. However, anthropogenic climate change could undermine ecological calendars due to adverse impacts on specific indicator species, but this issue remains unexplored. We address this knowledge gap by examining how anthropogenic climate change might affect selected species (birds, fish, and mammals) that are seasonal and key to Indigenous food systems in two Western Arctic communities. We leverage existing dietary animal datasets to which we apply a novel methodology for assessing organismal vulnerability to climate change. The methodology uses intrinsic species traits such as physiological tolerances, genetic variability, and life history traits to generate an empirical and integrative assessment of vulnerability for any given species. Subsequently, an aggregate view of vulnerability across calendar species is achieved through comparative statistical analysis across species both within and between communities. This exercise permits the first quantitative assessment of the continued relevance and effective use of an ecological calendar, thus demonstrating that food sovereignty and livelihood security is enhanced by biodiversity of indicator species.

**Plain Language Summary** Ecological calendars are a way in which human societies have historically anticipated seasonal change. These calendars help Indigenous and rural societies make effective decisions about food production. Like our food system, these calendars depend fundamentally on species biodiversity to predict changing seasons. For example, the arrival of a migratory animal, the appearance of an insect, the song of a bird or the call of a frog, and the blossoming of a tree may indicate the arrival of spring. Ecological calendars can be powerful tools for anticipating anthropogenic climate change. However, in order to secure our food system and keep ecological calendars updated, we need to be able to determine which species of bird, fish, and mammals will be resistant or resilient to climate change and which will be vulnerable. Here we present a methodological approach for such an assessment in order to safeguard our food sovereignty and achieve food security.

## 1. Introduction

Ecological calendars are knowledge systems that measure and give meaning to time based on close observation of one's habitat, and they play a critical role in the practice of food sovereignty and achieving food security of indigenous populations around the globe. Indeed, the historical use of ecological calendars is a testament to the exercise of food sovereignty by Indigenous and rural societies (Kassam et al., 2011).

Ecological calendars are fundamentally based on diverse biological and physical indicators that vary seasonally. These biophysical indicators may include: first and last frost; first snowfall; blossoming of a tree species; seasonal appearance of an animal, insect, or plant; or arrival of a particular migratory animal. In turn, the integration of these ecological phenomena with sociocultural systems. These context-specific relationships within space and time have enabled Indigenous and rural communities to anticipate weather and other seasonal processes

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in their environment (Clarke, 2009; Cochran et al., 2016; Kassam, 2021; Kassam, Ruelle, et al., 2021; Kassam et al., 2011, 2018; Mondragón, 2004; Prober et al., 2011; SantoDomingo et al., 2016; Turner, 2022; Turner & Singh, 2011; Woodward et al., 2012). Hence, ecological calendars provide anticipatory capacity for livelihood activities and contribute to food security.

The degree of robustness and resilience of ecological calendars in the face of our changing climate is an urgent practical concern of both indigenous communities and researchers alike but is a virtually unstudied question. Because food sovereignty and security both stem from the reliability of ecological calendars, a continued reliance upon them demands careful attention. In the twenty-first century, continued application of cocreated ecological calendars through transdisciplinary research with *communities of social practice* (such as Indigenous and local knowledge holders) and *communities of enquiry* (such as the biophysical and social sciences as well as the humanities) depends on a robust ecological foundation with species biodiversity (Kassam, Kaziev, et al., 2021; Kassam, Ruelle, et al., 2021; Kassam et al., 2018). As a part of the transdisciplinary Ecological Calendars for Climate Adaptation Project (ECCAP) research, our findings identify the role of specific indicator species in terms of visual or auditory cues that inform Indigenous and rural communities in coordinating their seasonal livelihood activities (Kassam, Kaziev, et al., 2021).

We attempt to address these issues using a two-pronged approach. First, we marshal insights from three varied and geographically widespread indigenous food system exemplars in which Indigenous or local knowledge has been carefully studied and documented within its specific cultural and ecological setting:

**Example 1** Farming Decisions in the Oneida Lake Watershed, New York, Section 2.1;

**Example 2** Herding with Fodder and Potato Harvesting in the Sary Mogul, Alai Valley, Kyrgyzstan, Section 2.2; and finally,

**Example 3** A comparison of two indigenous subsistence communities in the High Arctic of North America (Section 3).

The second prong is to employ several research approaches (“lenses”) to gain insights using a combination of descriptive narrative embedded in sociocultural research (Examples 1 and 2), and combining an intensive, biological, trait-based vulnerability assessment (Bernardo, 2014) with information about indigenous knowledge and diets previously derived from socio-cultural research (Example 3).

A key point to note here is that we are constructing our argument through the totality of these seemingly disparate examples. They vary in the level of detail of analysis; with respect to type of food system (fishing, farming, herding, hunting) being studied; and the sociocultural diversity and geographic locations of the communities. Based on recent research, below we will briefly examine Examples 1 and 2 establish the principle that food sovereignty in relation to food security. Furthermore, how both notions fundamentally rely on ecological calendars, (and its underlying biodiversity as indicator species) in two radically different systems. These examples provoke a discussion of the nexus among cultural livelihood practices and Indigenous or local knowledge of biodiversity and ecological context, much of which remains unexplored in food sovereignty literature.

These examples, and this conclusion set the stage for Example 3, which follows the same premise, but which then takes a deep dive into the specific issue of how biodiversity itself and its potential responses to climate change will influence ecological calendars. We hope to show that, taken together, these examples, the basic principles of food sovereignty, and conclusions we identify from them are broadly generalizable to both ecological calendars and to the food security of Indigenous food systems globally.

## 2. Setting the Stage: Biodiversity and Use of Indicator Species

As mentioned above, the impact of Anthropogenic climate change on vital indicator species remains unexplored. It is conceivable and likely that some of these specific indicator species will be adversely affected by climate change. How can this open question be addressed?

Ecological calendars are built upon knowledge of biodiversity patterns; for example, which species are present in a given system, where and when they occur, and the changes in their population sizes in time and space. It follows that the informational content and value of ecological calendars, and their continued usefulness in a changing

climate derives directly from understanding how biodiversity itself, where species individually and collectively, are responding or will respond.

Responses of biodiversity to climate change fall along a continuum, from resistant at one extreme to highly vulnerable at the other (Bernardo, 2014). *Resistant Species*—those which are little influenced by climate change—will lend stability to ecological calendars. At the opposite extreme are *Highly Vulnerable Species*—those whose population sizes may be substantially depressed, or which may even become locally extinct—and which thus undermine the stability of ecological calendars because they are unreliable predictors. Between these extrema are *Resilient Species*—those that are sensitive to varying degrees to acute climate perturbations, but which recover demographically—and thus have potential to still be reliable indicators in ecological calendars through time. Together, resistant species and resilient species will provide the basis of continued use of the ecological calendar with constant local level vigilance and modification resulting from the impact of climate change. In addition, resistant and resilient species may be suitable alternatives to existing vulnerable indicator species used in the calendar. Furthermore, it is possible to envision new species, that have become part of the ecosystem due to climatic variation, also becoming useful indicators for the calendar. This is consistent with the historical adaptive dynamism and rooted relevance to the local cultural and ecological context of ecological calendars (Kassam, Ruelle, et al., 2021).

Our idea that the indicator or specific food species underlying ecological calendars can be evaluated using biological species traits (Bernardo, 2014) is explored in a detailed case study in Example 3 (Section 3). This proof-of-concept is meant to be added to a continuing body of research on the efficacy of ecological calendars to anticipate Anthropogenic climate change. We address the knowledge gap concerning the impact of climate change on ecological calendars by examining the impact of Anthropogenic climate change on selected species (fish, birds, mammals) that are seasonal and key to Indigenous food systems in the Arctic. Polar regions are well-known to be experiencing the most dramatic effects of climate change on earth including the greatest rates of warming and concomitant loss of sea ice (reviewed by Robinson, 2022). The question of how Arctic organisms in general, and how peoples for whom they are fundamental to food security will be affected, are pressing, open questions.

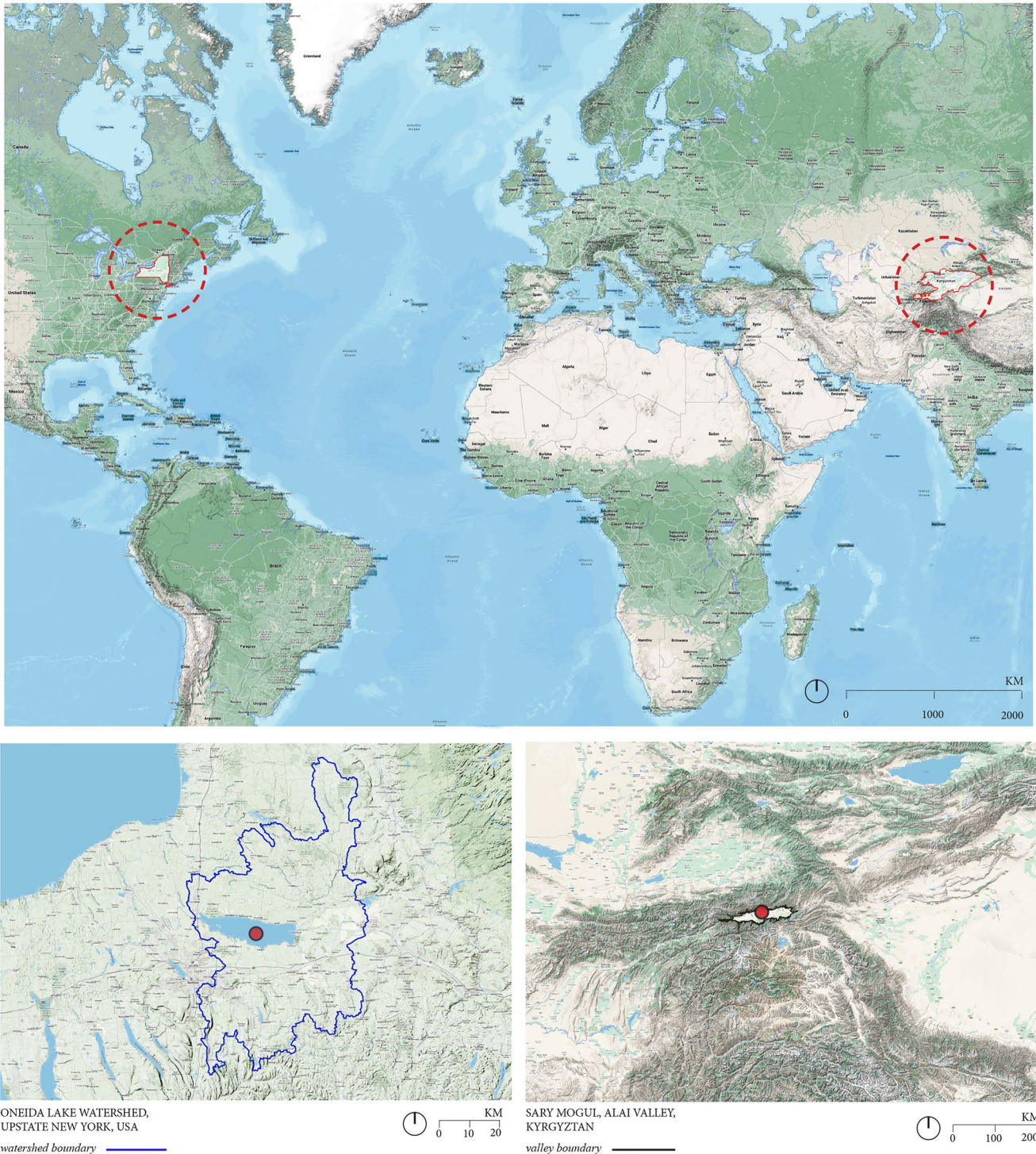
We explore these interrelated issues using a new methodology aimed at diagnosing relative vulnerability of biodiversity in indigenous food systems of the Arctic. This exercise is only possible by drawing upon Indigenous knowledge and collaborating with Indigenous communities to inform our study parameters such as which species are of interest. This nexus of academic work with Indigenous knowledge is extremely powerful (Gardner et al., 2022; Ullmann & Kassam, 2022). We leverage existing dietary animal datasets from two Western Arctic communities to which we apply a novel methodology for assessing organismal vulnerability to climate change. The methodology uses intrinsic species traits such as physiological tolerances, genetic variability, and life history traits to generate an empirical and integrative assessment of vulnerability for any given species (Bernardo, 2014). Subsequently, an aggregate view of vulnerability across calendar species is achieved through comparative statistical analysis across species both within and between communities. This exercise permits the first quantitative assessment of the continued relevance and effective use of an ecological calendar, thus demonstrating that food sovereignty and livelihood security is enhanced by biodiversity of indicator species.

We now begin this argument with Examples 1 and 2 (Figure 1)—the first from farming in Northeast United States of America; and the second from herding in the Alai Valley of the Kyrgyz Republic—to illustrate the role of biodiversity in identifying indicator species for seasonal change and their contribution to food sovereignty and security.

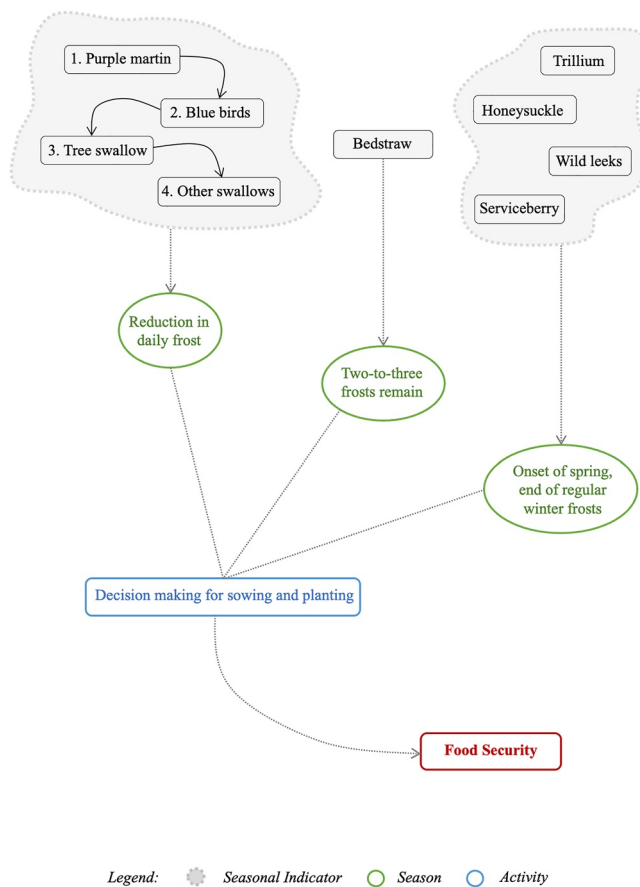
### 2.1. Example 1: Oneida Lake Watershed—Farming

The decision by farmers in the Oneida Lake watershed to begin preparing for agricultural activities is guided by observation of a sequence of phenological events that indicate the conclusion of frosts in the spring season (Figure 2). With the arrival of birds such as the purple martin; followed by blue birds, tree swallows; and concluding with the other swallows indicates that the daily occurrence of frost is rapidly concluding for the season. Similarly, the emergence of plants such trillium, wild leeks, honeysuckle, and serviceberry also point toward the onset of spring and the end of regular winter frosts. In fact, some farmers maintain that the surfacing of bedstraw suggests that two-to-three frosts remain. Observation of plants and birds collectively inform farmer decisions because sowing slightly early has the risk of crop damage and similarly, planting somewhat late runs to risk of





**Figure 1.** Location of the rural and indigenous communities where the indicator species of ecological calendars are used to illustrate decisions related to farming and herding, respectively. The diversity of locations and ecological professions illustrates the plurality of use and simultaneously the context specificity of ecological calendars.



**Figure 2.** Sequence of Bird and Plant Indicators of Spring for Oneida Lake Watershed. This example illustrates the role of bird and plant biodiversity that act as multiple and mutually reinforcing indicators to determine end of winter frost and advent of spring in order to guide decision making for planting crops. Thus, initiating action that contributes to food security.

This then sets the stage for movement of herds along with the sequence of planting of barley, sainfoin, and potatoes.

Similarly, in the autumn, the sequence of harvesting hay, barley, sainfoin, and potatoes is determined by temperature changes and concern for frost. Specifically, herders consider color changes in fodder grasses in the north and south facing hills in the pastures found in mountain valleys. Specifically grasses such as, *ak-bash godo* (*Stipa orientalis*), *budai bashy* (*Poaceae*), *kara-bash* grass (*Poaceae*), *kiyak* grass (*Leymus secalinus*), and *at-kulak* or common sorrel (*Rumex acetosa*) stop growing and turn from green to yellow. The growing season concludes when these rich fodder grasses bend and dry so that herders can begin harvesting. In addition, autumn is marked by arrival of wind, departure of migratory birds, disappearance of insects, frost, snow, and freezing of streams and rivers.

In the preceding autumn, to ensure food security through the winter and the next spring season, key decisions are made. For instance, herders prefer to time mating of their animals in the autumn, especially sheep and goats so that they birth in the warmer spring. But spring is a critical period when there is greatest pressure on fodder and food supply due to transition between seasons from winter to spring. As a result, dairy products prepared in summer pastures especially butter, cheese, yogurt are utilized during this stressful time of the year. Furthermore, fuel in the form of dried manure produced by livestock is used for energy in the winter and spring. Human food security is a result of livestock food security. They comprise a greater and dynamic food system informed by local biodiversity.

poor harvest (Kassam, Kaziev, et al., 2021, pp. 46–51). This has direct implication for food security with local and broader regional impacts.

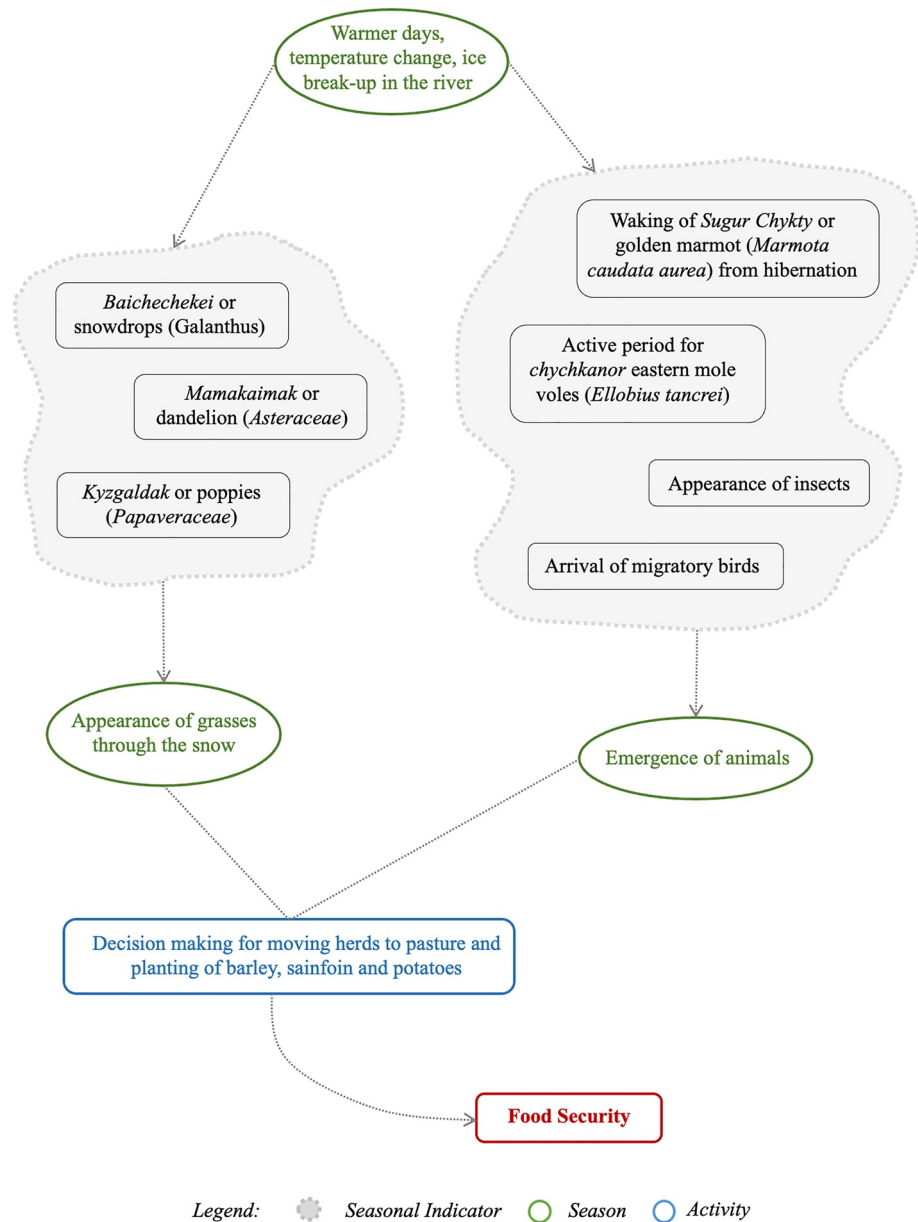
## 2.2. Example 2: Sary Mogul, Alai Valley—Herding With Fodder and Potato Harvesting

The village of Sary Mogul, located in the Alai Valley of Southern Kyrgyzstan (3,100 msl), primarily engages in animal husbandry while growing barley for livestock fodder and potatoes for human consumption. Among livestock, they specifically raise yaks, sheep, goats, and cows. They also tend to horses and donkeys. Changes in seasonal weather have direct implications for livelihood activities. In this example, we will focus on the efforts of herders to ensure food security of their livestock and therefore, their own cultural and nutritional wellbeing.

Changes in timing of snow and duration of snow cover in winter have direct influence on herding practices such as grazing, fodder production, mating, and birthing of young stock (primarily lambing). For herders, circular migration patterns from the village to pastures are determined by snow accumulation (autumn), snow cover (winter), snowmelt (spring), and snow free (summer) periods. Like in the case of the farmers in Oneida Lake Watershed above, herders make decisions based on a combination of co-occurring biophysical cues. Herders need to be able to anticipate seasonal variation especially in the Spring and Autumn to safeguard their livestock from fodder shortages, birthing of animals, as well as timing of planting and harvesting of crops.

Spring is determined by warmer days, indicating temperature change, ice break-up in the river, surfacing of grasses through the snow, waking of the marmots from hibernation, appearance of insects, and arrival of migratory birds (Figure 3). Specifically, the emergence *baichechekei* or snowdrops (*Galanthus*), *mamakaimak* or dandelion (*Asteraceae*) and *kyzgaldak* or poppies (*Papaveraceae*) indicate arrival of spring. However, the herders are also cautious of “false” spring and are able to identify these grasses. In addition, the emergence of *Sugur Chykty* or golden marmot (*Marmota caudata aurea*) from hibernation is an indicator of spring. In addition, spring seems to be a very active period for *chychkan* or eastern mole voles (*Ellobius tancrei*).

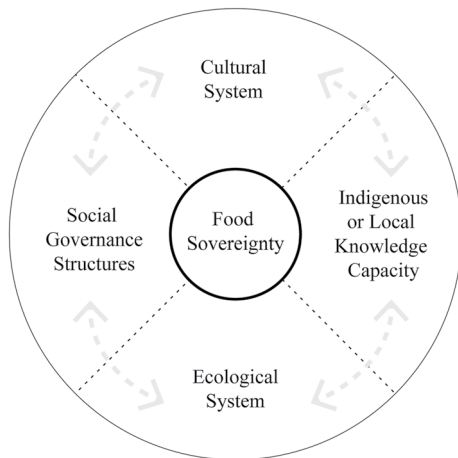




**Figure 3.** Sequence of animal and plant indicators of spring for Sary Mogul. This example illustrates the combination of specific animal and plant species in determining decisions that relate to movement of herds to pastures and planting of key fodder crops and potatoes. Thereby contributing to food security.

### 2.3. Stage 1 Implications: Food Sovereignty Is an Emergent Property of the Nexus of Ecological Systems, Cultural Systems Indigenous or Local Knowledge, and Social Governance Structures

According to the Plan of Action and Declaration of the World Food Summit (1996, p. 2): “Food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life.” In this sense, food security is a goal or an outcome. Whereas food sovereignty is a process that achieves the aim of food security as each unique community exercises its agency and self-determination (First Nations Development Institute, 2014; Hoover, 2017; Kassam et al., 2010, 2016; Ruelle et al., 2019). In the Declaration of Indigenous Peoples’ Consultation on the Right to Food (2002, p. 2) Indigenous communities, small farmers, fisherfolk, gatherers, herders, hunters, pastoralists, and farm workers from 28 countries argued that: “Food Sovereignty is the right of Peoples to define their own policies and strategies for the sustainable production, distribution, and consumption of food, with respect for their own

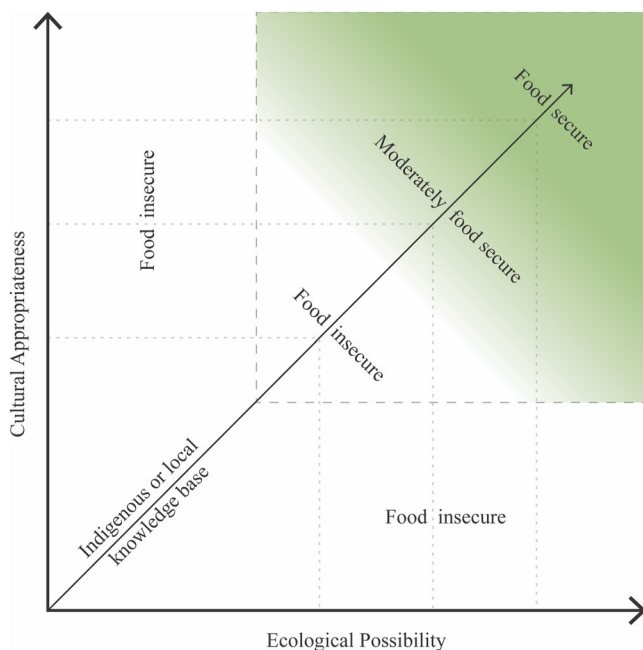


**Figure 4.** The Nexus of Food Sovereignty. Food sovereignty arises from four interacting, mutually reinforcing, but conceptually distinct dimensions. The first is the ecological foundation that provides the land and seascape for species abundance for the food system. The second is the cultural system that is appropriate to the context of its inhabitants by facilitating values that guide food production and stewardship practices to meet their physical needs and spiritual fulfillment. Third is the Indigenous and local knowledge capability, of which ecological calendars are one example, to practically engage in food production to meet nutritional needs. The fourth, are the social and institutional governance structures that facilitate the exercise of individual decision-making and collective self-determination.

cultures and their own systems of managing natural resources and rural areas, and is considered to be a precondition for Food Security.” A few years later, with representation from 80 countries, a larger group of these food producers and Indigenous peoples, further refined the concept of food sovereignty in the Forum for Food Sovereignty (2007, p. 1). Specifically, they said: “Food sovereignty is the right of peoples to healthy and culturally appropriate food produced through ecologically sound and sustainable methods, and their right to define their own food and agriculture systems.” Thus, food security is a policy objective at national, regional and household scales whereas food sovereignty is a process that asserts strategic action in achieving food security and recognizes the fundamental “right to food” which is asserted in the UN Declaration of Human Rights (1948).

It is important to consider definitions of food sovereignty as they are simultaneously an articulation made by, and an aspiration of, Indigenous peoples with respect to their food system. First, food sovereignty depends on the nexus between cultural distinctiveness of a peoples, the ecological niche they inhabit, their local or Indigenous knowledge capacity, and finally, the social structures that they use for governance which includes external regionally and nationally based administrations (Figure 4). Similarly, ecological calendars are also grounded in the local ecology and sociocultural system and are fundamentally an expression of cumulative Indigenous or local knowledge (Kassam et al., 2011, 2018). Second, sovereignty is an act of agency or self-determination that is future focused; namely, achieving the objective of food security (Figure 5). In the same manner, ecological calendars are a representation of anticipatory capacity to secure food in the climate crisis.

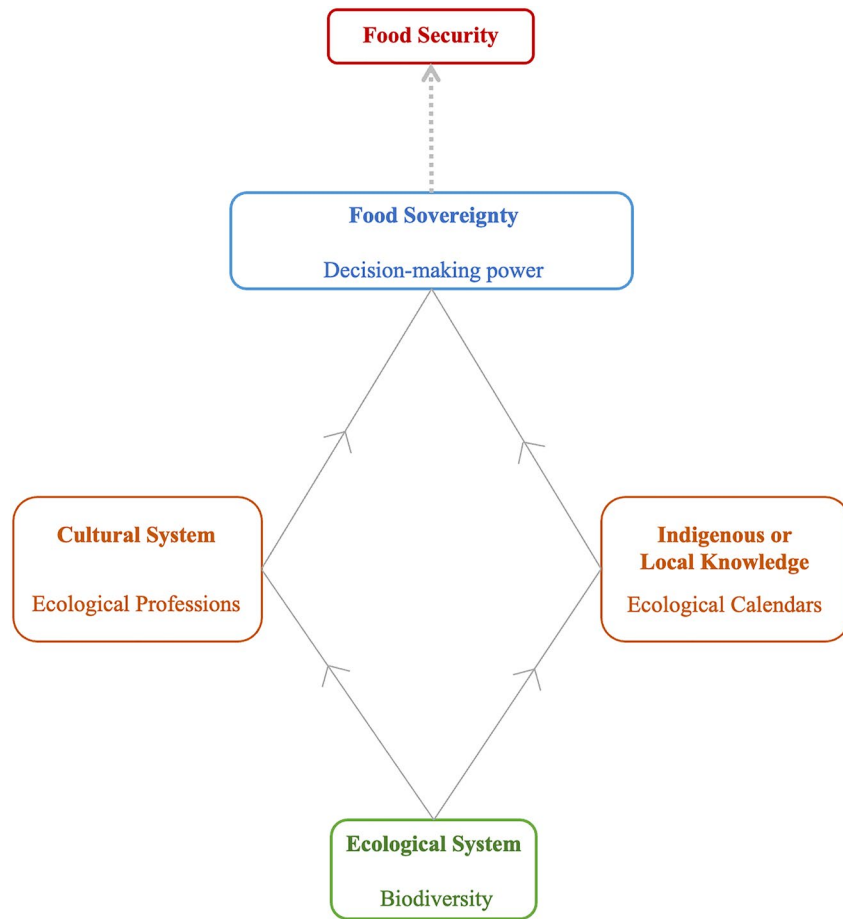
Here we are focusing on aspects of food sovereignty that are grounded to local context of ecological and cultural systems as well as Indigenous or local knowledge capacity arising from relations between these systems. We are not concentrating on the social governance component because a large part of the literature on food sovereignty already addresses the political dimension (Alkon & Mares, 2012; Boyer, 2010; Edelman, 2014; McMichael, 2010; Patel, 2009; Windfuhr & Jonsén, 2005). However, political rights, while clearly very important, are not sufficient because there are other systemic components to food injustice. Rather, we wish to demonstrate that ecological possibility, knowledge capacity and cultural relevance, working in tandem and in mutual interaction, are necessary precursors to the governance structures that enable food sovereignty. Without these fundamental elements, no amount of rights legislation will facilitate the exercise of food sovereignty. To put it tersely: “You can’t say you’re sovereign if you can’t feed yourself” (Hoover, 2017). Therefore, we will return to this in our conclusion (Section 4) because it is relevant to the discussion of the continued use of ecological calendars in a hostile political operating environment where many of the communities with whom we collaborate and cocreate knowledge live (Ibarra, J. T. et al., 2011; Kassam et al., 2011, 2018; Turner et al., 2013; Whyte, 2017).



**Figure 5.** Application of food sovereignty to achieve the outcome of food security. Food security is an emergent consequence of exerting sovereignty or agency using cultural and ecological systems based on practical wisdom derived from cumulative and empirical place-based knowledge.

#### 2.4. Synthesis

Under conditions of climate change, the primary purpose of ecological calendars is to achieve food security at the level of local communities. The examples from Oneida Lake Watershed and Sary Mogul, above, reveal the fundamental role of biodiversity expressed through seasonal indicators which influence decisions about the food system. In Oneida Lake in Upstate New



**Figure 6.** Role of biodiversity in food sovereignty. Ecological context through species biodiversity provides a basis for cultural systems to generate ecological professions with sophisticated knowledge of their habitat such as ecological calendars; thereby, contributing to decision-making or exercise of sovereignty that results in food security.

York, USA, the sequence of events involving specific bird and plant species directly guide farmer decisions related to growing crops. Similarly, in Sary Mogul in the Alai Valley of the Kyrgyz Republic, specific species of animals and plants shape decisions related to herding activities and growing of fodder such as barley and crops like potatoes. To put it succinctly, biodiversity is central to identification of a series of indicators relevant to the effective functioning of an ecological calendar. Therefore, cultural diversity, manifested through the professions of farming, fishing, gathering, herding, hunting and orcharding in part form the ecological reality of each society. Furthermore, this cultural distinctiveness is made dynamic and cumulative through Indigenous or localized knowledge of the biophysical processes in one's ecosystem (Kassam, 2009). Together, the ecological professions and Indigenous knowledge facilitate the exercise of decision-making power or sovereignty by each community, with the use of ecological calendars, to achieve the goal of food security (Figure 6).

### 3. Evaluating Seasonal Indicators in Ecological Calendars Through the Lens of Resistance and Resilience to Climate Change Vulnerability of Prey Biodiversity: An Empirical Case Study

Using Examples 1 and 2, we have established the foundational role of biodiversity in constructing and applying ecological calendars. We have also developed the argument that the exercise of food sovereignty and in turn the aim of food security are emergent properties of the context specific nexus of ecological possibility, cultural appropriateness, and Indigenous or local knowledge base (Section 2.3, Figures 4–6). Our overarching objective in Section 3 is to articulate and illustrate a methodology to assess the impact of Anthropogenic climate change on



indicator species of ecological calendars by identifying vulnerable, resilient, and resistant species that underlie them.

### 3.1. Methods

We studied the climate change vulnerability of the food organisms used by two Indigenous populations in the high Arctic whose foraging ecology has been intensively studied and depend primarily on hunting for their food system. The focal Indigenous populations are the Iñupiat of Wainwright and the Inuvialuit of Ulukhaktok (Figure 7).

Research in partnership with the Iñupiat of Wainwright, Alaska reveals the human ecological implications of climate change with respect to food sovereignty and security. Wainwright, is located 480 km north of the Arctic Circle and 136 km southwest of Barrow on the Chukchi Sea (Figure 7). The community consists of *Kuugmiut*, “people of the Kuk River,” and *Utuqqagmiut*, “people of the Utuqqaq River.” Both groups are Iñupiat (Braund, 1993). Known as *Ulguniq* by the Iñupiat, Wainwright is one of seven communities belonging to the North Slope Borough, the political subdivision or municipal government for northern Alaska. The population of Wainwright in 2001 was approximately 550 residents with 91 families (Kassam, 2009; Kassam & Wainwright Traditional Council, 2001).

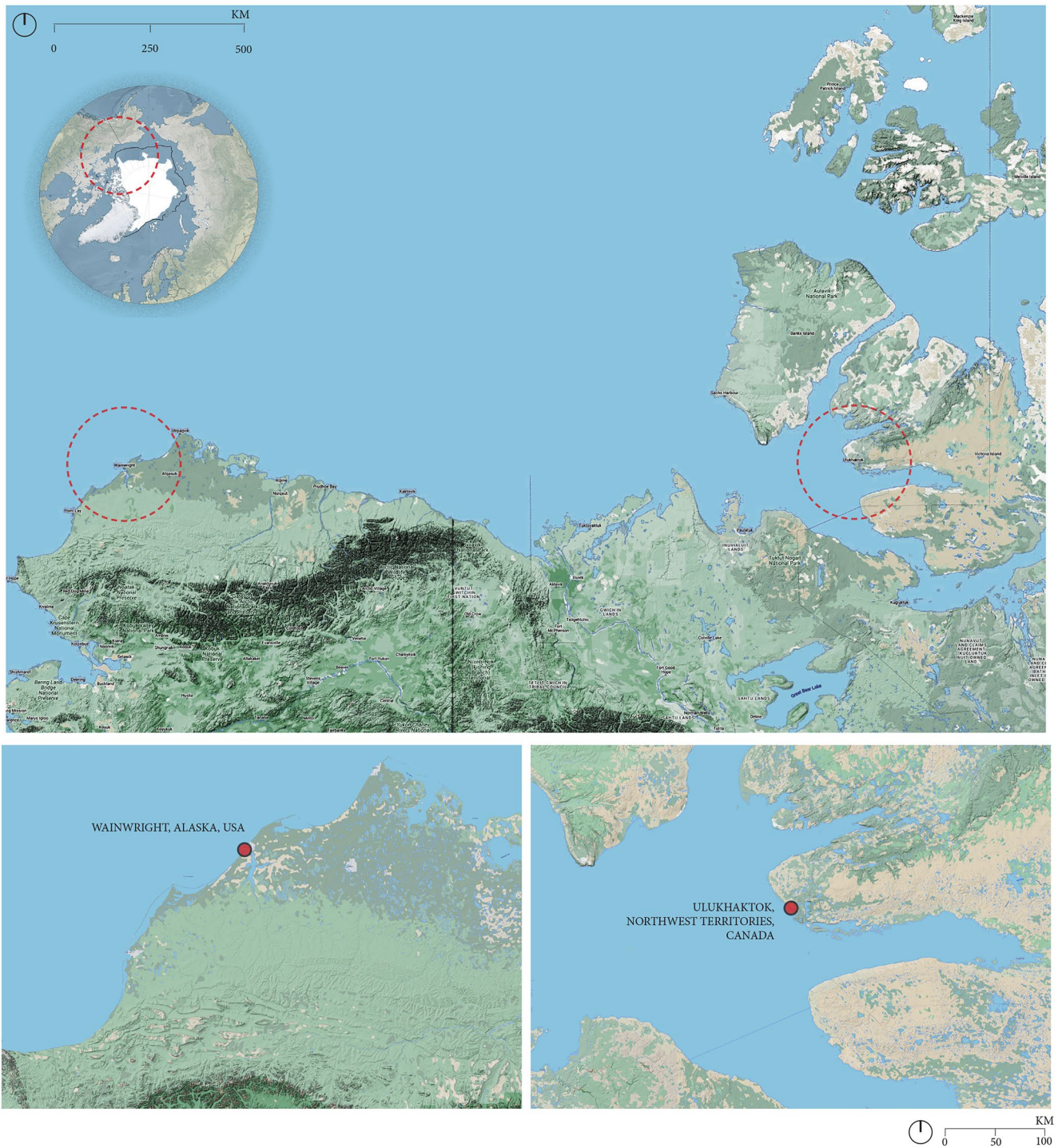
Like the Iñupiat of Wainwright, the Inuvialuit community of Ulukhaktok (formerly Holman) in the Northwest Territories, Canada, illustrates the complex connectivity of culture and ecology that is characteristic of food sovereignty. Ulukhaktok is a community that is part of the Inuvialuit Land Claim Agreement (modern day treaty) in Canada located on the western extent of Victoria Island on the Amundsen Gulf at the head of the Beaufort Sea (Figure 7). In 2001, the population of the Hamlet of Ulukhaktok was approximately 400 residents with 105 families.

Hunting and fishing of the Iñupiat and the Inuvialuit to secure their nutritional needs is an exercise of their sovereignty with respect to the diversity of species within their ecological homeland, informed by their cultural values, and made effective by their place-based knowledge (Figure 6). These hunting and fishing activities connect them to the biodiversity in their habitat and requires them to be keenly observant of ecological changes. Their knowledge of sea-ice, which is required for subsistence activities, has enriched our collective understanding of climate change in the Arctic (Kassam, 2009; Krupnik & Jolly, 2002; Nelson, 1969). The residents maintain relations with many sea mammals to meet their food needs despite risks associated with travel on open water and sea ice (Fuller & George, 1999; Ivie & Schneider, 1988; Kassam & Wainwright Traditional Council, 2001; Luton, 1986; Nelson, 1969, 1982).

Detailed studies (Kassam, 2009; Kassam & Wainwright Traditional Council, 2001) of the biodiversity routinely and historically used by these communities, and their specific uses (food, clothing, boat material, etc.) lay the foundation for this analysis. Based on these prior analyses of species utilization, we assembled a joint list of species used by either or both of the study populations (Table 1, and Tab 1 of Table S5A in Supporting Information S1). For this paper, we focused on marine mammals, terrestrial mammals, and fish species (Figures 8a and 8b). We categorized species as shared if both communities use them, or exclusive if a particular food species is only utilized by one community.

#### 3.1.1. Vulnerability Criteria

It is widely recognized that organismal persistence in the face of climate change will be dictated by three aspects of biology, which are not necessarily exclusive: **tolerance** to changing conditions within existing ecophysiological stress tolerance zones; **migratory capacity** or dispersal ability to track optimal habitat patches as climate change ensues; and the **evolvability of these two factors** in response to changing conditions by shifts in tolerance zones (height, breadth or optimum of tolerance norm). Over the last two decades, an expansive theoretical and empirical literature about the potential of organisms to respond in some or all of these ways has emerged. Yet a vexing issue in this expansive literature about the climate change vulnerability of organisms is how to take conceptual arguments and take them from conceptual to operational (Bernardo, 2014; Bernardo et al., 2007). Such insights have not been fully integrated in any effective way to the enterprise of actually evaluating how species differ in their relative vulnerabilities to climate change.



**Figure 7.** Map illustrating locations of focal Indigenous populations in the context of their environment.

To this end, Bernardo convened a working group (Integrative Conceptual Framework for Assessing Relative Endangerment due to Climate Change or ICFAREC) at Cornell University in 2009 of global experts in various relevant fields who were among many of the early proponents of the idea that species traits of various kinds could provide these critical insights about climate change vulnerability. ICFAREC sought to identify general species attributes—so called species' traits—that have been oft-hypothesized in the literature to relate to various aspects of species susceptibility or resistance to climate change (Bernardo et al., 2007; Bernardo, 2014, Table 1). These

**Table 1**

*Examples of Species Traits Related to Major Avenues of Response to Climate Change Useful for Assessing Vulnerability*

I. Ecological criteria (population size, trends, and landscape distribution)	Traits related to tolerance capacity (capacity to withstand locally changing environments)	Traits related to dispersal capacity (potential to disperse and track optimal habitat patches through space)	Traits related to evolutionary capacity (potential to evolutionarily adjust phenotypes associated with tolerance and or dispersal)
	Tolerance to environmental fluctuation	Relative vagility of species estimated via genetic markers or indirect methods	Genetic diversity in traits relevant to dispersal or tolerance
	Plasticity of tolerance	Dispersal rate	Demographic attributes (generation time, effective population size)
	Metabolic capacity	Dispersal distance	Life history attributes (body size, fecundity)

traits or properties merge insights from physiological ecology, stress theory, and population genetic theory to develop integrated, operational criteria for assessing the relative endangerment of diverse organisms to climate change and fall into four general categories (Table 1). Group I criteria are Ecological traits mostly pertaining to population sizes, trends and range size. Group II criteria pertain to physiological capacity and tolerance. Group III criteria consist of both genetic and non-genetic measures of dispersal. Group IV criteria pertain to evolutionary potential and include measures of genetic diversity and population structure as well as demographic and life historical traits.

From the formation of ideas to the conceptual list summarized in Table 1, ICFAREC developed a large number of operational criteria that could be applied to real data for a species to generate an objective conclusion about that species for each trait. The scheme was partially modeled on the extinction vulnerability criteria originally advanced by the International Union for the Conservation of Nature (IUCN) Red List assessment process (IUCN, 2001, 2011). The ICFAREC scheme includes 27 detailed criteria (Table S1 in Supporting Information S1) across four categories describing different species traits that are hypothesized to be related to resistance to climate change. Group I criteria pertain to ecological data such as range size and population trends, many but not all of which overlap with endangerment criteria long-established by IUCN (IUCN, 2001, 2011). The remaining criteria (Groups II, III, and IV; Table 1, Table S1 in Supporting Information S1) are based upon ongoing research themes in the literature that are attempting to understand whether and how species' traits—biological properties of species—may predict how they will respond to climate change (e.g., Bernardo, 2014; Bernardo et al., 2007).

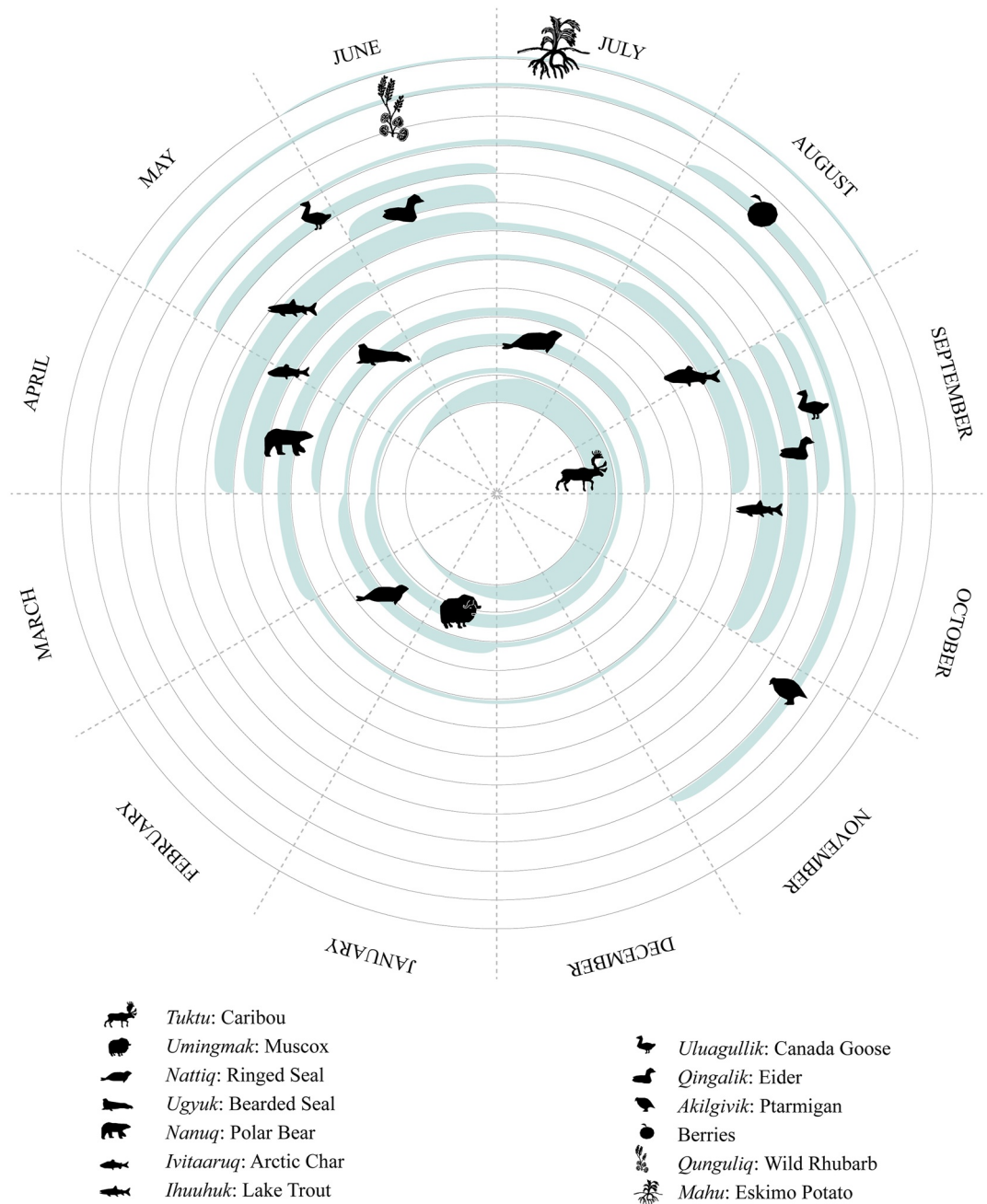
In addition to defining specific, operational criteria, the ICFAREC group drew upon the primary literature to define a priori thresholds (most quantitative, some qualitative) for each criterion to assign a species to one of three vulnerability states (Table 3). A value of +1 was assigned to species that were judged to be highly *vulnerable*. A value of 0 was assigned to species that exhibited moderate resistance and thus were judged to be along the continuum as somewhat vulnerable or *resilient*. A value of −1 was assigned to species that were judged not vulnerable or *resistant*.

### 3.1.2. Implementation

We used a biodiversity informatics/ecoinformatics approach to obtain and assemble species trait data related to the vulnerability criteria. These data were drawn from a broad variety of sources including the primary literature, government reports and assessments, scholarly books, and authoritative websites. We used Google Scholar searching on key word combinations that included species' Latin binomina in conjunction with key words such as “range size,” “basal metabolic rate” or “genetic variability.” We employed a wide variety of key words within each criterion to find relevant works (Table S2 in Supporting Information S1). Each paper was carefully reviewed for parameter estimates relating to specific criteria, and relevant data were assembled on worksheets for each species. The final score for each criterion was included in a spreadsheet (Table S5A in Supporting Information S1) which was also color coded as follows: blue indicated a −1, yellow indicated a 0, red indicated a 1, and gray indicated that the criterion was data deficient. Data deficient means that an effort was made to locate data relevant to that criterion, but none or insufficient data to make a determination were found.

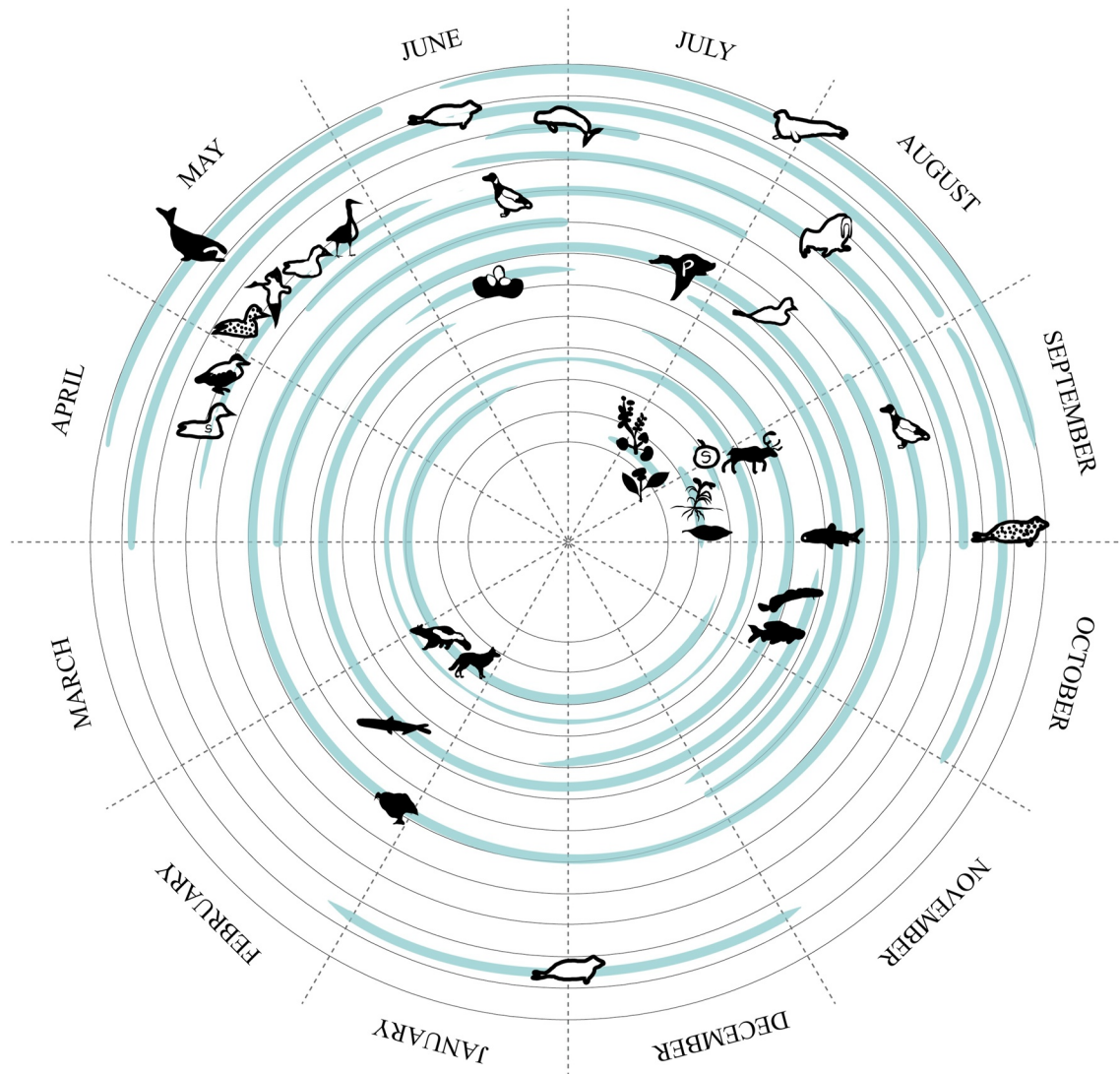
In order to streamline the flow of this paper around the topic at hand, additional and extensive methodological details concerning the ICFAREC protocols and methods as well as validity analyses are to be found in Supporting Information S1. For example, the detailed matrix species  $x$  criterion of assessment results is found in Tab 2





**Figure 8.** (a, b) These figures illustrate seasonal rounds for the communities of Ulukhaktok and Wainwright based on prior participatory research (Kassam & Wainwright Traditional Council, 2001, p. 63; Kassam, 2009, p. 118). Seasonal rounds summarize the timing and duration of availability of the entire food species basket of an Indigenous community. They “are deliberative articulations of a community’s sociocultural relations with their ecological system” (Kassam, Ruelle, et al., 2021, p. 509). Specifically, they provide the foundation for the species list generated for the case study (see Table 2). The extent of the blue lines indicates seasonal availability of each species, and thickness of the lines refers to the relative intensity of hunting, fishing, and gathering. The thicknesses of the lines are not strictly comparable between the figures but are simply a qualitative illustration. These rounds include birds and plants which were not all part of the focal species used in this analysis and are included here for completeness. The seasonal rounds also reiterate the overall difference in species richness and biodiversity between the two communities (see Figure 9).





- |   |   |  |  |
|---|---|--|--|
|  <i>Agviq</i> : Bowhead Whale    |  <i>Aahaaliq</i> : Long-tailed Duck    |  <i>Nigliiqaq</i> : Pacific Black Brant |  <i>Aqpik</i> : Salmonberries         |
|  <i>Sisuaq</i> : Beluga Whale    |  <i>Niglivik</i> : White-fronted Goose |  <i>Qargiq</i> : Willow Ptarmigan       |  <i>Qavvik</i> : Wolverine            |
|  <i>Ugruk</i> : Bearded Seal     |  <i>Kanuq</i> : Snow Goose             |  <i>Mannik</i> : Eggs                   |  <i>Amaguk</i> : Wolf                 |
|  <i>Quasigiaq</i> : Spotted Seal |  <i>Qinalik</i> : King Eider           |  <i>Qunulliq</i> : Wild Rhubarb         |  <i>Tuttu</i> : Caribou               |
|  <i>Natchiq</i> : Ringed Seal    |  <i>Qavaasug</i> : Spectacled Eider    |  <i>Sargigruaq</i> : Stinkweed          |  <i>Ilhuagniq</i> : Rainbow Smelt     |
|  <i>Aiviq</i> : Pacific Walrus   |  <i>Amauligruaq</i> : Common Eider     |  <i>Masu</i> : Eskimo Potato            |  <i>Tittaaliq</i> : Lingcod           |
|  <i>Kurugaq</i> : Pintail        |  <i>Tuutalluk</i> : Steller's Eider    |  <i>Uqpik</i> : Willow Leaves           |  <i>Sulukpaugaq</i> : Arctic Grayling |
|   |   |  |  <i>Tipuk</i> : Bering Cisco          |

Figure 8. (Continued)

of Table 5A in Supporting Information S1. These scores are the result of the assessment process, but they form the raw data for the actual analyses relevant to the questions posed in this paper and which are described below.

### 3.2. Analysis

Criterion scores were averaged to produce an overall “vulnerability score” for each species. To evaluate whether the new criteria (I.F–IV.D) gave concordant signal of vulnerability to the extant IUCN criteria (I.A–I.E) we regressed the species-specific average score from the new criteria against the species-specific average score from the IUCN criteria. We used analysis of variance (ANOVA) to test for a variety of differences in vulnerability scores across several dimensions: between the two criteria subsets (Table S6 in Supporting Information S1), among taxonomic groups (marine mammals, terrestrial mammals, fish), as well as whether criteria concordance differed depending upon which taxonomic group was being considered (Table S7 in Supporting Information S1).

### 3.3. Results

Below we will examine differences in species utilization by each of the two indigenous communities; explain the vulnerability assessment; explore ecological, physiological, dispersal, and evolutionary potential criteria; illustrate the value of the criteria used here; and provide a synthesis of the vulnerability assessment.

#### 3.3.1. Community Differences in Species Utilization

We evaluated 43 species of mammals and fish that are used by the two communities, including seven species of marine mammals, 12 species of terrestrial mammals, and 26 species of fish (Table 2). Four of these species (*Delphinapterus leucas*, *Ursus maritimus*, *Rangifer tarandus*, and *Salvelinus alpinus alpinus*) were comprised of distinct stocks occupying different areas which are used by the Inupiat of Wainwright and the Inuvialuit of Ulukhaktok.

There are clear differences between the two indigenous communities in both the total number of species used, and the availability of community-specific biodiversity resources. The community of Wainwright utilizes nearly twice as many species as Ulukhaktok (W: 36, U: 20; Table 2, Tables S4 and S5A Tab 1 in Supporting Information S1, Figure 9) with most of this difference attributable to having a greater proportion of exclusive species (Wainwright: 69%, Ulukhaktok: 45%; Table S5A in Supporting Information S1, Figure 9). Ulukhaktok has about the same number of exclusive species and shared species, whereas Wainwright has more than twice as many exclusive as shared species. The difference is mostly driven by terrestrial mammal and fish species exclusively used by Wainwright (Table S4 in Supporting Information S1, Figure 9).

#### 3.3.2. Summary of Research Effort and Extent of Information Gathered for Vulnerability Assessment Exercise

There was a total of 47 entities (43 species, 4 of which were represented by two genetic stocks (see Figure 9 and Table 2)) that had to be assessed across 27 criteria, a total of 1,269 assessment determinations. Bernardo and a student research associate, Victoria Roth, examined over 2,700 information resources over 3 years to complete the effort.

This exercise resulted in an average of  $13.28 \pm 0.41$  criteria/species being successfully assessed. Table 3 summarizes the descriptive statistics of vulnerability scores for criteria subsets and in aggregate scores for each taxon group and across all taxa. There were no major differences among the major organismal groups in terms of information we were able to use for assessments, as evidenced by the similar average number of criteria assessed (Table 3).

#### 3.3.3. Comparisons of Vulnerability Scores Between Criteria Subsets and Across Taxonomic Groups

Table 2 also summarizes the mean, standard error (SE) and range of criteria scores broken down by criteria subsets and taxonomic groups. The three taxonomic groups vary somewhat in average vulnerability score, but not substantially, with marine mammals exhibiting  $-0.45 \pm 0.08$  overall, terrestrial mammals with  $-0.55 \pm 0.04$ , and fish with  $-0.57 \pm 0.03$ . The grand mean score across all species was  $-0.54 \pm 0.03$  (Table 3).

**Table 2**  
Summary of Species Used in the Wainwright and Ulukhaktok Communities

	Species binomen	Common name	Species only in Wainwright	Species only in Ulukhaktok	Species in both
Mammalia:Cetacea: Balaenidae	<i>Balaena mysticetus</i>	Bowhead Whale	x	–	–
Mammalia:Cetacea:Monodontidae	<i>Delphinapterus leucas</i>	Beluga Whale	–	–	x <sup>a</sup>
Mammalia:Carnivora:Phocidae	<i>Phoca hispida</i>	Ringed Seal	–	–	x
Mammalia:Carnivora:Phocidae	<i>Phoca largha</i>	Spotted Seal	x	–	–
Mammalia:Carnivora:Phocidae	<i>Erignathus barbatus</i>	Bearded Seal	–	–	x
Mammalia:Carnivora:Ursidae	<i>Ursus maritimus</i>	Polar Bear	–	–	x <sup>b</sup>
Mammalia:Carnivora:Odobenidae	<i>Odobenus rosmarus</i>	Pacific Walrus	–	–	x
Mammalia:Artiodactyla:Cervidae	<i>Rangifer tarandus</i>	Caribou	–	–	x <sup>c</sup>
Mammalia:Carnivora:Mustelidae	<i>Gulo gulo</i>	Wolverine	x	–	–
Mammalia:Artiodactyla:Bovidae	<i>Ovibos moschatus</i>	Muskox	–	–	x
Mammalia:Carnivora:Canidae	<i>Canis lupus</i>	Wolf	–	–	x
Mammalia:Carnivora:Canidae	<i>Alopex lagopus</i>	Arctic Fox	–	–	x
Mammalia:Carnivora:Canidae	<i>Vulpes vulpes</i>	Red Fox	x	–	–
Mammalia:Carnivora:Felidae	<i>Lynx canadensis</i>	Lynx	x	–	–
Mammalia:Carnivora:Mustelidae	<i>Lutra canadensis</i>	River Otter	x	–	–
Mammalia:Rodentia:Erethizontidae	<i>Erethizon dorsatum</i>	Porcupine	x	–	–
Mammalia:Rodentia:Sciuridae	<i>Marmota broweri</i>	Marmot	x	–	–
Mammalia:Rodentia:Sciuridae	<i>Citellus parryi</i>	Arctic Ground Squirrel	x	–	–
Mammalia:Carnivora:Mustelidae	<i>Mustela nivalis</i>	Ermine	x	–	–
Mammalia:Lagomorpha:Leporidae	<i>Lepus arcticus</i>	Arctic Hare	–	x	–
Scorpaeniformes:Cottidae	<i>Myoxocephalus quadricornis</i>	Fourhorn Sculpin	–	–	x
Osmeriformes:Osmeridae	<i>Osmerus rnordax</i>	Rainbow Smelt	x	–	–
Gadiformes:Gadidae	<i>Lota lota</i>	Lingcod, American burbot	x	–	–
Pleuronectiformes:Pleuronectidae	<i>Liopsetta glacialis</i>	Flounder	x	–	–
Gadiformes:Gadidae	<i>Boreogadus saida</i>	Arctic Cod	x	–	–
Gadiformes:Gadidae	<i>Gadus ogac</i>	Greenland Cod	–	x	–
Gadiformes:Gadidae	<i>Arctogadus glacialis</i>	Polar or Arctic Cod	–	x	–
Gadiformes:Gadidae	<i>Eleginus gracilis</i>	Saffron Cod	–	x	–
Osmeriformes:Osmeridae	<i>Mallotus villosus</i>	Capelin	x	–	–
Salmoniformes:Salmonidae	<i>Thymallus arcticus</i>	Arctic Grayling	x	–	–
Salmoniformes:Salmonidae	<i>Coregonus autumnalis</i>	Arctic Cisco	–	x	–
Salmoniformes:Salmonidae	<i>Coregonus laurettae</i>	Bering Cisco (inconnu)	x	–	–
Salmoniformes:Salmonidae	<i>Coregonus pidschian</i>	Humpback Whitefish	x	–	–
Salmoniformes:Salmonidae	<i>Coregonus nasus</i>	Broad Whitefish	–	–	x
Salmoniformes:Salmonidae	<i>Coregonus clupeaformis</i>	Lake Whitefish	–	x	–
Salmoniformes:Salmonidae	<i>Prosopium cylindraceum</i>	Round Whitefish	x	–	–
Salmoniformes:Salmonidae	<i>Oncorhynchus gorbuscha</i>	Humpback Salmon, Pink Salmon	x	–	–
Salmoniformes:Salmonidae	<i>Oncorhynchus kisutch</i>	Coho, Silver Salmon	x	–	–
Salmoniformes:Salmonidae	<i>Oncorhynchus nerka</i>	Sockeye salmon	x	–	–
Salmoniformes:Salmonidae	<i>Oncorhynchus tshawytscha</i>	King or Chinook Salmon	x	–	–
Salmoniformes:Salmonidae	<i>Salvelinus alpinus alpinus</i>	Arctic char	–	x <sup>d</sup>	–

**Table 2**  
Continued

	Species binomen	Common name	Species only in Wainwright	Species only in Ulukhaktok	Species in both
Salmoniformes:Salmonidae	<i>Salvelinus namaycush</i>	Lake trout	–	–	x
Clupeiformes:Clupeidae	<i>Clupea harengus</i>	Herring	–	x	–

<sup>a</sup>Wainwright uses both Beaufort and Chukchi stocks; Ulukhaktok uses only Beaufort stock. <sup>b</sup>Wainwright uses both Beaufort and Chukchi/Bering stocks; Ulukhaktok uses only Beaufort stock. <sup>c</sup>Wainwright uses only Alaska stocks; Ulukhaktok uses only Northwest Territories stock. <sup>d</sup>This species comprises two stocks: one landlocked, one oceanic.

### 3.3.4. Discordance Between IUCN Criteria and New Vulnerability Criteria

In order to assess relative vulnerabilities of these population food supplies to climate change, we first asked whether the new criteria studied here, which were purposely designed to capture vulnerability related to climate change, provided any novel insights into climate change vulnerability compared with IUCN criteria. Table 4 summarizes the average and the range of vulnerability scores broken down by criteria subsets and taxonomic groups. On average, we were able to evaluate 4.26 out of six IUCN criteria and 13.28 out of 21 new criteria.

The vulnerability scores based on IUCN criteria were uncorrelated with those estimated from all of the new criteria taken together ( $r^2 = 0.018$ ,  $n = 47$ ,  $p = 0.3703$ ). This discordance in vulnerability scores was confirmed by ANOVA (Table S6 in Supporting Information S1:  $F_{1,93} = 139.8752$ ,  $p < 0.0001$ ). There was no significant difference among taxon groups although there was a marginally insignificant interaction term (Table S6 in Supporting Information S1).

It was also useful to ask whether the different categories of criteria are providing additional useful information to assess climate change vulnerability, or whether they are simply redundant to each other. One way to do this was to examine the bivariate correlations between all pairwise combinations of criteria. This exercise is summarized in Figure S1 in Supporting Information S1 which shows all the pairwise correlations and the correlation coefficients. In short, the conclusion that is readily drawn is that there is limited correlation structure between criteria classes. Thus, the new criteria added more than three times the information about vulnerability, and distinct information as well. Because the new criteria yield more and different information from the IUCN criteria, hereafter we consider the aggregate vulnerability score from all criteria taken together.

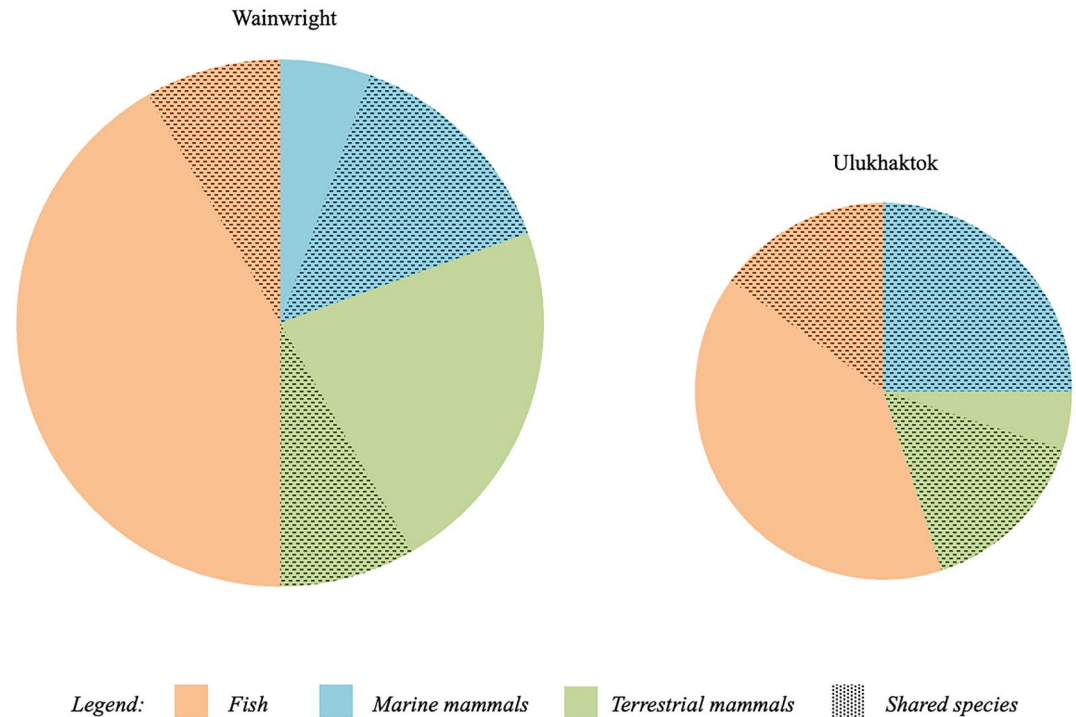
### 3.3.5. Comparisons Across Ecological, Physiological, Dispersal, and Evolutionary Potential Criteria

Considering only ecological criteria (Table S1 in Supporting Information S1, Criteria I.A.–I.H., which include the current IUCN criteria, I.A.–I.E.), most of the species would be considered “not vulnerable.” We obtained data for at least three of the nine ecological criteria for all species. For marine mammals, we obtained data for at least six of eight ecological criteria (one criterion, altitudinal breadth, is undefined for marine species). These data indicated that six of seven species are “not vulnerable”, excepting the Pacific walrus. For terrestrial mammals, we obtained data for at least five of the nine ecological criteria, which similarly indicated that most species are not vulnerable. The lone exception was the marmot, for which several criteria indicated moderate to high vulnerability. Lastly, for fish we obtained data for at least three of the eight criteria. As for the mammals, the overwhelming conclusion from these criteria is a lack of vulnerability. A notable exception was *Thymallus arcticus* in which recent trends in population size caused two criteria to be assigned the “highly vulnerable” status.

In contrast to the purely ecological criteria, the physiological, dispersal and evolutionary potential criteria reveal latent vulnerabilities across many species. As an example, the Dispersal criteria (Table S1 in Supporting Information S1, Criteria III.A.1.–III.A.2.) showed a wide array of dispersal abilities among the studied species. For instance, both marine and terrestrial mammals, where data were sufficient, were largely judged to be effective dispersers and therefore were assigned “not vulnerable” status. By contrast, fish displayed greater diversity in dispersal ability with several species being judged to have modest or poor dispersal. In general, the data show Salmoniformes to be excellent dispersers, whereas other groups, mainly coastal (shelf) and marine species, are less effective dispersers.

As another example, Evolutionary Potential criteria (Table S1 in Supporting Information S1, Criteria IV.A.–IV.D.) exhibited considerable variation across species. In terms of life histories, the marine mammals were





**Figure 9.** Comparative species richness and exclusivity of Wainwright and Ulukhaktok communities with respect to marine and terrestrial mammals, and fish. Proportional representation of terrestrial mammals (green), marine mammals (blue), and fish (orange) in the diets of the focal populations. Stippled slices illustrate unexclusive species. The areas of the pies are proportional to the total number of species in the diet (Table S4 in Supporting Information S1).

assessed as “highly vulnerable” because they all have long generation times, low fecundities, and modest population size. By contrast, the fish were largely assessed as not vulnerable because of their shorter generation times, high fecundities, and relatively large population sizes. The terrestrial mammals displayed broad variation in these life history traits and therefore a diversity of vulnerability scores. Other evolutionary potential criteria, based on neutral marker diversity and phylogeography revealed a wide range of vulnerability scores across all the species.

### 3.3.6. Synthesis and Discussion: Differences in Vulnerability of Food Assemblages Between Focal Indigenous Populations

Now that we have examined the success of the approach in terms of data availability and the usefulness of the criteria, we can address the results pertaining to the question at hand: How vulnerable to climate change are the food systems of two similar subsistence hunter-fisher Indigenous societies that have both similarities and overlap in their food systems, but also some distinctiveness culturally and in terms of biodiversity within their habitats (Figure 9).

Table 4 summarizes the aggregate vulnerability scores of each focal population's food supply, broken down by taxonomic groups. Vulnerability scores were very similar between the two populations, whether considered within each taxonomic group or overall, a result confirmed by ANOVA (Table S7 in Supporting Information S1). Thus, although Ulukhaktok uses far fewer species than Wainwright, the sets of species the two populations use are equivalently vulnerable to climate change. However, ANOVA did indicate a difference in vulnerability scores among taxonomic groups. This result contrasts with the overall analysis of the criteria which indicated no such difference (Table S7 in Supporting Information S1). This difference arises when we statistically account for which particular subsets of species are used by each human community.

The four criteria classes (ecological, physiological, dispersal, evolutionary potential) were completely uncorrelated or, in one case, weakly correlated (Figure S1 in Supporting Information S1) indicating that they are providing independent (non-redundant) information about vulnerability. Hence the new criteria are illuminating latent vulnerability implying arctic species are more vulnerable to climate change than would be predicted according

**Table 3**  
*Descriptive Statistics of Vulnerability Scores for Criteria Subsets and in Aggregate Scores for Each Taxon Group and Across All Taxa*

Taxon group	Criteria	Average score $\pm$ SE	Range	Criteria evaluated <sup>a</sup> ( $n \pm$ SE)
Marine Mammals ( $n = 9$ )	IUCN	$-0.89 \pm 0.11$	Min: $-1.00$ Max: $0.00$	$4.11 \pm 0.42$
	New	$-0.20 \pm 0.09$	Min: $-0.56$ Max: $0.17$	$8.00 \pm 0.58$
	Overall	$-0.45 \pm 0.08$	Min: $-0.69$ Max: $0.10$	$12.11 \pm 0.66$
Terrestrial Mammals ( $n = 14$ )	IUCN	$-1.00 \pm 0.00$	–	$4.21 \pm 0.11$
	New	$-0.31 \pm 0.07$	Min: $-0.70$ Max: $0.33$	$9.00 \pm 0.52$
	Overall	$-0.55 \pm 0.04$	Min: $-0.79$ Max: $-0.20$	$13.21 \pm 0.57$
Fish ( $n = 24$ )	IUCN	$-0.87 \pm 0.06$	Min: $-1.00$ Max: $0.00$	$4.33 \pm 0.13$
	New	$-0.41 \pm 0.03$	Min: $-0.67$ Max: $-0.13$	$9.42 \pm 0.63$
	Overall	$-0.57 \pm 0.03$	Min: $-0.77$ Max: $-0.21$	$13.75 \pm 0.69$
All Taxa ( $n = 47$ )	IUCN	$-0.91 \pm 0.04$	Min: $-1.00$ Max: $0.00$	$4.26 \pm 0.11$
	New	$-0.34 \pm 0.03$	Min: $-0.70$ Max: $0.33$	$9.02 \pm 0.38$
	Overall	$-0.54 \pm 0.03$	Min: $-0.79$ Max: $0.10$	$13.28 \pm 0.41$

<sup>a</sup>Not data deficient.

**Table 4**  
*Descriptive Statistics of Vulnerability Scores for Focal Populations for Each Taxon Group and Across All Taxa*

Taxon group	Population							
	Wainwright				Ulukhaktok			
	Number of species	Mean criteria score $\pm$ SE	Range of criteria score	Criteria evaluated <sup>a</sup> ( $n \pm$ SE)	Number of species	Mean criteria score $\pm$ SE	Range of criteria score	Criteria evaluated <sup>a</sup> ( $n \pm$ SE)
Marine mammals	9	$-0.45 \pm 0.08$	Min: $-0.69$ Max: $0.10$	$12.11 \pm 0.66$	5	$-0.38 \pm 0.13$	Min: $-0.69$ Max: $0.10$	$11.6 \pm 0.81$
Terrestrial mammals	12	$-0.54 \pm 0.04$	Min: $-0.79$ Max: $-0.20$	$13.17 \pm 0.59$	5	$-0.58 \pm 0.06$	Min: $-0.79$ Max: $-0.40$	$13.2 \pm 1.16$
Fish	16	$-0.57 \pm 0.14$	Min: $-0.77$ Max: $-0.21$	$14.13 \pm 0.91$	11	$-0.56 \pm 0.05$	Min: $-0.77$ Max: $-0.31$	$12.91 \pm 0.72$
All taxa	37	$-0.53 \pm 0.03$	Min: $-0.79$ Max: $0.10$	$13.32 \pm 0.48$	21	$-0.52 \pm 0.04$	Min: $-0.79$ Max: $0.10$	$12.67 \pm 0.50$

<sup>a</sup>Not data deficient.

to the original IUCN criteria. This implies that the new criteria are a valuable tool for quantitatively evaluating a species' vulnerability to climate change. For example, in four species of salmonids (*Oncorhynchus nerka*, *Oncorhynchus kisutch*, *Oncorhynchus tshawytscha*, and *Oncorhynchus gorbuscha*), safety margins (Criterion II.E.2.) ranged from 8.9° to 13.6°C under current conditions and 8.3°–13°C under future conditions. This indicates that all four species have substantial latent capacity to tolerate extreme habitat temperatures. By contrast, the performance optima (Criterion II.F) of all four species are currently closely aligned or slightly lower than contemporary habitat temperatures (0.23°–2.9°C lower than optimum), but future temperatures will push all four species slightly or well past their  $T_{opt}$  (0.58°–3.25°C higher than optimum). Therefore, the impacts of climate change will be realized via extended periods of diminished performance and consequent sublethal effects on fitness, rather than through direct mortality selection.

Despite the conclusion that the studied species have more vulnerability to climate change than expected from IUCN criteria, they are relatively less vulnerable than has generally been surmised based on nonevaluative reasoning. Numerous overviews of arctic biodiversity susceptibility to climate change have concluded that arctic organisms are going to be highly vulnerable to climate change (Reviewed by Robinson (2022)). However, these conclusions seem to be based more on the magnitude of expected environmental change but little to do with the actual sensitivity of the species. Our approach, which examines species traits related to various dimensions of responding to climate change (physiological tolerance, dispersal capability, evolutionary potential) overall, lead to a different conclusion which is that arctic species have a surprising amount of biological capacity to respond adaptively to climate change.

As we argued earlier (Figures 5 and 6), the concept of food sovereignty for subsistence hunter-fisher populations is an emergent property of the cultural system and Indigenous knowledge (including ecological calendars), which are in turn underlain by the ecological system itself—the biodiversity of organisms that act simultaneously as both indicators in ecological calendars and as food organisms. However, strikingly, and despite a large research program examining food security and food sovereignty in Indigenous populations (reviewed above), researchers have not examined in detail in any system, to our knowledge, the vulnerability of a subsistence population to a changing climate through an empirical lens of how the organisms on which they depend will respond.

How resistant or vulnerable are the food systems of these communities, and what are the implications for both ecological calendars and food security? In this case study, we demonstrate that overall, the aggregate sets of species (based on the taxonomic groups we included, which comprise a large fraction of the diets) used in these two communities are *Resilient to climate change somewhat resistant as well*. Recall that the vulnerability score continuum ranges from +1 to –1, with –1 being the most resistant, and +1 being most vulnerable. The mean scores for each community are statistically identical: Wainwright:  $-0.53 \pm 0.03$ ; Ulukhaktok:  $-0.52 \pm 0.04$  (Table 4). Which are not completely resistant but certainly on the overall higher end that indicates a high degree of resilience and resistance. Consequently, we can conclude that the resistance or resilience of the food systems applies to the ecological calendars as well. Recall from Figure 6 that biodiversity is the foundation underlying ecological calendars. Furthermore, coupled with a vibrant and dynamic cultural system combined with local or Indigenous place-based knowledge, communities are able to exercise their food sovereignty and food security emerges from these linked sociocultural and ecological processes.

One key finding from our approach is that there were no systematic differences in vulnerability scores among the three taxonomic groups, indicating that the overall system's stability (e.g., not marine vs. terrestrial, not mammals vs. fish) drives the vulnerability of human populations. It is true that certain species are more vulnerable than others, but our finding that overall vulnerabilities of the species assemblages utilized by Wainwright and Ulukhaktok are essentially identical implies that they have equivalent food security risk. However, the fact that Ulukhaktok uses far fewer species implies that the loss of a few species would have disproportionate effects on overall food security compared with Wainwright for which the loss of a few species would be expected to have lower overall impact. Ulukhaktok utilizes fewer species in each taxonomic group than Wainwright, and overall, 43% fewer species (Table S4 in Supporting Information S1 and Figure 9). Nonetheless, not every species will persist within this region in numbers that are sustainably accessible for human consumption. Shifts in spatial occupancy could affect food security, although our data do not describe this effect.

#### 4. Overall Conclusion and Next Steps

We have drawn on examples of seasonal indicators using ecological calendars of farming and herding societies. Furthermore, the methodological proof-of-concept offered herein provides an example from modern-day fishing and hunting communities in the Arctic. To demonstrate the applicability of our methodology, we have covered at least four ecological professions (farming, herding, fishing, and hunting). We believe this approach is more widely applicable to other such communities globally. In addition, this approach could be useful to human endeavors that are significantly tied to their habitat such as ecotourism, environmental stewardship, road and other physical infrastructure construction et cetera. These activities fundamentally depend on biodiversity and cultural diversity within specific habitats. The very act of socioeconomic and political governance of coastal, forest, mountain and other environments depends upon this type of sensitivity to ecological details. While there was keen interest from farmers, fishers, herders, hunters, and orchardists in our research cocreating new ecological calendars and identifying indicator species, its relevance to other professions is understated. For instance, in the Oneida Lake Watershed, bait and tackle shop owners, fishing and hunting operators, the Sheriff's office, and New York State Environmental Conservation Police also saw value in ecological calendars research and participated in collaborative cogeneration of insights. Although seemingly removed, societal governance structures and entrepreneurial endeavors directly benefit from this work in their decision making and policy formulation. Arguably, it is this type of cognitive dissonance that has brought humanity to the abysmal edge of the climate crisis.

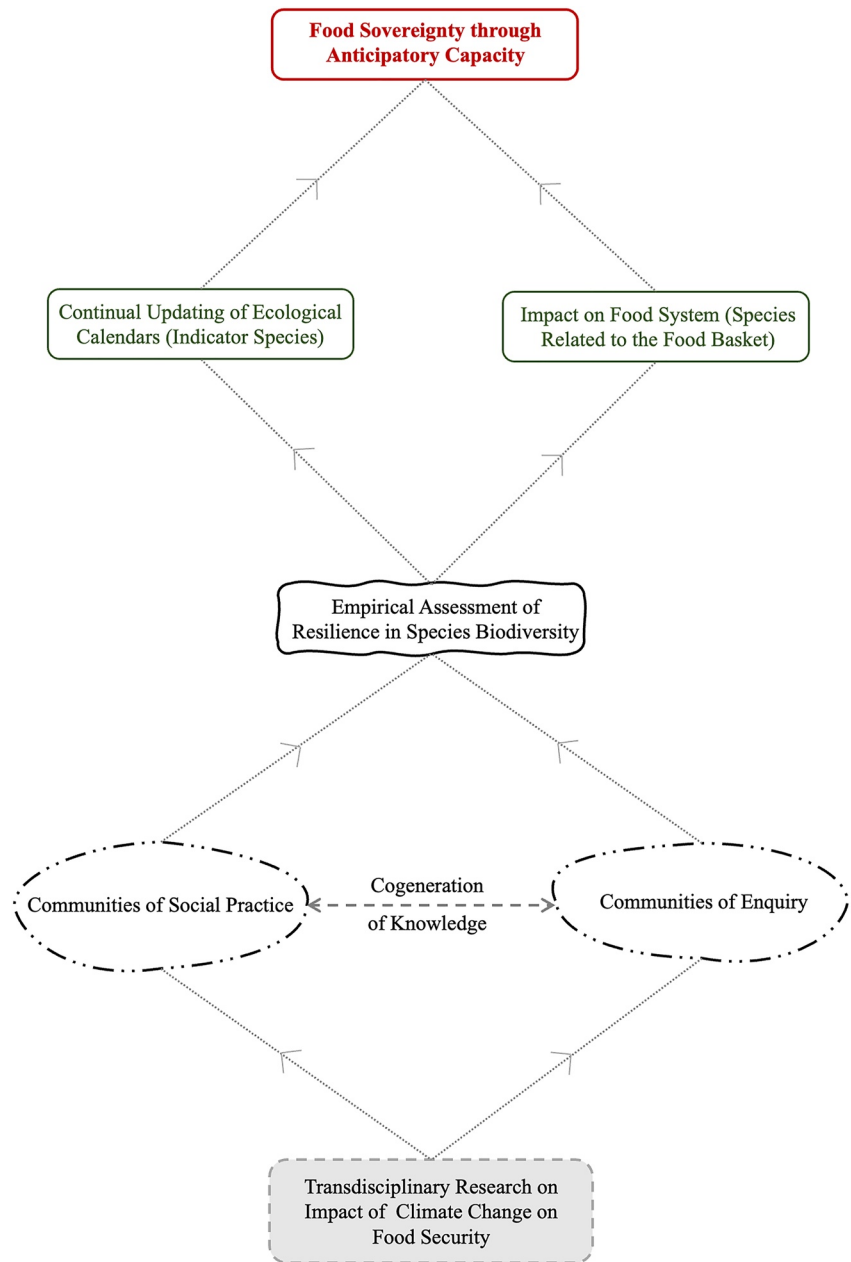
Historically, externally imposed social governance structures have been the greatest threat to sustainable use and application of ecological calendars through colonialism and cultural genocide of Indigenous populations. We and others have documented the impact of these forces on ecological calendars, in particular, and Indigenous knowledge, in general (Battiste & Youngblood Henderson, 2000; Kassam et al., 2011, 2018; Kimmerer, 2013; Whyte, 2017). Again, arguably, the Anthropocene is a direct result of societies and their institutions that devalue intellectual pluralism, cognitive diversity, and specifically Indigenous and local knowledge. Similarly, these oppressive structures weakened or diminished the food sovereignty of communities and placed them in a food insecure situation thereby, creating dependency on the very institutions that oppress them. Food sovereignty addresses strategic needs by challenging and rearticulating power relations through control of resources in the food system to achieve self-determination. While outside the focus of this paper, it is necessary to clearly state the relevance of future investigation of how the undermining of knowledge systems that inform ecological calendars has also weakened food sovereignty and jeopardized food security.

This proof-of-concept opens-up two key areas of future research (Figure 10). First, is the aim of this paper; namely, in collaboration with Indigenous knowledge holders, inquiry into indicator species that are resilient or resistant to climate change and determination of vulnerable species that may require to be substituted. Second, this proof-of-concept reveals that it is useful in assessing the impact of climate change on the food system itself. Both these approaches build anticipatory capacity. The first strengthens the role of ecological calendars as a mechanism to anticipate seasonal change and the second helps determine which food sources are viable in the climate crisis. Both facilitate the exercise of local food sovereignty and enhance regional and national level food security. We conclude with a recommendation that echoes our initial remarks in the introduction—effective future research will necessitate continued transdisciplinary collaboration that valorizes multiple ways of knowing through cogeneration of insights between *communities of social practice* and *communities of enquiry*.

#### Conflict of Interest

The authors declare no conflicts of interest relevant to this study.





**Figure 10.** Model for participatory transdisciplinary research and cocreation of knowledge. This figure outlines the transdisciplinary research process that utilizes multiple ways of knowing valorizing the diversity of Indigenous or local knowledge in tandem with the biophysical and social sciences as well as the humanities. Examples 1 and 2 speak to the role of this empirical approach in monitoring the impact of climate change on indicator species to regularly update ecological calendars. Example 3 uses the assessment to determine impact on the food species directly. With this proof-of-concept we recommend its continued application and improvement for future research on food sovereignty and anticipatory capacity to climate change.

## Data Availability Statement

Figures were made with Microsoft PowerPoint 16.0. 11727.20104 under Cornell University Microsoft Office 365 license (<https://www.microsoft.com/en-us/education/products/office>), Adobe Illustrator 2022 version 26.4.1, Adobe Photoshop 2022 version 23.4 under Cornell University Adobe Creative Cloud license (<https://www.adobe.com/education.html>). Maps were made with QGIS\_LTR long term release version 3.22 (<https://www.qgis.org/en/site/>)—Oneida Lake Watershed source: <https://www.water.usgs.gov>, Map imagery source: <https://www.maps.google.com>, post processing on Adobe Illustrator 2022 version 26.4.1, Adobe Photoshop 2022 version 23.4 and Adobe Indesign 2022 version 17.0 under Cornell University Adobe Creative Cloud License (<https://www.adobe.com/education.html>).

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## Acknowledgments

Funding for Research in the Arctic Communities of Ulukhaktok, Northwest Territories, Canada and Wainwright, Alaska, USA was provided by the Cooperative Institute for Arctic Research (CIFAR) supported by the National Oceanic and Atmospheric Association (NOAA) and the Human Dimensions of the Arctic System (HARC) supported by the National Science Foundation (NSF). Seed funding was provided by the Cornell Atkinson Center for A Sustainable Future's “Academic Venture Fund—Ecological Calendars to Anticipate Climate Change” Project which facilitated research in Oneida Lake Watershed. International funding for research in the Pamir Mountains of Central Asia was provided by the “Mountains as Sentinels of Change—Collaborative Research Belmont Forum: Ecological Calendars and Climate Adaptation in the Pamirs (ECCAP)” Project, supported by the National Science Foundation (NSF, Award Number 1630490). Funding to support open access publication of this work was provided by the Rita Allen Foundation under agreement NS-2111-02233. The authors wish to express our great appreciation to the ICFAREC (Integrative Conceptual Framework for Assessing Relative Endangerment due to Climate Change) working group members (Salvatore J. Agosta, Jennifer E Buhay, Keith A. Crandall, Suzanne Estes, Cameron K. Ghalambor, Matthew Hare, Ary Hoffmann, Hans-Otto Pörtner, Jonathon Stillman, Kelly Zamudio) The authors also thank the Cornell University Atkinson Center for Sustainability, and the Encyclopedia of Life Biodiversity Synthesis Center at the Field Museum and its director, Mark Westneat for seed funding to support the two workshops that produced the criteria scheme used here. Undergraduate Research Assistant Victoria Roth worked diligently, over a 3-year period, to help develop the Empirical Case Study presented in this paper. Graduate Research Assistant Aishwarya Shankar helped design the figures presented this paper. The authors thank Raj Pandya, Guest Associate Editor, for this special collection, and the three anonymous reviewers for their valuable comments and suggestions on the manuscript. The authors are grateful for the logistical support provided by the Cornell Biological Field Station and University of Central Asia, Khorog Campus. Finally, none of this work would have been possible without the insightful contributions, direct participation, and generosity of the leadership and community members from Ulukhaktok, Northwest Territories, Canada; Wainwright, Alaska, USA; Oneida Lake, New York, USA; and Sary Mogul, Osh Region, Kyrgyzstan.

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