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PAPER

Integrated analysis of socio-ecological impacts on underground food storage in Beringia

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Abstract

Underground storage utilizing natural cold energy, a long tradition of communities in Beringia closely integrated within their lifeways, is challenged by malfunctions or difficulties in appropriate use, affecting food security and food sovereignty, and community wellbeing. Previous studies tend to center on physical aspects in individual ice cellar cases in permafrost zones. In this study, we investigated impacts of climate and socio-ecological changes on underground food storage through analysis of local community interviews and proactive dialogues between local community experts and scientists to illustrate (1) the roles of cold storage in supporting their sustainable foods and lifestyles, (2) the causes and factors related to the issue of dysfunction of and/or decrease in underground cold storage use and eventual decline in use, and (3) consequent losses and damages these changes brought. Thereby, we enhanced and applied a 'Food Life History' framework, a working hypothesis constructed to address human-environment issues in a holistic, multiperspectival, and integrated way. The results show that changes in underground cold storage practices are not caused by a single factor (e.g. climate change or permafrost degradation alone), but through a variety of agents that have influence on different time scales (e.g. colonization, globalization, food changes, technologies for subsistence). Included is a relational diagram depicting the interrelations of relevant factors impacting the role and functionality of underground cold storage practices of a tradition more than a century old. It will serve to provide suggestions for sharing ideas and intuitive understandings of current situations, and a template to address and examine key points and potential policy options for future planning with respect to the resilience and wellbeing of communities, fostering open and transparent discussion.

1. Introduction

The practice of food storage through the use of 'underground storage facilities utilizing natural cold energy such as frozen ground, ice, snow, and cold air' (hereafter, underground cold storage) has been employed for more than one hundred years, and likely much longer (Naiden 2025), by Indigenous communities in the Arctic, especially in the Beringia region (Alaska and eastern Siberia (Russian Far East), both coastal and inland areas). Traditions of underground cold storage are referred to by different terms in different languages: *siġḷuaq*/*hiġḷuaq* (Iñuipaq), *siqlugaq* (Siberian Yupik) or *elagyaq* (Central Yup'ik) in Alaska, and *buluus* (Sakha) and *lednik* (Russian) in Siberia. In the permafrost zones (areas where the ground freezes for many years in a row), storage space for long-term preservation, and in some cases for fermentation, was dug into the ground (e.g. Hughes 1960, Binford 1978, Jolles and Oozeva 2003, Burch 2006, Brubaker *et al* 2009,

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2011, Nyland *et al* 2017). Underground cold storage was/is mainly used for storing and/or preserving hunted meat (e.g. whales, walruses, caribou, etc) between harvest seasons, for community and individual needs. The form of the underground cold storage, however, varies from temporary caches to long-lasting cellars with deeper and larger structures. In the seasonally frozen ground zones (i.e. areas where only the surface layer freezes seasonally) in Alaska, a pit covered with insulation was used for temporary preservation during hunting and gathering (Andrew 2008).

Previous academic investigations of cold storage, mostly focusing on ice cellars in permafrost zones, tend to center on physical aspects of individual cases on the northern Alaskan coast (Klene *et al* 2012, Nyland *et al* 2017), the Russian Far East (Siberia) (Maslakov *et al* 2020), and the Sakha Republic (Yakutia) (Yoshikawa *et al* 2016). Yoshikawa *et al* (2022) provided histories and typologies of the various underground cold storage in the Beringian region. Saito *et al* (2024) reported the results of a preliminary interdisciplinary survey on underground cold storage uses that were conducted in the Beringia region (Alaska and eastern Siberia), Mongolia, and Japan from 2020 to 2023. Saito *et al* (2024) demonstrated and discussed the broad range of diversity in forms, styles, and uses of the underground cold storage practices, as well as their shared conditions and experiences closely related to their historical contexts and cultural identities. Their study suggested that the issue of decline in underground cold storage use is not only the result of climate change and permafrost degradation (a natural aspect), but also has social dimensions and ecological factors. During field research conducted in communities in the region over the past decade, we learned directly from local residents about recent changes in underground cold storage-use due to malfunctions, or difficulty in appropriate use, as had previous generations. In many cases their concerns have been associated with a warming environment in parallel with global-scale climate change (i.e. causes from the natural dimension) alongside the expanding global capitalist economy that creates product and production dependencies for local communities (the social dimension).

In this entire project, we seek to investigate and understand the integrated impacts of climatic and socio-ecological changes on cold storage practices through interdisciplinary dimensions, including investigations of natural, ecological, social, and other cultural aspects of the practice, and, ultimately, the subsequent effects on Beringian communities in terms of culture change, food security and food sovereignty, and its impact on overall wellbeing (FAO 1999, Nyéléni 2007, FAO *et al* 2021). We specifically focus on the storage component of the food system because it has been under-evaluated in previous investigations that put more attention on resources, power structures, and distribution patterns.

Through our systematic literature reviews focusing on topics of underground food storage and related issues, and learning from local knowledge holders about concerns for maintaining underground cold storage in their regions, our project developed several research questions: What are the factors that require(d)/enable(d)/condition(ed) underground cold storage use? What are the roles of cold storage in supporting sustainable foods and lifestyles? What are the causes and factors related to the issue of dysfunction of and/or decrease in the underground cold storage use? How are these factors related to underground cold storage and to each other, and how do they affect their use?

In addressing the underground cold storage issues from various aspects (e.g. different disciplines and methodologies) and scales (e.g. local and global), Saito *et al* (2024) proposed a conceptual working hypothesis, called 'Food Life History' (FLH), which is intended to provide a common framework to address human-environment issues of different sizes, locations, and socio-historical situations, and to evaluate and compare these issues comprehensively in a holistic and integrating way (e.g. examinations with respect to actors, perspectives, locations, and scales by employing multiple disciplines in a coordinated manner). We enhanced the construction of the conceptual framework proposed by Saito *et al* (2024) with theoretical orientation and background, and provided diagrams to demonstrate its application to Indigenous lifeways, and to contemporary urban lifeways. However, in Saito *et al* (2024), detailed discussions were not provided on the natural, social, and ecological background behind underground cold storage practices, the attributions and aspects of the relevant factors, and their interrelated influences.

In this paper, we focus on the Beringia region, especially in coastal and inland communities in western and northern Alaska, where we find the interconnection of natural, social, and ecological factors are most prominently observable. We review the general sociocultural background underlying the underground cold storage issue in the study region, from literature reviews on specific topics related to our research questions, onsite interviews during fieldwork, and dialogue between local community experts and researchers, and examine closely the relevant factors and situations that led to the current malfunction or decreased use of underground cold storage. We demonstrate qualitative relationships between these relevant factors within the FLH framework. The resulting tables and relational diagrams enable explicit representation of the issue within the context of related factors, will provide aides for sharing ideas and intuitive understandings of current situations, and a template to address and examine the issues for future planning.

2. Methods

2.1. Positionality

The project team is composed of academic researchers from Japan, the United States, and Russia, including men and women of various ages and cultures, some Indigenous and the majority non-Indigenous, and from multiple academic disciplines. With such diversity among members, the research team works to employ knowledge traditions from multiple backgrounds culturally and academically, and recognizes the value of local, traditional, and Indigenous knowledge. Our field research and analysis are overseen and reviewed by local community members and/or Indigenous researchers on the research team. Community members have participated in the research process according to their interests and preferences.

2.2. Study area

Beringia, a northern high-latitude region extending from northeasternmost Eurasia (Siberia/Russian Far East, Russia) to northwestern North America (Alaska and westernmost Canada) has a unique ecosystem and biota that evolved under cold and dry environments. During the glacial periods, it formed a large land area called the Beringia Land Bridge (Hopkins 1959), which was divided into Eurasian and North American parts after deglaciation. As such, it may be called the 'divided twins,' as the eco-climate system in both continental portions resembles each other greatly (Hopkins *et al* 1982). After these two continents were separated due to submergence, humans continued to socioeconomically maintain their societies through hunting, fishing, and plant gathering (Dixon 2013), and maintained interactions between both sides for thousands of years, as evidenced by DNA analyses (Moreno-Mayar *et al* 2018, Potter *et al* 2018, Flegontov *et al* 2019). The people living in the region nurtured and conveyed their own worldviews, food customs, and other traditions. Beringia has been a homeland of various Indigenous peoples for more than 14 000 years (Wygal 2018, Smith 2022). Indigenous peoples have been partially culturally, and fully politically, assimilated by colonizers through history to the present period. Indigenous people in Beringia are separated by very different sociopolitical systems under Russian and U.S. American influence, to the west and east of the Bering Sea.

This paper focuses on traditionally used underground cold storage, especially in Siberian and Alaskan areas. The Indigenous communities of the Canadian Inuit (Inuvialuit) in the Mackenzie Delta region and Beaufort Sea Region in westernmost Canada are reported to have similar underground food storage traditions and share similar issues and needs (Fillion *et al* 2014, Pokiak 2022, Snook *et al* 2022, Ovitz *et al* 2024). Canadian Inuit, as well as Dené (Athabascans) and other Indigenous communities in Alaska, are not included in this paper because we have not conducted direct fieldwork with these communities, which are left for future investigations.

2.3. Methodologies

The information learned and data collected about underground cold storage practices in Indigenous communities in Alaska and Siberia were acquired through onsite interviews during fieldwork conducted from 2020 to 2024, and through dialogues between local residents and researchers from multiple disciplinary backgrounds as coordinated through three workshops (WSs) (table 1) that were conducted as a part of the project at the Research Institute for Humanity and Nature (Kyoto, Japan), the National Science Foundation project (USA), and the Grant-in-Aide project (Japan).

The partnering communities include Gambell (*Sivuqaq*. Geographical location: 63°47′N 171°42′W) and Savoonga (*Sivungaq*. Geographical location: 63°42′N 171°28′W) on St. Lawrence Island (2022–2024. Indigenous group: Saint Lawrence Island Yupik), Point Hope (*Tikiġaq*. Geographical location: 68°21′N 166°46′W. 2022–2024. Indigenous group: coastal Iñupiat), and Anaktuvuk Pass (*Anaqtuuvak*. Geographical location: 68°09′N 151°44′W. 2022–2024. Indigenous group: Inland Iñupiat *Nunamiut*) in Alaska, and Tattinsky (Geographical location: 62°12′N 133°25′E. 2021. Indigenous group: Sakha) and Verkhnevilyuisky (Geographical location: 63°27′N 120°18′E. 2022. Indigenous group: Sakha) in Sakha Republic, Siberia.

Our project team organized the WSs which were held in the hybrid format (i.e. online and in-person) on November 12 and 13, 2020 (the 1st WS. 14 Beringian Indigenous participants out of 51. Hirasawa *et al* (2021): www.chikyu.ac.jp/publicity/events/etc/2020/img/1112-13_2.pdf), on 28 and 29 October , 2021 (the 2nd WS. 10 Beringian Indigenous participants out of 50), and on 30 September –1 October 2022 (the 3rd WS. 9 Beringian Indigenous participants out of 34. Unpublished). We openly solicited the public for participation, as well as invited selected community members (leaders and knowledge holders) from various regions and scholars from various disciplines for presentations at the WSs to share knowledge and build networks (table 1). The expertise of the scholars varies including cultural anthropology, archaeology, ecology, economy, climatology, geocryology, geographer, and sericulture science. Most of them either reside in or have year-long fieldwork experiences in the region.

Table 1. Summary of the three international workshops on 'Food Life History of the North' held from 2020 to 2022.

#	Date	Main theme and goals of the WS	Major programs	Participants
1st	November 12 and 13, 2020	Why and how do we study the practices of underground cache in the arctic communities? · Share a broad understanding of underground cache practices in communities in Alaska, Japan, and Siberia. · Learn about climate change and melting frozen ground and hear local voices regarding food sovereignty/security challenges in the study areas. · Discuss current concerns of traditional ways of life in northern communities. · Introduce research approaches of One Health and community-based participatory research.	Case introduction of various types of cold storage practices with their geographic, climatic, socioeconomic, and historical backgrounds from Alaska, Japan, and Siberia.	Total 51. 14 Indigenous (Alaska/Siberia): community leaders, knowledge holders, language teachers. Expertise: cultural anthropology, climatology, geocryology, geographer, economy, ecology, archaeology, sericulture science, local traditional knowledge (Indigenous participants).
2nd	October 28 and 29, 2021	What and how do we reify and implement the research plan? · Share ethical consideration on conducting research with Indigenous communities in Alaska, Siberia, and Japan. · Learn from various discipline scholars their experience and limitations in conducting research in the northern communities (panel discussion). · Share preliminary reports/results from the field studies conducted in 2020–2021.	• Panel discussion on 'Research of Global Issues in Local Communities' were conducted among 6 researchers of different backgrounds: disciplines (3 cultural anthropology, climatology, geocryology, economy), and geography (2 Russia, 2 Japan, 2 USA), 3 Indigenous and 3 non-Indigenous. Session on 'Ethics in Research with Indigenous Communities'.	Total 50. 10 Indigenous (Alaska/Siberia): community leaders, knowledge holders, Elders. Expertise: cultural anthropology, climatology, geocryology, economy, ecology, archaeology, local traditional knowledge (Indigenous participants)
3rd	September 30 to October 1, 2022	What is Food Life History?, and next steps. · Share preliminary reports/results from the field studies conducted in 2021–2022. · Listen to local voices (Indigenous presenters) and their concerns of food sovereignty. · Focus on case studies in various regions from Indigenous/social scientists' perspectives. · Investigate physical structures of underground food storage by natural scientists. · Lessons learned about food lifeways from Indigenous/academic perspectives.	• Sessions on 'tangible' and 'intangible' aspects of Food Life History. Plenary discussions on 'Food Life History' from Global to Local perspectives, from local residents of different regions/locals (Ainu, Alaska Natives, US National Park) and researchers (Climatology, Geocryology, Cultural Anthropology, Archaeology, Ecology, and Health science).	Total 34. 9 Indigenous (Alaska/Siberia): community leaders, educators, knowledge holders, traditional food harvesters, Elders. Expertise: cultural anthropology, climatology, geocryology, economy, ecology, archaeology, local traditional knowledge (Indigenous participants).

All the WSs were held in hybrid format combining online (Zoom connections) and in-person (the Research Institute for Humanity and Nature, Kyoto, Japan) participation. Calls for participation to the WSs were announced through the RIHN webpage. The registration was open to the public.

Onsite key respondent interviews conducted in each community provided the researchers with a historical and practical use context of underground cold storage facilities, as these vary in design, scale, and usage. Through these interviews we were able to understand the intent and motivations for building and maintaining these facilities, and the contexts of culture change associated with them in terms of causes and outcomes, and in terms of future usage. Coupled with dialogues with community members and leaders, interviews helped researchers to better understand local usage and interest in the continued use of underground cold storage, and in order to make better-informed decisions regarding community planning.

2.4. Working conceptual framework 'FLH'

We also conducted a literature investigation to incorporate various previously considered aspects and perspectives into the analysis of the underground cold storage topic. These literature reviews not only enabled the researchers to learn about the technical variations in underground cold storage, but also provided a historical context for their use, and also for their study by previous researchers. This enabled us to create and frame our research questions and goals in ways that were not a repetition of past efforts, and that were relevant to research communities. Community members are not only interested in underground cold storage issues to be analyzed to detect the causes that led to current situations, but also for these to be solved for the wellbeing of their communities. Therefore, the approach includes proactive dialogue between local community experts and scientists (from natural and social sciences and humanities), revealing that a local contextualization of research results is needed in the context of both global and local environmental changes. The construction of a conceptual framework bridging communities and academia is needed to address the issues. The FLH framework proposed by Saito *et al* (2024) attempts to incorporate wide knowledge, methodologies, and perspectives from interdisciplinary viewpoints, including economics, history, anthropology, sociology, mathematics, geography, climatology, geochemistry, ecology, health science, and food science, to capture qualitatively and quantitatively dynamic and multidimensional connections and relationship between nature, ecosystems, and humanity. It is also intended to overcome the division of 'nature and culture' based on Western cosmological traditions (e.g. Descola 2013). From this point of view, we consider the entire range of relationships between humans, non-human organisms (that may serve as food), the surrounding nature that they see themselves as a part of, and the livelihood and culture nurtured there, along with its temporal changes and spatial characteristics (Sakakibara 2017, Kondo and Yoshida 2021).

The food system concept is a generic framework to integrate the flow of food, from production/procurement, transportation/storage, distribution/consumption to disposal from various social, cultural, and ecological perspectives (Ericksen 2008, Ingram 2011). It can be approached from different aspects, such as technological (e.g. processing, preservation, transportation), social (e.g. selection and partitioning, packaging, consumption), and economic (cooking for eat-in and take-out food, wholesale/retail).

In this project, we specifically focus on the 'storage' component of the food system. It has played different roles in hunter-gatherer, pastoral-nomadic, agrarian, and urban societies. Whatever the role of storage in different social systems, it has been under-evaluated in previous discussions on sovereignty and security of food and energy (Houlette 2009, Kuijt 2009). In addition, storage is not only used to preserve food for long periods, but also creates a locally specific added value of 'flavor' through fermentation and aging (Shepherd 2000, Yamin-Pasternak *et al* 2014), which promotes preservation. Thus, the use of storage facilities needs to be addressed not separately, but in conjunction with other parts and the entirety of the local food system, e.g. the harvest, storage, and distribution of traditional food, and how their food lifeways have changed over time. At the same time, the development of storage technology to achieve a stable food supply has contributed to population growth and maintenance, health, and social complexity enabled by food surpluses, in addition to economic dependencies to maintain modern storage technologies (electric freezers, fuel for electricity production, mechanical parts and maintenance).

Through the panel and plenary discussion sessions at the 3rd International Workshop (October, 2022), participating community members from various regions, and scholars of various disciplines (e.g. cultural anthropology, climatology, archaeology, geography, ecology, hydrology), discussed the conceptualization of the FLH framework and its applicability to the issues of underground cold storage in context of the food system concept. The discussion produced dialogues and findings that are summarized in two tables and visualized in two figures as provided and discussed in section 3.

3. Results and discussions

3.1. Food system comparison between Indigenous and global/urban lifeways

The food systems that formed in accordance with, and in reaction to, the environment and history of each place are unique, reflecting the environmental culture of the community (Wade 1999, Ericksen 2008, Food Safety Network 2009, Ingram 2011, Mandiwana 2018, Sunano 2020). This is one of the key factors in our

analysis. Tables 2 and 3 are produced based on dialogues and discussions derived from Indigenous and academic participants in the plenary discussion session at the 3rd workshop (table 1). Table 2 attempts to demonstrate the flow of food in its entirety, by illustrating aspects and attributions of the food system components when interpreted from the FLH framework. Because the FLH framework is intended to be a common template for comparison between various cases (e.g. Indigenous, industrial, rural, ancient, large, and small communities), the examples shown here are described in general terms. It includes actors (e.g. who are in charge, whether a single person or group for different parts of the system, or separated), time range/scales (e.g. daily, seasonal, or annual scales; specific seasons or year-round), spatial scales (e.g. local, regional, or global extent; natural or artificial environment), tools (e.g. what sort of gears/materials/modes are used for what purpose), objectives (e.g. for selves/community or industry/commerce), and the inter-element relationships.

Table 3 shows an application of the FLH framework to typical cases of the food system to contrast Indigenous lifeways using underground cold storage and urban-industrial lifeways, by extracting and generalizing their typical features.

In a harsh natural environment of limited access, low temperatures, and clear seasonality, underground cold storage is used in a variety of ways and is a central social function for maintaining local and sustainable communities with little dependence on others (Gerlach and Loring 2013, Martens *et al* 2016). In coastal Alaska, it is used for value-sharing and product-exchange within communities and with neighboring communities, through the distribution and exchange of large mammal products; in interior Alaska, as insulated pits for temporary storage during fishing, and hunting and gathering; in coastal Siberia, as storage until transport to market; in interior Siberia, as ice storage to secure clean and safe drinking water in summer (Walker 1962, Spencer 1976, Binford 1978, Campbell 1998, Burch 2006, Brubaker *et al* 2009, Houlette 2009, Maslakov *et al* 2020, Yoshikawa *et al* 2022). Thus, underground cold storage is used to preserve food during the non-hunting/fishing/harvest seasons, to add specific value such as flavor, aroma, and texture by aging and fermentation, and to share among the communities for the purpose of building relations, all of which combine to improve food security and quality of life.

Issues on Indigenous food security and food sovereignty, discussed in relation to climate change, concentrate more on autonomous securing and consumption of culturally appropriate food resources. However, this is a small part of the entirety of problems that Beringian peoples face, for whom the entire flow of food is important, such as resource acquisition, transportation, storage and preservation, processing, distribution, and consumption in communities. This is developed through their holistic, interconnected worldview of a community that embraces the natural environment, ecosystems, and human communities and livelihoods (Kawagley 2006). This worldview is based on Indigenous knowledge, which is most concerned with successful coexistence with other life-forms/entities of the local environs, who are perceived as equally important in terms of right-to-life, and a conservation ethic is inherent in this worldview (Koskey 2020).

In the urban food system, the social and economic aspects become important with the development of complex society (Nakashima 2021). Due to increases in population size, economic growth, and urbanization, expansion of the distance between the production and the consumption requires the building of a stable logistics to supply safe foods effectively and efficiently. Distance is not only a geographical and physical consideration, but is also an issue of sociality and psychology. Each element of the food system is related but separate at the same time, and each is integrated within the global supply chain (cf figure 6(b) of Saito *et al* 2024). From a systems science viewpoint (Prigogine and Defay 1954), with respect to the food system, the traditional lifeway (upper row in table 3) is close to a 'closed system,' which is self-constrained with limited exchanges beyond local surroundings, while the urban lifeway (lower row in table 3) is an 'open system,' which exchanges material, energy, capital, information, and people with the externals (that is, outside of the boundary).

3.2. Global perspective and local viewpoints around the underground cold storage issue

Beringia is a region with great contrasts including landscape and climatic conditions from permafrost to seasonally frozen ground areas, ecological characteristics and subsistence activities that differ between inland and coastal areas, and political and social regimes between the Soviet Union/Russian Federation and the United States. These demonstrate very diverse conditions, causes of change, and direction of policy, as well as traditions of usage, history, and the cultural significance of storage. This region, therefore, provides multiple axes of comparison and topical consideration, i.e. geo-climate, ecological resources, livelihoods, and historical and political factors (IPCC 2019, 2021, Sustainable Development Working Group 2019, Zhegusov *et al* 2020).

The underground cold storage practices and their changes are associated with several topics in different aspects, scales, and categories. We collected the topics significantly associated with the underground cold

Table 2. Aspects, examples, and attributions of food systems from the FLH perspective.

	Acquisition/production	Transportation	Storage/preservation	Distribution/consumption	Disposal
When	Seasonality	Season, length of period	Post-harvest/ post-production	Daily meals, festivals/rituals	After acquisition/after consumption
Where	Natural environment/human facilities	Short/long distance	Inside/outside of house/community, under-/above-ground/ high-floor	House/community/Society	Within/outside
Who	Selves/producers	Selves/transporters	Selves/community/wholesalers	Selves/community/society	Selves/workers
What		Harvest, product			Perishable/unperishable
Why	(Procure)	Logistics	Secure foods, logistics	With…/for …	Return/Cycle Discard
How	Spear, bow-and-arrow, gun, field, factory	Man/horse/dog-power, machine	Natural/electric/factorial facilities for drying/condensing/ oiling/smoking/salting/ pickling/freezing, fermentation bottling/canning	Direct/indirect	Natural capacity/managed system

#1: Includes actors, time range/scales, spatial scales, tools, objectives, inter-element relationships. Entities shown in the table are not exhaustive.

Table 3. Generalized features of Indigenous food systems using underground cold storage, and those of urban-industrial lifeways.

	Acquisition/production	Transportation	Storage/preservation	Distribution/consumption	Disposal
Indigenous Non-urban Non-industrial using underground cold storage	Hunting, fishing, gathering, sharing	Sites to the community by humans, horses, dogs, vehicles, airplanes, boats, etc	Natural energy use; processing (aging, maturing), freezing, drying, canning; between-harvest	Festivals; Sharing within and trading beyond communities through Indigenous trading network; sharing multi-generational skills	Back to nature, offering
Industrial urban and rural	Husbandry, industrial fishing, factory production	Logistics by trucks, train, ships, planes, etc	Electric freezer/refrigerator, Canning/restorable	Wholesale/retail, house kitchen, restaurants	Garbage/sewage system; Away from the consciousness

storage issue, through literature review and field observations, and classified them in four categories addressed from global perspectives (outer circle) and local viewpoints (inner circle) in figure 1. The four categories consist of the natural and ecological system (Natural System in figure 1), social system (similarly, Social System), community-level characteristics (Knowledge of Place), and cultural and individual concerns (Wellbeing/Culture). The position of each topic in the categories were determined according to its context and relevance to the storage practice, which we learned by direct communication through onsite interviews and dialogues with the community members.

Some of these topics have global extent, or stemmed from global issues, e.g. climate change, and ecosystem changes in the natural system, which affect locally not only the physical conditions such as thawing of permafrost and enhanced hydrological cycles (AMAP 2011, 2017, Saito 2021), but also seasonal cycles (i.e. seasonality) of harvests and activities associated with subsistence (fishing, hunting and gathering), health of animals and plants, and availability of food resources to be stored (Heeringa and McFarland 2018: https://snap.uaf.edu/tools/living-off-the-land/images/seasonal-cycle.svg?). Globalization and monetization of the economy have spread to Beringia as well, such as the penetration of Western distribution systems and lifestyle technologies (electrification, information technology; Lance and McKenna 1975), introduction of Western-style education systems (Meyer 2010, Grigorenko 2013), and the spread of industrially processed foods (Inuit Circumpolar Council-Alaska 2020).

The geographical remoteness of the region causes high prices for imported food, energy, and other commodities due to transportation and storage costs, and the problem of securing and procuring these commodities (i.e. food security), and maintaining healthy nutrition is becoming increasingly acute (Inuit Circumpolar Council-Alaska 2015, Cold *et al* 2020). Widespread accessibility and use of commercial food and industrially processed food also affects the preference of foods and enhances culture gaps between generations.

Underground cold storage practice is closely related to local history and its landscape (environment), ties to family and ancestors in the community, and food preferences such as flavor and aroma. Continual use involves passing down traditions and other culture traits surrounding the use and maintenance of underground cold storage as an integral aspect of food security and food sovereignty, as its use does not involve non-local economic dependencies. Indigenous knowledge is intimately tied to the conditions of the local environment and provides a holistic, relational knowledge of the entities of the local environment. This condition is inherently conservationist and adaptive, as Indigenous knowledge traditions are practically oriented and seek to enable survival. Ideally, intimate knowledge of the local environment and its human and non-human inhabitants enables a group to thrive in even the most severe natural conditions through deep knowledge of the conditions and processes of the local ecology.

Lifeways based on traditions of deep knowledge of the environment were disrupted in most parts of the world by colonial imperialism, followed by globalism (with capitalism as its vehicle). Seeking resource extraction, colonial and capitalist interests little-cared for local or traditional knowledge, or for the Indigenous carriers of this knowledge, whose territories contained the coveted resources. Through colonization and the policies of national governments (many of which are colonially derived), environments are increasingly disrupted by extractive industries, and coupled with climate change and permafrost degradation, this has led to rapidly changing local environments.

Under such conditions, the nature of local knowledge changes and traditional knowledge is increasingly limited in its applicability under conditions of rapid change. This is one of the primary threats to the maintenance of underground cold storage knowledge. Nevertheless, as among the cultures of Beringia, adaptation is an inherent value in most Indigenous knowledge systems, and as conditions change, so too changes the focus of local Indigenous knowledge traditions, and this applies to changing food traditions in terms of preservation, preparation, and consumption. Such adaptations include the movement from semi-nomadism to permanent, year-round settlements–an event experienced by most Beringian peoples, integration into the global capitalist economy, and borrowing of non-local traditions to facilitate adaptation. These postcolonial conditions stem directly from the colonial experience that invariably included forced assimilation that threatened Indigenous languages and other culture traits, and wellbeing overall declined. This process has affected all communities participating in this study. Recently, in the so-called postcolonial period, colonial populations have become more tolerant of sociocultural diversity, and colonized populations have begun a vigorous revitalization of their traditions.

Above, we summarize the issues associated with underground cold storage from different aspects and scales as depicted in figure 1. In the next subsection, we examine more detailed factorization and inter-relational influences between the processes associated with the changes in underground cold storage, and the consequential loss and damage.

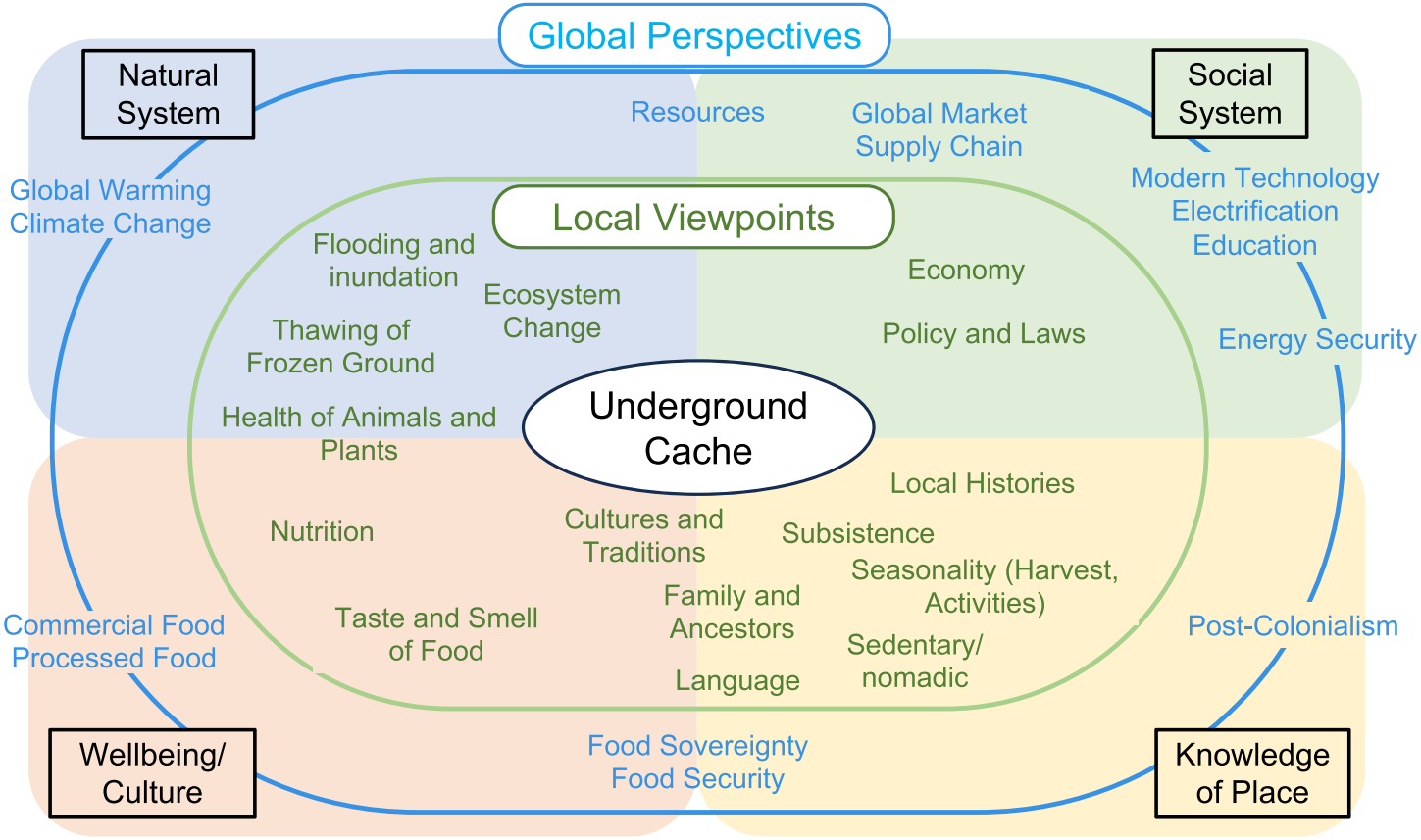

Figure 1. Important topics around underground cold storage depicted from global and local perspectives.

3.3. Relational diagram affecting the underground cold storage practice

We qualitatively analyzed the factors and agents leading to changes in underground cold storage practices with directions of influence indicated in figure 2. It consists of three environmentally significant realms including natural [A], social [B], and ecological [C], and two communal aspects, that is, changes in underground cold storage due to dys- and malfunction of the facilities leading to decline in use [D], and the resulting losses and damages to communities [E]. The environmental sections [A to C] were mostly derived from the literature review and our previous research and studies, while the community sections [D and E] were summarized from our onsite interviews and workshop dialogues.

Firstly, factors and changes in the natural environments are summarized in section [A]. The northern polar region is experiencing more than twice as fast warming as the global mean in recent decades (IPCC 2019, 2021) due to the most pronounced warming caused by polar amplification (Druckenmiller 2022) [A1], affecting various components of natural and social systems in the Arctic region (AMAP 2011, 2017). Not only temperatures above ground [A2], but also below ground [A3], have shown increasingly remarkable trends since the 1980s (Biskaborn *et al* 2019). Associated with warming temperatures in the atmosphere, the hydrological cycles have intensified accordingly (Ye 2021) [A4], bringing prolonged wetter periods [A5] by greater precipitation and resulting flooding [A9] in Siberia (Iijima *et al* 2010) and Alaska (Ikawa *et al* 2015). Warm summers [A7], as well as insufficient cooling in winter, leads to changes in seasonality [A6]. Thermokarst [A11] and ground subsidence [A12], induced by melting of ground ice due to ground warming and wetting, have increased the transport of the sediments by enhanced river runoff [A12], eventually affecting the nutrients [A14] and fresh water that flows into the Arctic Ocean. Discharged warmer water enhances sea ice loss [A15]. These tendencies are projected to continue at possibly increasing trends (Saito 2021). Rapid climate change challenges northern communities' cultural capacities to react in a timely and effective way (McNeeley 2012), as climate change in the past was far more gradual, enabling experience-based, locally rooted, and more effective responses.

Secondly, factors of societal change in the context of underground cold storage practices are summarized in section [B]. Indigenous people inhabited Beringia for millennia before colonization, and they continue to practice their cultures that are rooted in the local environment (Hughes 1960, Ager 1982, Halffman *et al* 2015, Potter *et al* 2018). However, the resource-consuming system of global capitalism [B1] causes resource exploitation, natural degradation, and widening inequality. Introduced urban lifeways [B3], which brought modern technology, materials, and cash economy [B4] and processed foods [B5], has caused changes in Indigenous communities and cultures that endanger people's food and health (Barret and Armelagos 2013, Mallee *et al* 2022, Tamura 2022). One of the major factors impacting cold storage is the introduction of electricity [B6], which enhanced non-local energy dependency in the communities [B7]. Wide use of electrification [B6] and processed food [B5] enhance the spread of electric refrigerators and freezers [B8], which has been a major driver to replacing natural-energy cold storage with electric freezers, not only in the Beringia regions but also in other parts of the world (Saito *et al* 2024). In addition to the material aspects, colonization [B2] greatly affected social systems in the region with different political and historical pathways between Russia and the USA [B10]. Under different sociopolitical systems, however, pressure to shift from semi- or full nomadism to permanent settlement [B11], and education in the colonizer's language (Russian in Russia and English in the USA) [B12], made it difficult for community members to maintain aspects of their local traditional lifestyle [B13] and weakened the use of Indigenous languages [B14]. Indigenous cultures practicing ancient traditions continue throughout Beringia, with the cold storage practices of Indigenous people in the region also being threatened by the penetration of the capitalist monetary economy and technological innovations (e.g. use of processed foods, electrification, petroleum-based transportation) [B4], which create economic dependencies. These impact local traditions, through assimilative processes, in the northern reaches of Asia and North America [B11, B12]. There are also other cultural changes such as declining interest in maintaining older traditions, and the breakdown of sharing practices in some communities. It is becoming more difficult for communities to pass down knowledge and traditions about subsistence (Koskey 2020), food qualities (such as culinary arts, food aromas and flavors), and management of tools and infrastructure (Reyes-García *et al* 2013) [B15]. Some other factors of societal changes in the context of historical (i.e. colonial) impacts on Indigenous knowledge, culture, and lifeways are presented in section 3.2.

Thirdly, impacts on the ecosystem due to changes in natural and social environments and their relevance to the use of underground cold storage are described [C]. Even under current conditions of global warming [A2], agriculture is mostly not feasible in this environment (Westergaard-Nielsen *et al* 2015, Scott 2017, King *et al* 2018, Altdorff *et al* 2021, Unc *et al* 2021, 2022), and subsistence livelihoods are maintained based on fishing, hunting, and gathering. The terrestrial and marine ecosystem providing food resources has been impacted by environmental changes; for example, productivity and phenology of the low trophic level organisms (i.e. producers such as terrestrial vegetation and phytoplankton) are impacted by seasonality

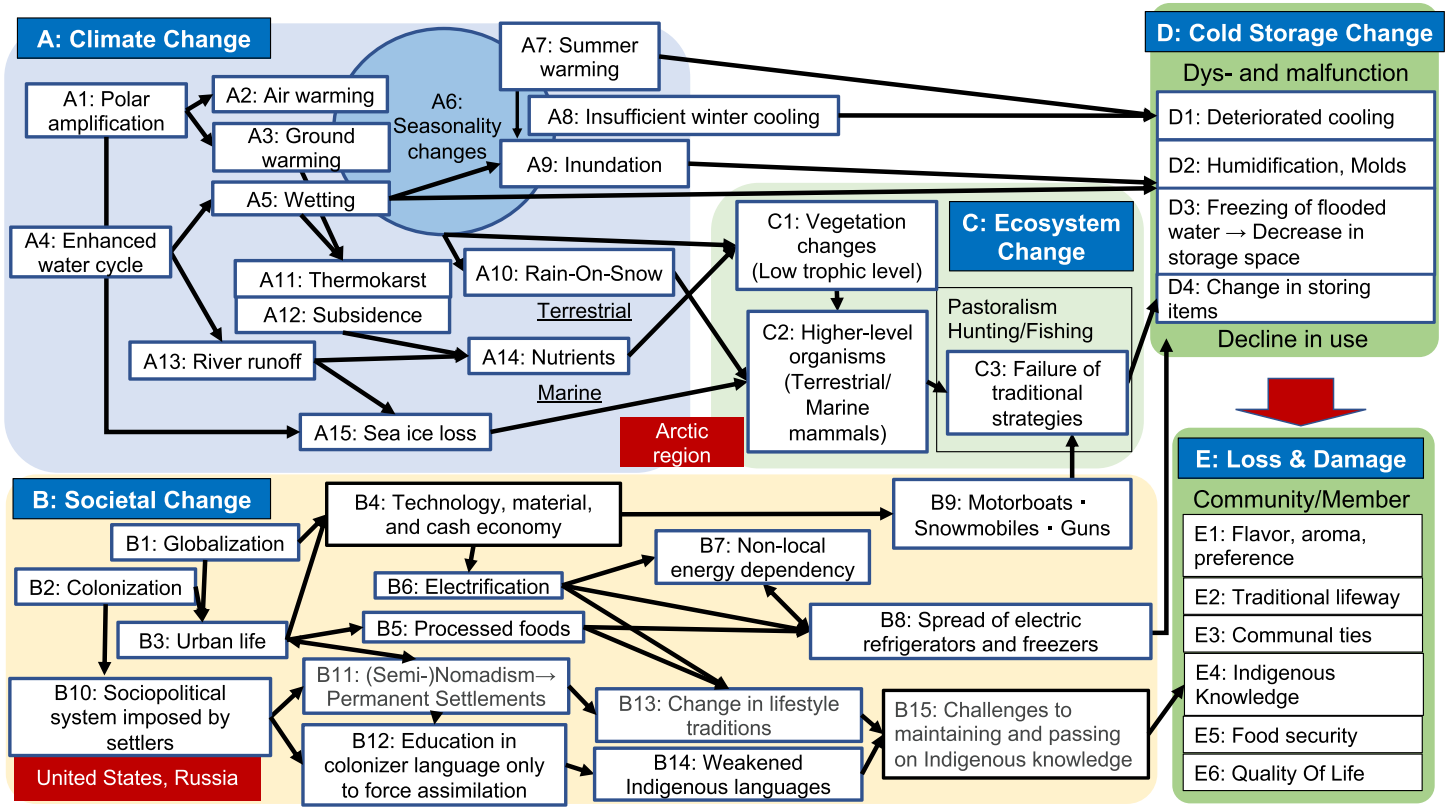

Figure 2. Integrated relational diagram demonstrating environmental factors (natural [A], social [B], and ecological [C]) and community-level aspects of changes in underground cold storage practices [D] and their impacts [E]. Black arrows indicate direction of influence. The red broad arrow indicates a consequential relationship.

changes [A6] resulting from overall warming [A1] and modified hydrological cycles [A4] (Rantanen *et al* 2022), and riverine nutrients changes [A14]. This influences the trophic conditions to the higher-level organisms such as consumers, including terrestrial and marine mammals [C2]. In addition, climate change directly modifies the habitability of those wild and domesticated animals both in space (locations) and time (seasons). The numbers of caribou and reindeer (*Rangifer tarandus*) continue to decline with changes in location and amount of vegetation (animal foods), impacting the activities of hunting and herding (Vors and Boyle 2009, Moon *et al* 2024). Also, increase in rain on snow [A10] during warm winters hinders animals' ability to graze due to the icing-over of tundra (Dolant *et al* 2017, 2018), and its obstruction to reindeer and caribou to break through the ice to access lichens. Changes in annual and inter-annual sea water temperature regimes, and seasonal progress of sea ice such as late onset of land-fast ice, early retreat of sea ice, decline in coverage extent, and the resulting shortened period of sea-ice coverage, have been observed in the Arctic and Bering Sea areas (e.g. East Bering Sea: Siddon 2024, Arctic: Kumar *et al* 2020) [A15], resulting in changes in seasonal activities and conditions of regional ecosystems (Sydeman *et al* 2015, Grémillet and Descamps 2023, Young *et al* 2023, Overland *et al* 2024, Overland and Wang 2024, Siddon 2024). Indigenous communities have become more dependent on material goods provided by the global industrial market (Nelson 2019), for example, modern tools for fishing and hunting such as manufactured nets, guns, motorboats, and all-terrain vehicles [B9]. These environmental and societal changes have led to changes, or sometimes failure, of traditional practices and strategies of pastoralism, hunting/fishing, and gathering [C3]. In combination with climate change issues, global capitalism's environmental limitation has been recognized (Moore 2016, Scott 2017, Yuki 2018).

The factors and agents described above affect the physical capacities of underground cold storage [D], leading in some cases to dysfunction of cold storage facilities, such as deterioration of cooling [D1] because of summer warming [A7] and insufficient winter cooling [A8]; quality degradation due to humidification and molds [D2] and storage capacity loss by refreezing of water [D3] caused by wetting [A5] and seepage and inundation in spring and summer [A9]. Failure or changes in traditional hunting or pastoral strategies [C3] limit the sorts and amount of items stored [C3]. Introduction of electric refrigerators and freezers [B8] replaced the major role that the traditional cold storage played. The dysfunction of cold storage practices reduces the effectiveness of traditional values of maintaining a sustainable food supply and way-of-life, and potentially threatens the future wellbeing of Indigenous communities.

The losses and damages [E] that the community member bears due to cold storage changes include loss of the aromas, flavors, and preferences of food that are traditionally stored (sometimes fermented) [E1]. It also impairs the traditional lifeway of the community where members share and consume traditional foods within and across communities [E2]. These challenges to maintaining the traditional lifeways [E2], as well as to maintaining and passing on Indigenous knowledge [B15], lead to weakening the communal ties [E3] and possible loss of Indigenous knowledge [E4] relevant to food traditions and culture (food security) [E5]. This poses a substantial threat to traditional lifeways of Indigenous people of Beringia who draw their identity from the land through association with and interdependence with the land and waters of their regions. Thus, their quality of life is at risk [E6].

3.4. Implications

In the previous subsections, we provided the attributions, purpose, and characteristics of underground cold storage from a general point of view through the food system concept, and through comparison with modern urban lifeways (FLH framework). Underground cold storage is used to preserve and store meat and other products to provide for food security during the non-hunting/fishing seasons, to add specific value by aging and fermentation, and to share these foods with community members and between communities to reinforce social cohesion. In doing so, they support traditionally sustainable lifeways, and this sustainability is present across Indigenous cultures in Beringia. Even in cases where cultural and linguistic differences are many, worldviews and associated value systems show many similarities, especially concerning ethical conduct. This conduct is reinforced by sustainable cultural behaviors and values that have conservation effects, and it is this sociocultural (traditional) knowledge that enables a well-attuned adaptation to local environments. Now that the stability of these climates are in flux, so too is the traditional Indigenous knowledge that is fine-tuned to support and be supported by local conditions. Consequently, due to century-long environmental changes in nature, ecosystems, and societies, underground cold storage facilities show dysfunction physically and operationally, as illustrated in figure 2.

Understanding that underground cold storage use is in decline, what would motivate residents to maintain underground cold storage facilities in addition to electric freezers? Replacement with electric freezers is in fact a common option, and most households that participated in the survey reported by Saito *et al* (2024) have shifted to electric substitutes. However, it is reported insufficient in some respects, such as the capacity to create the preferred flavors, and reduced storage capacity (Oliver 2017), in addition to

electricity and fuel (to generate electricity) dependency. This would include such factors as the ability to ferment meat in ways that achieve the desired flavors, and the skills to safely ferment (and the product itself) are symbols of cultural identity, expressed through cultural practice. Also, when subterranean meat caches are shared communally, or between families/clans, sharing traditions are reinforced, as is community cooperation. The formation and maintenance of communal ties are based on key factors that differ from community to community, that are based on ecological and cultural factors, and are the basis of social and cultural resilience (Kassam 2009, Koskey 2020, Inamura *et al* 2022).

In the next, future step of our project, we intend to create, with the data already collected for this project, a diagram of a seasonal round that depicts the resources and the seasons or environmental conditions for each phase of the subsistence cycle, together with changes due to natural, social, and ecological environmental and cultural changes (cf Heeringa and McFarland 2018: https://snap.uaf.edu/tools/living-off-the-land/images/seasonal-cycle.svg Last accesses on 26 March 2025). In an upcoming publication, seasonal round diagrams will be produced separately for each study site including St. Lawrence Island, Point Hope, and Anaktuvuk Pass, as each has different seasonal round traditions. This is expected to provide key information for the FLH of underground cold storage practices, and information specific to each of the communities, to easily visualize their traditional seasonal rounds and changes. In contrast, the diagrams provided in this article provide depictions of broad regional conditions that can be found throughout Beringia.

It has been pointed out that economic disparities cause a difference in the scale of damage caused by climate change (UN News 2019: https://news.un.org/en/story/2019/06/1041261 Last accesses on 26 March 2025). Climate apartheid focuses on 'economic disparities' and the difference in climate change damage, based on cultural differences in each region. The more directly dependent a population is on the natural environment of a region, the more quickly and severely the effects of climate change impact the culture in terms of wellbeing. Embedded within Indigenous knowledge systems, however, are the tools for resilience under conditions of culture change, and the sociopolitical allowance of the continued practice of Indigenous knowledge at local scales fosters this capacity for resilience (Berkes *et al* 1994, Koskey 2020). In the Beringia case, culture changes stemming from globalization are ubiquitous, arriving through government regulations, multimedia access, and especially through the global market that provides products that create outside dependencies and lowers local sustainability, potentially jeopardizing local sociocultural stability and encouraging culture change, including assimilation into colonial or global cultures.

Concerns about the simultaneous collapse of environments and cultures in northern regions have already been pointed out (Brubaker *et al* 2009, 2011, Cochran *et al* 2013). Criticism of Eurocentric perspectives was made during the 1970s with Edward Said's 'Orientalism' (Said 1978), and in the time since, the value of traditional knowledge to local communities' resilience and adaptation to environmental changes has been widely noted (Berkes *et al* 1994, 2000, Berkes 2017, Koskey 2020). The role of underground cold storage in this cultural resilience has changed in reaction to changes in the conditions of the natural and social environments: As the climate warms and technological capacities provide new alternatives for food storage and preservation, older traditions of underground cold storage are practiced less frequently. Instead of being central to food security, underground cold storage traditions in some communities are primarily maintained to acquire specific conditions for food flavors (by fermentation in Gambell and Savoonga), others continue to use underground cold storage for food preservation and food security (Point Hope), while some have recently ceased usage of underground cold storage, though the knowledge continues to be maintained by elders (Anaktuvuk Pass). In all of these Beringian cases, however, the knowledge and use of underground cold storage traditions continue to serve as a symbol of community cohesiveness and cultural identity.

In addition to the older underground cold storage traditions, solutions that integrate modern technology are also being sought (Oliver 2017, Tribal Climate Adaptation Guidebook Writing Team 2018, Naiden 2022). In some North Slope Iñupiaq communities in Alaska, modern building materials have been used partially or in full to construct new community cellars, and some of these make use of thermal siphons to stabilize colder temperatures in the underground cold storage facility, demonstrating the flexibility of local, Indigenous cultures to adapt to the changing natural and social environmental situations, a flexible adaptability long demonstrated by Indigenous cultures through the traumas of colonization and its aftermath.

Sharing information and knowledge through dialogue under the unique conditions of the circumpolar North reinforces community resilience (e.g. Climate and Traditional Knowledges Workgroup 2014, John and Koskey 2016, Chabay 2018, Kugo and Koskey 2024), and this adaptability under conditions of change that are beyond the control of local people is a feature of most Indigenous cultures. Indigenous cultures change to meet the conditions of the environment, rather than the culture attempting to change the environment in severe ways to meet cultural preferences, as is typical of colonial cultures. The continued but changing utilization of underground cold storage reflects this resilient adaptive tradition.

4. Conclusion

The underground cold storage facilities and related practices in Arctic communities, which have been developed and maintained for different purposes in different forms, reflect the varying local conditions and needs of communities. These include natural, social, and ecological environments, and geographical, historical, and other cultural elements. These differ from community to community, but commonly contribute to the wellbeing of communities and individuals.

This paper shows, through analysis of onsite interviews during fieldwork, and dialogue between local community experts and scientists, that changes in underground cold storage practices are not caused by a single factor (e.g. climate change or permafrost degradation alone), but through a variety of agents that have influence on different time scales. Therefore, the issue cannot be treated in isolation, apart from the multiple factors and situations. It requires a multiperspectival framework that integrates various relevant sociocultural and ecological factors to fully understand and address the issue. It is important to evaluate the role, functionality, and meaning of underground cold storage (and related facilities and practices) from an integrated perspective of the food system (naturally, economically, conceptually), worldview (as an expression of culture), and background factors such as the natural, social, and ecological environments, including geography (spatial) and history (temporal).

A holistic conceptual framework that captures the global perspectives and local standpoints is necessary to evaluate the issue. This involves interplay between human societies, their food systems and traditions, and environments, as described above. The FLH framework is intended to serve this purpose as a (working) template. It illustrates that storage is an element in the food system that has drawn less attention in previous research, but is a factor worth addressing independently, as well as in association with other identified associated factors. By incorporating different place-specific cultural and ecological perspectives obtained from local community interviews and dialogues in WSs, a relational diagram was produced that depicts the relevant factors impacting the role and functionality of underground cold storage practices of a tradition more than a century old. The resulting diagram captures the relationship between factors that affect the use of underground cold storage. The analysis presented in this study still lacks quantitative methodologies and considerations of overall effects of underground cold storage on food quality, the microenvironment, and health needs, which will be investigated in future research. It will provide key points and potential policy options for future planning with respect to the resilience and wellbeing of communities, fostering open and transparent discussion, planning, and policymaking.

By the resilient adaptive capacities of Indigenous knowledge, attuned to and drawn directly from the local environment, Indigenous communities and their leaders can work cooperatively with regional and national policymakers to ensure the protection of their local cultures, according to their own values. This requires flexibility among non-Indigenous leaders who are committed to respecting local, Indigenous traditions and capacities to sustainably manage their resources within conditions of food sovereignty that enable a stable food security. Underground cold storage is one adaptive method to achieve food stability in far northern communities, and the transformation of associated traditions demonstrates local capacities for sociocultural resilience.

Data availability statement

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

Acknowledgments

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Ethical statement

The Alaskan portion of the project was reviewed and approved by the University of Alaska Fairbanks Institutional Review Board (IRB#1610 810). The research was conducted in accordance with the principles

embodied in the Declaration of Helsinki and in accordance with Federal and State requirements. All participants were adults and gave written informed consent to participate in the study.

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