The Pennsylvania State University

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A NOVEL FRAMEWORK FOR THE DEVELOPMENT OF A SPATIAL SOCIAL-ECOLOGICAL SYSTEMS MODEL OF CLIMATE CHANGE ADAPTATION: AN ARCTIC CASE STUDY APPLICATION IN NORTH CENTRAL ICELAND

A Dissertation in

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by

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Abstract

There is a globally recognized need for adaptation efforts to reduce the risks posed by climate change impacts through policies and strategies informed by research, in conjunction with climate change mitigation efforts. Climate change adaptation can be a cultural process of adjustment owing to individuals and their collective behavior that seek to reduce adverse effects on health and wellbeing, and to find opportunities that arise from changes. However, future uncertainties mean that adaptation is more often a value judgement than a calculated measure.

This dissertation investigates how social-ecological systems modeling can be developed to analyze climate change adaptation at the household level. First, I draw together human-environment geographies of social-ecological systems, ecosystem services, and sense of place to examine the associations between these social-ecological dynamics and household climate change adaptation. I then apply this dissertation's research framework to the social-ecological system of North Central Iceland, which is situated in the Arctic.

The Arctic has experienced a mean temperature increase of nearly 2 degrees Celsius since the year 1990, compared to the global average increase of 1 degree Celsius. Additional indicators of climate change impacts in the Arctic include the degradation of Arctic ice, changes in ecosystems, weather patterns, and hydrogeological risks. Furthermore, the effects of these changes stem beyond the ecological system to linked social systems. Thus, this dissertation examines the questions: 1) what social-ecological processes are most supportive to households' ability to implement adaptive actions within the context of rapid environmental change, and what variables can reliably measure those processes? 2) to what extent do the valuation of ecosystem services and sense of place play a role in supporting adaptive behavior at the household level, and are there associations between these variables? and 3) how can human-environment relationships within a social-ecological system be modeled spatially, using adaptation to climate change as an example, and what might we learn about adaptation from such modeling?

This dissertation research has 4 main findings. First, there are observed lasting changes in the local climate characteristics of North Central Iceland. Second, the majority of household adaptations focus on changing consumer practices and improving financial security. Third, 3 social-ecological system variables were most facilitative of households who adopted a greater number of adaptations: 1) feeling concern for future local impacts of climate change, 2) having historical knowledge of ecosystem change, and 3) highly valuing provisioning ecosystem services.

Together, these insights suggest that adaptation may be most well-received in North Central Iceland if it addresses people's feelings of concern for the future of their local area and its place identity, including how adaptations are situated within local ecological histories and how they promote the continuation of provisioning ecosystem services. Applying the social-ecological system framework developed in this dissertation research highlighted the important roles of feeling and scale in the adaptation process. These insights suggest that social-ecological systems modeling, supported by spatial methods and visualization, can aid in identifying areas for adaptation that are valued for their social-ecological significance and that are perceived as presenting high hazard risk.

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Chapter 1

Introduction to the need for a social-ecological systems approach to model household implementation of adaptation actions

Throughout the world, the impacts of climate change are projected to increase in extent and severity as time passes, and the emission of greenhouse gasses continues (IPCC, 2014), which will inevitably require adaptation strategies for social and ecological systems to persist (Pelling M. , 2011; Adger, et al., 2009). In response to the global need to adapt to changes, this dissertation research sought to understand the experiences and perceptions of change that support household adaptation, including those related to the early indicators of climate change impacts in the Arctic. Namely, the goal of this dissertation research was to ascertain the extent to which households value ecosystem services and sense of place and if these values encouraged households to implement more adaptation actions. To accomplish this, I proposed a novel model based on Ostrom's Social-Ecological System Framework (SESF) (Ostrom E. , 2009) for integrating biophysical climate processes with social-ecological systems modeling. I then applied the framework using North Central Iceland as a pilot project area.

To begin, in this Chapter (1), I give a brief overview of the early impacts of climate change in the Arctic and make a case for why adaptation is necessary. From this foundation, I present the research questions and hypothesis. I then describe the theories that guide this research: an integrative framing of biophysical climate characteristics and social-ecological systems modeling. I then justify North Iceland as the study area for this research where the framework was applied and tested. I conclude this Chapter with a discussion of the methods and plan of analysis, which are articulated in-depth in Chapter 3.

Climate change impacts in the Arctic and the case for adaptation

Globally, we are on target to reach a 1.5-2 degrees Celsius (^{0}C) increase in average global atmospheric temperatures by the year 2100, even if sweeping emissions reduction efforts are enacted, and notably greater warming otherwise. In Arctic regions, polar amplification is causing climatic changes to occur sooner and with faster-than-global-average rates of warming (Serreze, Barrett, Stroeve, Kindig, & Holland, 2009; Bekryaev, Polyakov, & Alexeev, 2010). Under all emissions scenarios, the annual Arctic temperatures are predicted to warm by 2-2.5 times the global average by the year 2100 (Collins, et al., 2013).

This rapid rate of temperature increase is already impacting the functioning of Arctic ecosystems, including the controls on biodiversity and landscape dynamics (ACIA, 2005). For example, climate change impacts on Arctic tundra and boreal forest ecosystems raise important questions about the long-term availability of local fresh water supplies—an important resource for every social-ecological system. The Arctic receives little precipitation compared to much of the midlatitudes. However, continued warming is likely to threaten freshwater supplies by increasing evapotranspiration and resulting precipitation, which amplifies the hydrologic cycle of the Arctic climate system (Bintanja & Selten, 2014). These regional changes can alter local water channels' sediment loads, chemistry, stability, and thermal regime (Milner, Brown, & Hannah, 2009), thus impacting their associated habitats and species diversity, among other ecological characteristics (Prowse, et al., 2006). These and other secondary impacts of climate change will require increasing attention over time as their effects accumulate, increase, and interact across scales, inevitably requiring adaptation of social-ecological processes (Chapin, et al., 2006).

Social-ecological processes refer to the relationships between the human and non-human domains that cohabitate in a specific environment. For example, warming temperatures have impacted offshore Arctic sea ice conditions over the past half-century, in ways including a delayed seasonal freeze-up and earlier spring break-up of sea ice, thinner and less multi-year sea ice, and less shore-fast sea ice (Markus, Stroeve, & Miller, 2009; Krupnik & Jolly, 2002). At present, the Northern Sea Route is navigable for 1 to 1.5 months. However, as the sea ice in the Arctic Ocean wains, the navigation season will extend for an additional 4.5 to 6.5 months by the year 2100 under a radiative concentration pathway scenario of 4.5 or 8.5, respectively (Khon, I., & Semenov, 2017). Indeed, under high-emissions scenarios, the Arctic Ocean is projected to be entirely or nearly ice-free by the year 2100 (Serreze, Holland, & Stroeve, 2007), which will continue to allow some countries (e.g., Greenland, Russia) increased geographic and temporal access to their exclusive economic zones (EEZs). In this case, secondary climate change impacts on sea ice influence social-ecological processes, inevitably requiring adaptation.

Even with aggressive emissions reduction efforts, our global climate system is and will continue to undergo profound changes. Indeed, the biophysical environment is already changing rapidly, particularly in coastal areas that are themselves under pressure from an ever-increasing human presence, under second-order climate change impacts, and first-order impacts from land-use activities. For example, traditional methods used to preserve wild foods in the Arctic—including ice cellars, fermentation, and drying—are examples of ecosystem services compromised by the secondary impacts of climate change. Ecosystems' healthy functioning allows humans to benefit from ecosystem services. In this case, compromising secondary impacts are widespread permafrost thaw, rising temperature, and air humidity (Cozzetto, et al., 2013; Nuttall, 2017).

Indeed, up to half of the Arctic tundra will transition to boreal forest by the year 2100 under a high-emissions pathway (Larsen, et al., 2014), and the access to and use of Arctic terrestrial transportation networks will decline if not adapted to these new environmental conditions (Instanes, et al., 2016). Further, changes in wildlife migration patterns of species such as caribous are occurring alongside changes in the seasonal timing of spring blooms, resulting in a trophic mismatch (Post & Forchhammer, 2008) and catalyzing declines in human and ecosystem health alike (Mallory & Boyce, 2018; Allen, et al., 2018). These and other secondary impacts of climate change will require increasing attention over time as their effects accumulate, increase, and interact across scales, inevitably requiring adaptation of social-ecological processes.

Problem statement, research questions, and hypothesis

The first- and second-order effects of climate change will not be evenly distributed and are difficult to predict at the local scale, making impacts on social-ecological systems less predictable and therefore even more challenging to adapt to (Duerden, 2004). People have lived in the Arctic for thousands of years. However, local social-ecological systems are now facing rapid change amid uncertainty in what was otherwise a relatively predictable, though extreme, environment. Therefore, methods need to be available to identify spatial and social-ecological processes for community-backed and ecologically sound adaptation interventions. As such, this dissertation research explored the household-level experience of environmental and climatic change to ascertain the extent to which the valuation of ecosystem services and sense of place played a role in supporting adaptive behavior. To do this, I propose a novel model for integrating biophysical climate processes with social-ecological systems modeling to analyze which, if any, variables are associated with adaptation. This dissertation research is guided by the following research questions and hypothesis.

> Research Question 1: What social-ecological processes are most supportive to households' ability to implement adaptive action(s) within the context of rapid environmental change, and what variables can reliably measure those processes?
>
> Research Question 2: To what extent do the valuation of ecosystem services and sense of place play a role in supporting the adaptive behavior of households? Are there associations between these variables?
>
> Research Question 3: How can human-environment relationships within a social-ecological system be modeled spatially, using adaptation to climate change as an example? What might we learn about adaptation from such modeling?

Hypothesis: When facing rapid environmental changes, the ability of households to implement adaptive action is regulated by place-based experiences within a framework of social-ecological relationships, such as the availability and valuation of ecosystem services. I hypothesize that the distribution of these place-based experiences will be uneven across space and that clusters of social-ecological characteristics will emerge as influential, each resulting in household tendencies toward adaptation outcomes.

Background and Supporting Literature

Adaptation

A consciously planned adjustment in response to realized or expected system changes is an adaptation strategy (IPCC, 2012) and can range from short-term reactive coping mechanisms to long-term planning or transformational change (Pelling M. , 2011). In the context of social-ecological systems and climate change, an adaptation aims to reduce negative impacts of change and to realize new opportunities that come from change (Adger, Arnelll, & Tompkins, 2005; Larsen, et al., 2014). The adaptation process is a transformational cycle of growth (Holling C. S., 1973) that involves the accumulation, restructuring, and renewal of system resources (Holling & Gunderson, 2002). These system resources collectively hold natural and social assets that enable a system to deal with change (i.e., adaptive capacity) (Brooks, Adger, & Kelly, 2005).

For all adaptation strategies, we must ask what is being adapted, who is adapting at what scale, and how the adaptation is occurring (Smit B. , Burton, Klein, & Wandel, 2000). For example, in the Arctic, many adaptation strategies were and are implemented under the auspices of “the urgency to do good” (Cameron E. S., 2012) by using top-down adaptations initiated from higher levels of governing hierarchy, such as at the national scale. However, top-down adaptations can leave a legacy of colonialism, marginalization, disempowerment, and questions of sovereignty (Keskitalo & Kuulyasova, 2009). Ultimately, scholars are calling for bottom-up adaptation strategies initiated locally while recognizing that any action set to increase the adaptive capacity of certain actors may simultaneously reduce the adaptive capacity of others (Moser & Ekstrom, 2010), including the non-human actors of the system.

Modeling Social-Ecological Systems

A system is a set of elements (variables) that are directly or indirectly connected, such as through causal relationships or through the flow of energy, materials, or people. Systems analysis was adopted into the discipline of Geography during the quantitative geospatial revolution of the 1960s. It served to link theories and methods across the human and physical geographic sciences. Thus, complex systems and social-ecological systems are 2 concepts subsumed in systems theory, and they inform this dissertation research.

Complex systems are highly coupled, interdependent, non-linear systems that exhibit feedback loops and path dependencies in the flow between system variables (Hepple, 2009). Complex systems theory began in the mathematical sciences and was adopted by Geography during the cultural turn of the 1990s because it served as a helpful tool for engaging with spatial questions of nature and society. Importantly for this research, complex systems theory inherently engages with chaos theory and catastrophe (bifurcation) theory by focusing on deterministic or ‘chaotic’ systems that can lead to properties of self-organization and emergence at scale (Levin, 1998). Adaptation strategies, for example, are an outcome of complex social-ecological interactions, making social-ecological systems modeling the ideal framework for this dissertation research.

A social-ecological system integrates a social system, an ecological system, and their feedbacks into one ‘system of systems’ (Gallopin, 1991; Herrero-Jáuregui, et al., 2018). Methods used in social-ecological research include historical profiling, scenario-building, impact analysis, and spatial mapping and analysis (de Vos, Biggs, & Preiser, 2019), all largely in ecology, environmental science, and human-environment geography (Herrero-Jáuregui, et al., 2018). For example, the SESF (Ostrom E. , 2009) is widely used in research focused on social-ecological issues of sustainability and the governance of natural resources (Chaffin, et al., 2016; Fischer, et al., 2015; Schlueter, et al., 2012). The SESF aims to give equal focus to a system’s social and ecological processes by allowing for specificity within hierarchical tiers of sub-sets of (inter)connected variables. This categorization allows for complexity theory principles, such as emergence, to be revealed by analyzing iterative processes at the micro-scale within a social-ecological systems model.

This dissertation research expands on the potential usefulness of social-ecological systems modeling, such as the SESF, by seeking to identify typologies or sets of processes between variables of social-ecological interactions (Partelow, 2018, p. 35), leading to a diverse range of characteristic adaptation outcomes. In doing so, this dissertation research advances methods to pinpoint pathways most suitable for a diverse array of risk reduction efforts that maximize the fulfillment of community values while promoting ecosystem health. Spatial methods for identifying targeted climate change adaptation strategies are increasingly called for in research and in the application as climate change impacts continue.

Sense of Place and Ecosystem Services in Social-Ecological Systems

As the impacts of climate change continue to increase, so too do hazard risks. Hazard risk is mathematically expressed as the probability of a hazard event’s occurrence or frequency at differing magnitudes multiplied by the relative exposure unit, such as population density and property value (Schmidt, et al., 2011; Sutter II, 1992; Kates R. W., 1978). Political ecology reminds us that social causes of hazard intersect with age, class, race, and gender to produce differing vulnerabilities to hazard risk (Cutter, 1996; Frazier, Thompson, & Dezzani, 2014). However, how the knowledge of 'objective' hazard risk is understood and acted upon is place-based and multi-faceted (White, Kates, & Burton, 2001). Even when presented with objective facts, individuals will not always act rationally (Burton I. , 1993).

Risk is perceived through analysis—logical, verbal, deliberative, or reasoning—and through feeling, such as instinctual, non-verbal, or intuitive reactions. The place-based influence of feeling on risk perception is known as the affect heuristic (Epstein S. , 1994) because feeling filters a person's analysis of risk depending on their positive or negative experiences associated with place. Here, complexity theory can help account for the variation in reactions among people with similar place-based feelings (Slovic & Peters, 2006; Wachinger, Renn, Begg, & Kuhlicke, 2013). I argue this variation in risk perception can be accounted for in part by sense of place, which is shown to affect how people engage with processes of environmental change (Adger, et al., 2009; Clayton, et al., 2015).

Sense of place is an interdisciplinary concept that acknowledges "how different individuals and groups, within and between places, both interpret and develop meaningful attachments to areas specific to where they live" (Castree, 2003, p. 158). In the 1970s, early humanistic geographers conceptualized sense of place by focusing on understanding individual and community senses of affection, belonging, and attachment to place (Tuan, 1977; Rowles, 1978), which inherently conceptualizes a place as a center of strong positive emotion or felt values (Eyles, 1989; Hay, 1998). For example, Hay (1998) showed that an individual's sense of place could affect how they use and value their la and influence their feelings of security and belonging. More recent research on sense of place use measures of place attachment, place identity, and place dependency. These domains represent the affective, cognitive, and behavioral elements of attitude theory (Ajzen & Fishbein, 1975), respectively. Following the logic of attitude theory, place attachment interfaces with affective processes of feeling and emotion; place identity interfaces with cognitive processes, such as beliefs and knowledge systems; and place dependency interfaces with behavioral processes of experiences *in situ,* such as livelihoods and ecosystem services.

Ecosystem services (MEA, 2005) are the direct and indirect benefits humans obtain from functioning ecosystems (Costanza, et al., 1997; Daily, 1997), and are tied to the spaces in which they are provided (Busch, La Notte, Laporte, & Erhard, 2012). Ecosystem services are direct or indirect and fall into 4 types of services: provisioning services (e.g., direct use of the ecosystem, such as for fuel, food, water), regulating services (e.g., indirect use, such as pollination, water filtration, erosion control), cultural services (e.g., direct and indirect uses, such as for recreation, education, spirituality, ancestral ties to land), and supporting services (e.g., indirect use required for the other services to function such as nutrient cycling, photosynthesis). Research on ecosystem services primarily uses quantitative and socio-cultural assessments. Quantitative assessments of ecosystem services focus on generating numerical (e.g., monetary) values from which to assess ecosystem services on the demand-side, that is, those who are knowingly or unknowingly consuming or utilizing the ecosystem services in support of their wellbeing (Martín-López, Gómez-Baggethun, García-Llorente, & Montes, 2014).

Socio-cultural assessments of ecosystem services focus on understanding the non-material values and perceptions of ecosystem services (Chan, et al., 2012; Dendoncker, Keune, Jacobs, & Gómez-Baggethun, 2013). For example, a socio-cultural assessment of ecosystem services may aim to understand how landowners value and perceive these benefits (Costanza, et al., 2017). In contrast, a quantitative assessment of ecosystem services may aid in developing incentivized conservation payment schemes (Gómez-Baggethun, De Groot, Lomas, & Montes, 2010). Despite their usefulness, strictly quantitative or qualitative assessments of ecosystem services tend to under-develop the coupled nature of social and ecological processes in their models (Carpenter, et al., 2009) and downplay the biophysical and spatial dynamics of ecosystem services on the supply side (Kühne & Duttmann, 2019); thus, calling for a mixed-methods approach to assessing ecosystem services from multiple value domains, which remains limited in application (Hattam, et al., 2015).

Study Area

The Arctic and North Central Iceland

The Arctic is geographically bounded as the areas of Earth above 66 degrees North latitude. (Other delineations of the Arctic include the tree line extent, the 10ºC isotherm, and the semi-permanent permafrost extent.) The territories of 8 countries extend above 66 degrees North latitude, forming a circumference around the Arctic Ocean—the United States (Alaska), Canada (Yukon, Northwest Territories, Nunavut), Greenland, Iceland, Norway, Sweden, Finland, and Russia. Roughly 14 million people live in the Arctic, and many self-identify as indigenous (e.g., Inuit, Saami, Siberian Yup'ik Eskimos, Chukchi). Critically, in the Arctic, even globally minor temperature fluctuations can bring about significant states of Arctic environmental change due to their magnification within narrow ecosystems (Duerden, 2004; Stien, et al., 2012), which puts the functioning of these ecosystems and their services in jeopardy for social-ecological systems of the Arctic.

Located in the Arctic and sub-Arctic, Iceland and is an environment of extremes. It is one of the most mountainous, volcanically active, and glaciated regions of the world—commonly regarded as "the land of fire and ice." Located between 63- and 67-degrees North latitude at the divide of the North American and Eurasian plates, the Iceland summer sees near-continuous or continuous daylight. An island in the Atlantic Ocean, the primary regional influences on climate include the North Atlantic Oscillation (Hanna, Jónsson, & Box, 2006), the East Greenland current (i.e., cold waters), and the North Atlantic Drift (i.e., warm waters) (Einarsson M. A., 1984). Iceland's land falls within the subpolar oceanic, tundra, and ice cap Köppen–Geiger climate classifications. For example, the interior highlands of Iceland are glaciated deserts of snow and ice where temperatures traditionally stayed below 0ºC year-round. The remainder of Iceland sports tundra-dominated landscapes with semi-permanent or permanent expanses of permafrost.

Despite accounting for less than 0.012% of average global greenhouse gas emissions (Ritchie & Roser, 2017), Iceland has experienced a continued annual average temperature increase between 0.8 and 1.6ºCelsius since the 1970s (Sigurđsson, 2007). Most apparently, warming temperatures have produced secondary impacts, or early climate change indicators, such as the degradation of glacial ice (e.g., the loss of Okjökull Glacier[1]), the increasing depth and extent of permafrost degradation, and resultant instances of (coastal) erosion. These and other secondary impacts of climate change pose a variety of hazard risks to local social-ecological systems of the Arctic. For example, the glaciers in North Central Iceland have almost completely retreated, yet these biophysical features serve as the area's primary source of fresh water and as a site of strong socio-cultural heritage (Whalley, Hamilton, Palmer, Gordon, & Martin, 1995; Norðdahl, 1991).

North Central Iceland's most defining feature is the Eyjafjörður fjord—one of the tallest, deepest, and longest fjords in Iceland—where grasslands, wetlands, and highland tundra dominate the landscape (see Figure 1 at the end of this Chapter). The Eyjafjörður fjord has a relatively dense population pattern centered around Akureyri—Iceland's second-largest settlement following the capital of Reykjavik (Statistics Iceland, 2020). Net immigration to the area has slowly and steadily increased over the past 50 years, with the highest concentration in the municipalities of Akureyri and Svalbarðsstrandarhreppur (Statistics Iceland, 2020); the first- and second-most populous municipalities in the study area. There are historic socio-cultural sites of value throughout North Central Iceland, such as Pagan burial sites from the early Viking periods (Price & Gestsdóttir, 2006). There are also local ecological sites of value, such as ancient hydrothermal vents that support a unique thermal microbial habitat (Marteinsson, et al., 2001) and the islands of Hrísey and Grímsey that provide critical nesting habitat for birds, such as the Common Eider and the Arctic Tern.

Data Collection and Analysis

Model Components

Amid rapid climatic and environmental change, it is critical to identify characteristics and sites of social-ecological value and potential hazard risks across space to target successful

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[1] Okjökull Glacier was the first permanent glacier lost in Iceland. A commemoration plaque placed on August 18, 2019. It reads, "A letter to the future:/ Ok is the first Icelandic glacier to lose its status as a glacier/ In the next 200 years all our glaciers are expected to follow the same path/ This monument is to acknowledge that we know what is happening and what needs to be done/ Only you know if we did it/ August 2019/ 415ppm CO^2".

adaptation strategies. I put forth a novel model for developing a spatial social-ecological systems framework model of adaptation to climate change impacts characterized by linked subsets of biophysical and social indicators to advance efforts to target adaptation risk reduction efforts to sites that are socio-culturally appropriate and that serve to maintain or enhance the health of ecosystems and their services. This model highlights the coupled nature of social and ecological systems and their interconnected flows that, for example, can help guide governance through the implementation of adaptation interventions. Model components were guided by the SESF (Ostrom E. , 2009) and widely accepted social-ecological system variables (Partelow, 2018), including those variables that are specific to the Arctic and those that are identified as locally important in North Central Iceland.

The SESF is widely used in social-ecological systems research to analyze sustainability issues and the governance of natural resources (Chaffin, et al., 2016; Fischer, et al., 2015; Schlueter, et al., 2012). The strong foundation theory, empirics, and the multi-tiered network structure of the SESF make it a rigorous framework to base this dissertation research model on. The SESF features 4 first-tier system categories, 2 of which are featured in this dissertation's social-ecological model: the resource system and actors (see Figure 2 at the end of this Chapter). Social-ecological processes work to connect this biophysical and social system. Specifically, the social-ecological model features 2 concepts—ecosystem services and sense of place. The concept of ecosystem services provides a foundational interdisciplinary language to assess changes in ecosystem functioning and the impacts on human well-being (Carpenter, et al., 2009). The concept of sense of place provides an understanding of individual and community senses of place attachment, identity, and dependency, which interface with the affective, cognitive, and behavioral processes of actors' place-based experiences. Together, social-ecological processes link hierarchical sub-sets of variables representing the resource system and actors, as described further in Chapter 2 of this dissertation.

Methods of Data Collection

I used an online (Qualtrics) survey method to solicit numerical, categorical, text, and spatial data from households in the Eyjafjörður area of North Central Iceland. The survey consisted of fewer than 20 questions in multiple-choice, multi-select, Likert, constant sum, and matrix formats, with options to elaborate via open-ended text entries. Additionally, the survey integrated 2 participatory maps at the scale of the social-ecological system. Survey questions and participatory maps were tested and improved based on the informal feedback of colleagues and were finalized in consultation with a small team of native Icelanders that provided me with valuable translations, from the phrasing of questions to the cultural competencies that may have influenced how the questions were interpreted. This locally based team also provided support in the methods of survey dissemination and participant recruitment.

I took a two-part approach through survey mailers and media outreach to inform households of this dissertation research survey. I sent survey mailers to every household in the Eyjafjörður area, approximately 10,121 households across 7 municipalities covering approximately 4,300 square kilometers (or approximately 1,650 square miles). One side of the mailer was in English, the other in Icelandic. The mailers offered a brief description of the research project goals, a QR code and link to the survey, and mention of an optional $25 Visa gift card entry[2] to encourage participation. Supplemental media outreach consisted of broadcasting through social media posts and conversations (i.e., Facebook) and emails through informal academic and local social networks (i.e., University of Akureyri, local government agencies) to further encourage local interest and participation in this research.

Methods of Analysis

I used a mixed-methods approach to answer the research questions put forth above. Namely, a survey questionnaire gathered data related to the variables of the social-ecological system model to measure participants' amount and diversity of household adaptation actions and measure their sense of place, hazard risk perception, and valuation of ecosystem services. I describe the data each survey question sought to solicit in detail in Chapter 3 of this dissertation. Together, these measures were used to identify sets of intercorrelated variables clustered around general underlying dimensions of the data (i.e., clusters of coupled social-ecological variables that lead to a higher number of adaptation actions). To identify these underlying dimensions, I used statistical analysis, including descriptive statistics and ridge regression. I also used online

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[2] I hope the gift card serves as an incentive and as a token of appreciation but that it does not solicit "noise", which is why I did not offer compensation to all nor did I offer more than a chance to win nor more than $25.

participatory mapping exercises to solicit the identification of areas of collective social-ecological value and of areas prone to hazard risks.

In sum, the purpose of this dissertation was to explore household experiences and perceptions of climate change to ascertain the extent to which the valuation of ecosystem services, risk perception, and sense of place played a role in supporting the adoption of household adaptation actions. To do this, I proposed a novel model based on the SESF framework for integrating biophysical climate processes with social-ecological modeling, using North Central Iceland as a pilot project area. Next, in Chapter 2, I discuss the theories underpinning the research proposed in this Chapter. In Chapter 3, I discuss the methods used to construct a social-ecological system framework model. In Chapter 4, I discuss the analysis and present the results of the methods used to answer the research questions. Finally, in Chapter 5, I summarize the main conclusions of this dissertation research based on the outcome of the test of the central hypothesis and research questions.

Figure 1. This study area map of North Central Iceland highlights the Eyjafjörður fjord and its biophysical features and political boundaries.

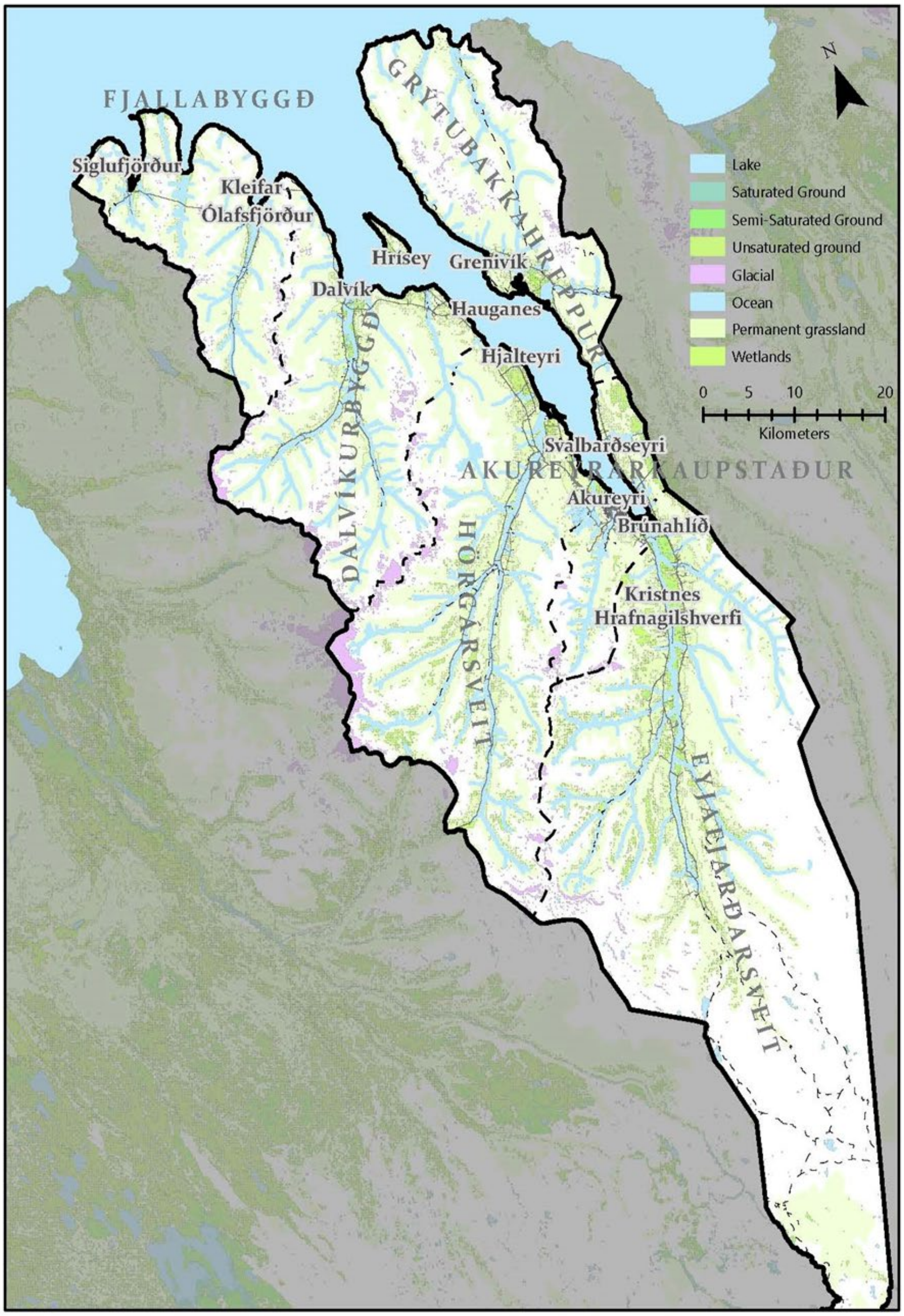
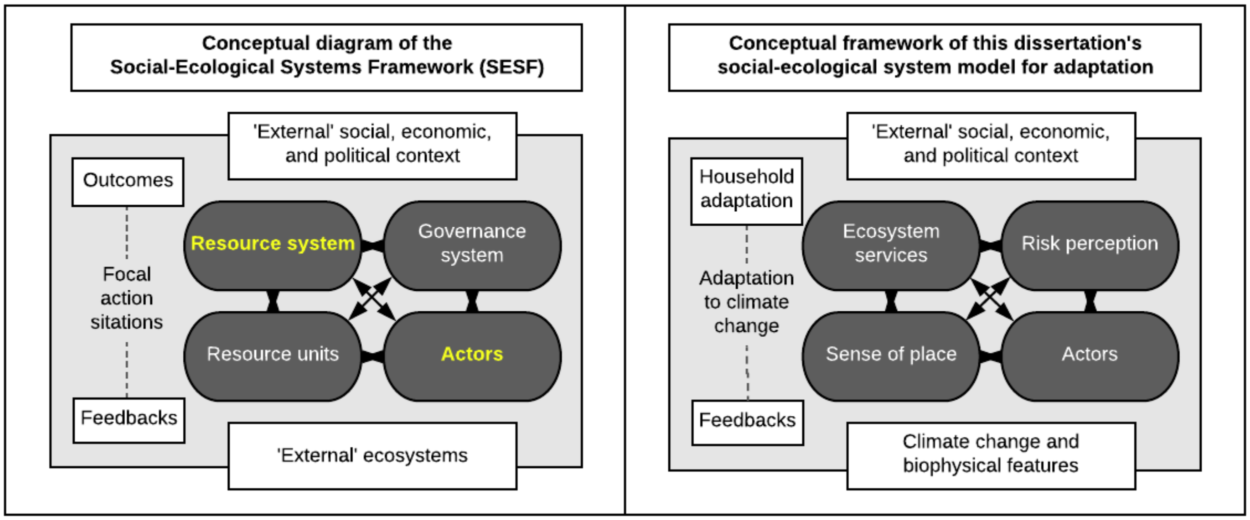


Figure 2. The conceptual diagram featured in the left-hand panel represents Ostrom's SESF (2009; 2007). Here, the 2 top-tier system categories adopted in this dissertation's social-ecological system model are denoted using yellow bolded text. The conceptual diagram in the right-hand panel represents this dissertation's social-ecological model and features the focal action situation, outcome, and system categories.



Chapter 2

Climate Change Adaptation in Social-Ecological Systems

As noted in Chapter 1, methods need to be available to aid in identifying spatial and social-ecological processes for community-backed and ecologically sound adaptation interventions. The aim of this dissertation is to develop a novel model for social-ecological systems that integrates biophysical indicators to explore what household experiences and perceptions may play a role in supporting their adaptive behavior. In support of this aim, the objective of this Chapter (2) is to construct a theoretical basis for investigating the spatial and social-ecological dynamics of climate change adaptation while paying particular attention to the Arctic. In what follows, I define and characterize climate change adaptation as it is used in the academic literature from the context of geographic and social-ecological theory. Then, I present a systematic literature review of case studies that evidence the social-ecological indicators representing early climate change impacts in the Arctic. I conclude with a discussion of gaps in the scholarly literature.

Defining and characterizing adaptation

There is a globally recognized need for adaptation efforts to reduce the risks posed by climate change and variability impacts through policies and strategies informed by research, in conjunction with climate mitigation efforts (Smith & Lenhart, 1996; UNFCCC, 1992). Climate change adaptation can be a cultural process of adjustment owing to individuals and their collective behavior that seek to reduce adverse effects on health and well-being and find opportunities that arise from change (Smit B. , Burton, Klein, & Wandel, 2000; Deneva, 1983). Both social and ecological systems collectively hold the assets that enable systems to adapt (Brooks, Adger, & Kelly, 2005). Mitigation is also an important and complementary option for combatting the risks posed by climate change by halting or slowing climate change to prevent further impacts (IPCC, 2014).

Climate change alters the frequencies and timing of annual climatic patterns and extreme events (Smit B. , Burton, Klein, & Wandel, 2000), requiring attention to the interplay between climate means, variabilities, and extremes. This is a critical step for social and ecological systems alike (Parry, 1986) to adapt to climate change because the experience of each stimulus varies (Kates R. W., 1971; Hewitt & Burton, 1971). In the natural hazards tradition (Burton I. , 1997), the development of adaptation strategies typically starts with an impact assessment that includes such a review of climate characteristics, as does this dissertation research (developed in Chapter 4). In addition to differences in the climatic stimuli that necessitate adaptation, there are distinguishing temporal adaptation features. Adaptation can be proactive or reactive, depending on if it is in response to or in anticipation of climate change impacts. It can also be autonomous or planned, depending on the degree of spontaneity underlying the action (IPCC, 1996).

Despite current knowledge of the multi-faceted space-time characteristics of adaptation, future uncertainties and the limits of scientific knowledge mean that adaptation is more often a value judgement than a calculated measure (Paavola & Adger, 2006). This is important because it highlights a gap between the purportedly objective science and the lived experience of linked social and ecological processes that lead to adaptation. Thus, there is still a need for methods that can inform the development of adaptation strategies, such as by identifying the forms that adaptation takes and examining the underlying processes that contribute to it, as this dissertation seeks to do. Engaging with personal lived experience, or the individual lived realities and day-to-day experiences of broader social-ecological conditions (Eyles, 1989), can help inform decision-making by actively engaging with local knowledge, place attachments, and risk perceptions (Hovelsrud, Karlsson, & Olsen, 2018).

In this research, a conceptual model was developed to represent system relationships and feedbacks, including climate change stimuli, which can then provide frameworks for conducting empirical analyses and numerical impact assessments (Easterling, 1996; Riebsame, 1991). Conceptual models of adaptation have co-developed alongside empirical analyses on the impacts of climate change, which have led to the discovery of novel features such as direct and indirect impacts, initial (fast) and residual (slow) impacts, and proximal and distal impacts (Parry, 1986). For example, the activity spaces in Harvey's framework "methodology of moments" (Harvey, 2008), originally presented in Marx's *Economic and Philosophical Manuscripts* (Marx K. , 1975), were recently re-presented as co-evolving climate change adaptation activity spheres. These adaptation spaces/spheres include (1) individuals (e.g., identity, values), (2) behavior (e.g., habits, routines), (3) environment (e.g., biophysical dynamics), and (4) institutions (e.g., cultural, regulatory). In re-presenting adaptation as activity spaces, the underlying conceptual framework shifts from a political economy to a political ecology perspective to analyze climate change adaptation (Pelling, O’Brien, & Matyas, 2015).

The development of conceptual frameworks for analytical and empirical use, such as the one presented above, helps understand the forms that adaptation can take. This information can lead to an understanding of the processes that enable the management of climate change impacts (Burton I. , 1997; Downing, Ringius, Hulme, & Waughray, 1997). Research has been conducted to determine the forms that adaptation takes, resulting in a collection of categories most typically including technological, structural, legal, regulatory, behavioral, financial, institutional, and informational forms of adaptation (Agrawal, 2008; Smit B. , Burton, Klein, & Wandel, 2000). Critically, much of the research on climate change adaptation stems from studies of resilience. Resilience is the capacity and ability for systems to adjust to a disturbance in ways that maintain the essential structure, function, and identity of the system while maintaining the capacity and ability for adaptation (IPCC, 2018; Arctic Council, 2018).

Resilience and social-ecological systems modeling

The concept of resilience in ecosystem ecology formed as an alternative to the ecological stability theory in studies of predator-prey interactions (Holling C. S., 1961; Morris R. F., 1963), going against the notion that biophysical dynamics perpetually sought a state of equilibrium (Clements, 1936). Holling (1973) proposed that resilience is the capacity of an ecosystem to persist within multiple domains of stability, represented later using the concept of panarchy. Panarchy is described as the ‘adaptive cycle,’ a dynamic process across scales between rapid change and memory, disturbance and diversity, and their interplay (Holling & Gunderson, 2002). The adaptive cycle views systems as evolving in the process of spontaneous reorganization, characterized by looping phases of rapid growth (r), stabilization (K), collapse (Ω), and reorganization (α) (Holling & Gunderson, 2002). Ultimately, the concept of panarchy further propelled resilience literature by emphasizing the role of adaptive capacity, viewing system dynamics in configurations that allow for change, as opposed to configurations that seek to mitigate or avoid change (Folke, Colding, & Berkes, 2003; Holling C. S., 1973).

The rejection of an ecological equilibrium spurred the new ecology paradigm (Botkin, 1990), which focused on the system dynamics noted above—non-linearity, space-time variations, complexity, and uncertainty (Scoones, 1999). Inspired by the new ecology paradigm, resilience literature sought to understand the multiple stable states of biophysical dynamics. Furthermore, it highlighted the importance of system disturbance and unpredictability in adaptation processes (Holling C. S., 1987). Notably, Holling led the formation of the Resilience Alliance within the Stockholm Resilience Centre in the 1990s. The goal of the Centre was to develop a cohesive resilience framework by examining connections between the ecological and social sciences (Gunderson, S, & Light, 1995).

Gunderson (2010) suggested that social systems embed similar dynamics (e.g., resilience, adaptation, feedbacks) as ecosystems and that those dynamics often intertwine. This ultimately led to the concept of 'social-ecological resilience' as viewed through systems theories, and the concept of a 'social-ecological system' evolved. A system, in this context, is a set of elements that are directly or indirectly connected, such as through causal relationships or through the flow of energy, materials, or people. A social-ecological system, then, integrates a social system, an ecological system, and their feedbacks into one 'system of systems' (Gallopin, 1991; Herrero-Jáuregui, et al., 2018). This integrated system views humans as part of, rather than separate from, nature due to the interactions and interdependence of social-ecological subsystems (Berkes & Folke, 2000; Carson & Peterson, 2016). This integration makes social-ecological systems dynamics ideal for modeling the human-environment relationships that lead to climate change adaptation.

Drawing from Holling, a resilient social-ecological system has the ability and capacity to absorb disturbance and maintain its structure, processes, and identity over time (Cumming, et al., 2005; Walker, Holling, Carpenter, & Kinzig, 2004). Social-ecological resilience is inherently tied to self-organization. In ecological systems, self-organization is tied to pattern-process interactions of biodiversity and natural disturbance regimes (Adger W. N., 2000). In social systems, self-organization is tied to institutions (e.g., governmental, familial, cultural). Here, social and ecological systems hold different underlying self-organization processes (Cote & Nightingale, 2012).

The above-noted difference in social and ecological systems dynamics needs to be accounted for when engaging normative questions that imply a policy preference (Lackey, 2001), as much of the social science climate change literature seeks to do (Adger W. N., 2006; Smit & Wandel, 2006; Duit, Galaz, Eckerberg, & Ebbesson, 2010). Further, due to the role of agency within some systems, engaging with studies of resilience and adaptation from the social sciences can produce ontological clashes between those that benefit from the current or proposed system and those that do not (Levin, 1998; Leach, 2008; Hornborg, 2009). Together, variations in the self-organization and agency of social and ecological systems call for additional constructive pathways for developing social-ecological analyses (Brown K. , 2014; Hahn, Schultz, Folke, & Olsson, 2008), such as this dissertation sought to do.

Instead of adapting to preserve resilience, a social-ecological system may adapt in a way that leads to a major transformation. Transformation is the act of a system changing fundamentally in form and function that produces a distinctly new system (Pelling, O'Brien, & Matyas, 2015). Transformation may occur when ecological or social tipping points are passed, otherwise rendering the existing system unsustainable (Walker, Holling, Carpenter, & Kinzig, 2004). In a transformational adaptation of social-ecological systems, a current (potentially resilient) state is perceived as undesirable and so is purposefully eroded to redefine the system structure, function, and identity (Walker, Abel, Anderies, & Ryan, 2009). This pathway builds on proposed response-based triggers of transformational adaptation[3] (Kates, Travis, & Wilbanks, 2012) by purposefully overwhelming system capacities to initiate a shift in states (Lackey, 2001).

Transformation can also be a reactive process to severe vulnerability and climate impacts that overwhelm system capacities (i.e., a disaster) (Kates, Travis, & Wilbanks, 2012). When a critical system threshold is passed, transformation causes a shift to an alternative stable state (or regime). This shift is often very rapid, even if the pressures leading to the transition are gradual (Scheffer, Carpenter, Foley, Folke, & Walker, 2001), such as incremental increases in the average temperature of the global climate (IPCC, 2014). The perceived rapidity of stable state

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[3] Kates et al. (2012) identify categories of transformational adaptations as those that: (1) occur at a global or near-global scale with intensity, (2) are new to a specific region, or (3) shift and transform places or locations.

changes may be due to biophysical processes that collectively act to stabilize the current state through system feedbacks, giving little warning that a system threshold may soon be passed (Rockström, et al., 2009), and further demonstrating the need for research on the processes of adaptation in social-ecological systems.

Social-ecological systems modeling emerged as a promising framework methodology for answering research questions about the interactions between people and the environment. As noted above, the SESF (Ostrom E. , 2009) is a widely used analytical tool in social-ecological systems research (Chaffin, et al., 2016; Fischer, et al., 2015; Schlueter, et al., 2012) that shows potential for development as a spatial model to study social-ecological outcomes of adaptation (Janssen, Anderies, & Ostrom, 2007). The SESF allows for specificity within hierarchical tiers of sub-sets of (inter)connected system variables. This nested structure follows broader complexity theory principles such as adaptive cycles (Holling C. S., 1973).

The 4 top-tier categories of system variables in the SESF are the resource system, the resource units, the actors, and the governance system. Each tier is composed of social and ecological variables, which may themselves have subsets of variables (Ostrom E. , 2007). This core structure of tiers is (inter)linked by social-ecological processes, dubbed interactions, that center around a thematic ‘action situation’ (McGinnis & Ostrom, 2014). The nested structure of social-ecological variables produces interactions that are assumed to influence the outcomes of the action situation in focus. Critically, the SESF can be adapted to serve sector-specific frameworks that are informed by diverse cases (Partelow, 2018; Thiel, Adamseged, & Baake, 2015). Further research on climate change adaptation using the foundations of the SESF is needed to continue the development of the SESF and to expand the applicability of social-ecological analyses to climate change studies. This dissertation contributed to such development by identifying typologies or sets of social-ecological processes between variables (Partelow, 2018, p. 35) that may influence the number and diversity of adaptations a household undertakes (see Chapter 4).

Two such social-ecological processes are particularly promising in this pursuit: sense of place, and ecosystem services. As noted in Chapter 1, sense of place is a dynamic temporal and spatial process that is considered fundamental to existence (i.e., perceiving, understanding, and engaging with the world) (Malpas, 2018). In the 1970s, early humanistic geography conceptualized sense of place as individual and community senses of place affection, belonging, and attachment (Tuan, 1977; Rowles, 1978). This framed place as a center of felt values[4], strong positive emotions (Eyles, 1989; Hay, 1998), or a "center of meaning or field of care" (Tuan, 1977). Many subsequent descriptions and evaluations of sense of place were represented by the strength of the emotional bonds between people and their environment (Riley, 1992; Shumaker & Taylor, 1983; Williams, Patterson, Roggenbuck, & Watson, 1992). For example, Low and Altma (1992) posited that people are predisposed to prefer certain landscapes, inspiring studies on the role of a setting's biophysical features in the development of place attachment (Stedman, 2003; Beckley, 2003).

The above studies showed that sense of place is an individual experience developed through place-based interactions[5] with a set of biophysical features (Masterson V. A., et al., 2017). Collectively, sense of place constitutes place meanings[6], or descriptive cognitive factors, of the types of places in question (Stedman, 2003). The presence of linked biophysical and social mechanisms in forming sense of place highlights the need for a social-ecological approach to advance understandings of the role of sense of place in climate change adaptation. Further, Hay (1998) showed that an individual's sense of place could affect how they use and value their environment. In effect, this means place attachments can transfer environmental concerns and preferences at scale and across space (Masterson, Enqvist, Stedman, & Tengö, 2019; Chapin & Knapp, 2015; Shamai, 1991).

Individuals' environmental preferences and concerns are also indicative of a second social-ecological process—their valuation of ecosystem services. Ecosystem services are the direct and indirect benefits humans freely obtain from the functioning of healthy ecosystems (Costanza, et al., 1997; Daily, 1997; MEA, 2005). In this way, the valuation of ecosystem services can account for system interactions (Daily, 1997) by identifying flows from ecological to social values and from social to ecological values (Munange, Thiaw, Alverson, Mumba, &

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[4] Feelings of group membership can influence the development of place attachment (Greider & Garkovich, 1994) and can vary within a community, such as between local and non-local peoples (Kaltenborn & Williams, 2002).

[5] Individuals can also form attachments to places they may not have had direct contact with, known as symbolic place attachment (Blake, 2002).

[6] Somewhat problematically, the term 'sense of place' is used interchangeably in the literature with 'place meanings', which can lead to a reduction in the efficacy of their use (Kruger, Hall, & Stiefel, 2008).

Liu, 2013). There are 4 categories of ecosystem services. Supporting services provide the foundations of the ecosystem, such as through biomass production and soil formation (MEA, 2005). Regulating services are moderating processes that stabilize the ecosystem, including carbon sequestration and pollination (CBD, 2009). Provisioning services are raw products harvested from the ecosystem, such as potable water and minable minerals (Nassl & Löffler, 2015). Cultural services, then, are the non-material benefits provided by ecosystems, such as spaces for recreating and aesthetic pleasure (Scholes, Reyers, Biggs, Spierenburg, & Duriappah, 2013).

Cultural ecosystem services are more than subjective and personal preferences; they represent shared social and historical values (Irvine, et al., 2016). For example, sense of place is considered a cultural ecosystem service because it serves to identify the bonds people have with particular places (Williams & Stewart, 1998), including the place values they support (Chapin & Knapp, 2015; Cantrill, 1998). In this way, sense of place and ecosystem services are important and potentially complementary social-ecological processes that may influence climate change adaptation. Further, as a cultural ecosystem service, Hausmann et al. argue that sense of place is the least represented (Kudryavtsev, Stedman, & Krasny, 2012), further justifying its inclusion in this dissertation research as these 2 sets of literature continue to merge[7].

In sum, the presence of linked biophysical and social mechanisms highlights the need for a social-ecological approach to advance understandings of their role in climate change adaptation (**Research Question 1**). The SESF was an ideal foundation for answering this dissertation's research questions because it allowed for the creation of a framework marked by specificity within hierarchical tiers of sub-sets of variables as they related to system outcomes (**Research Question 3**). Namely, when viewed from a social-ecological perspective, the concepts of sense of place and ecosystem services present as promising pathways to understand local perceptions and mechanisms that enable people and communities to adapt to the impacts of climate change (**Research Question 2**). Sense of place is an ideal concept for engaging with the relationships between place-based knowledge and adaptation by connecting to the experience of local

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[7] The MEA and the TEEB acknowledge sense of place as a distinct cultural ecosystem service (MA, 2005; TEEB 2010), and there are calls for CICES to do the same (Ryfield, Cabana, Brannigan, & Crowe, 2019).

communities and their histories (**Research Question 1**). In complement, ecosystem services provide the context for changes in biophysical features of place within social-ecological systems (**Research Question 1**).

Systematic Review of Climate Change Adaptation in the Arctic

Originating in the field of medicine, a systematic review provides a comprehensive overview of a body of literature by addressing a specific research question using evidence-based practices (Grant & Booth, 2009; Gough, Oliver, & Thomas, 2017). This enables precise examination of a specified topic within a body of literature. A systematic review also seeks to minimize bias by including an evaluation of the quality of studies selected. A mixed set of literature and researcher-defined criteria protocols must be followed before and during the review process (Moher, et al., 2015). For example, criteria for finding, selecting, and analyzing the literature must be defined (See Appendix 1 for complete protocol criteria.) Due to the rigor of the screening process and the focus of the research topic, a systematic literature review may include fewer studies than other types of reviews (Petticrew & Roberts, 2008; Fink, 2020).

While systematic reviews are common in health science fields (Purssell & McCrae, 2020), fewer examples exist in the social and environmental sciences (Landauer, Juhola, & Söderholm, 2015). Despite their underrepresentation, systematic reviews have been conducted since at least the 1970s (Hunt, 1997), including in the climate change adaptation literature (Hahn & Nykvist, 2017). Problematic to the advancement of adaptation literature, many current assessments, reports, and studies do not describe their selection criteria when attempting to uncover generalizable trends (Ford, McDowell, & Jones, 2014), which reduces the replicability and usability of the studies (Eisenack & Stecker, 2012). This ultimately limits our global understanding of the adaptations taking place in response to climate change impacts (Dupuis & Biesbroek, 2013), further justifying the need for a systematic review.

In recognition of the knowledge gaps noted above, I systematically reviewed the literature on climate change adaptation in contribution to the development of this dissertation's social-ecological system framework. Namely, I analyzed a set of peer-reviewed case studies of adaptation in the Arctic to offer an understanding of who is adapting to what and why as gleaned from (collective) human experience (Pelling M. , 2011). I build on literature reviews of similar topical scope, i.e., that of adaptation knowledge production stemming from natural hazard and geographic research traditions (Janssen, Schoon, Ke, & Börner, 2006; Ford, McDowell, & Jones, 2014).

The most recent review of similar topical and geographical scope was published in 2014 (Ford, McDowell, & Jones, 2014), 7 years ago at this writing, further justifying the need for an updated review. In what follows, I present the results of the systematic literature review as gleaned through content analysis (Franzosi, 2008). Using this procedure, I identified 4 indicators of social-ecological change necessitating adaptation, and topical areas where more research is needed. This review contributed to developing a social-ecological systems framework for climate change adaptation by identifying and defining system components and processes using diverse cases as inputs that reflect changes in biophysical features.

Adaptation terminology and application in Arctic case studies

Case studies presented applications of adaptation terminology that stemmed from 2 foundational terms—resilience and adaptation—as defined above. Adaptations are the product of the collective coping process with induced changes within a system (Ford, Smit, & Wandel, 2006). Adaptive capacity refers to the ability of a system to address and manage change and combat exposure (Ford, et al., 2008), such as by modifying practices in the social-ecological environment (Berkes & Dyanna, 2002). Systems with comparatively increased or enhanced adaptive capacity are cited as less susceptible to loss from exposure because these systems can more easily reconfigure to reduce vulnerabilities (Smit & Pilifosova, 2003). In this way, adaptive capacity operates synonymously with resilience in much of the literature (McCarthy, et al., 2005).

It is reasonable to assume that if adaptive capacity is a set of characteristics that enable a system to adapt, then adaptive governance is the process by which this capacity is transformed to adaptation. Adaptive governance refers to the institutional and political frameworks that develop and enact adaptation to change (Carpenter & Folke, 2006). This builds on the concept of adaptive management of ecosystems by including the broader social contexts that enable such management (Folke, Hahn, Olsson, & Norberg, 2005). For example, some case studies call for the identification of what is being done to prepare for adaptation within existing governance structures (i.e., adaptation readiness) as a form of adaptive capacity building (Ford, Labbé, Flynn, & Araos, 2017; Ford & King, 2015).

Sustainable adaptation is promoted to enhance adaptive capacity, and refers to the fact that adaptation is not inherently “good” or politically neutral, calling for accountability in decision-making processes to increase the capacity-building of communities and empower constituents (Cameron E. S., 2012). Further, studies argue that focusing only on adaptation risks shifts attention away from the slowing of climate change and the accountability of peoples in distant places whose actions impact Arctic communities (Crump, 2008). Instead, adaptations need to be evaluated in relation to sustainable outcomes and local values (Loring, Gerlach, Atkinson, & Murray, 2011).

The systematic review revealed that most adaptations are behavioral[8] and take place at the individual or household scale. Further content analysis of adaptations at the household scale revealed 7 distinct categories of climate change adaptation. I identify and describe these categories, as supported by examples from case studies and in the context of the broader climate change adaptation literature, as follows:

1. Structural safety improvements,
2. Emergency preparation,
3. Financial safety improvements,
4. Livelihood changes,
5. Practicing energy efficiency,
6. Changing consumer practices, and
7. Educational opportunities.

First, structural safety improvement refers to adaptations that seek to improve the physical safety and material resources of a person or household, such as in response to climate- and hazard-induced health risks. For example, Arctic communities have expressed health concerns related to heatwaves (Gosselin, Bélanger, Lapaige, & Labbé, 2011) and water quality (Martin, et al., 2007). These concerns have prompted adaptation across scale to improve the health and safety of people, for example, by improving access to quality healthcare systems

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[8] Additional categories of climate change adaptation include organizational, regulatory, educational, and financial mechanisms; monitoring and evaluation; and infrastructure and technology (Ford, McDowell, & Jones, 2014; Hofmann, Hinkel, & Wrobel, 2011).

(Driscoll, Sunbury, Johnston, & Renes, 2013), by implementing environmental and heath monitoring systems with educational components (Martin, et al., 2007), and by continually revising fire management options, plans, and building standards (Trainor, et al., 2009).

At the individual level, the adoption of ‘hard’ structural safety improvements may be constrained by household financial capacity and residential ownership status (Jorgensen & Stedman, 2006), and may preclude the adoption of some emergency preparations. Emergency preparations refer to adaptations that seek to improve the preparedness of households and communities in the event of a disturbance. For example, climate-induced changes often mean that longer, riskier, and costlier travel is required for activities on the land, such as hunting and fishing (Berkes & Dyanna, 2002; Ford, et al., 2007). Here, adaptations include the use of a personal emergency locator beacon to reduce emergency response times (Brubaker, Berner, Chavan, & Warren, 2011), the use of a publicly available hazard map and GPS to enhance hazard awareness and disaster planning (Pearce T. , Ford, Caron, & Kudlak, 2012; Labbé, Ford, Araos, & Flynn, 2017; Ford, Smit, & Wandel, 2006), and the knowledge of how to survive on the land (Pearce T. , Ford, Willox, & Smit, 2015). Indeed, being on the land is recognized as a protective factor that improves youth mental health in the context of climate impacts (MacDonald, et al., 2015), and land-based knowledge is a key determinant of adaptive capacity in the Arctic (Pearce T. W., 2011).

As alluded to above, financial capacities can constrain the options of a household seeking to improve their safety and emergency preparedness. This means that adaptive capacity can be enhanced by improving financial safety. Here, financial safety improvements refer to adaptations that seek to increase the financial capital and security, such as in response to changing financial needs and anticipated risks (Skrylnikova, Lozhnikova, Muravyov, Kirpotin, & Ozheredov, 2014). For example, some rural Arctic communities show that federal transfer payments may enhance capacities for resilience (Ford & Furgal, 2009) amid the increasing costs associated with adaptation (Ford, McDowell, & Pearce, 2015). Indeed, there is a continued need to acquire financial resources to support adaptation efforts (Ford, 2009). For example, more coastal communities experiencing erosion require relocation efforts, and current governmental support remains insufficient (Manrique, Corral, & Pereira, 2018). Sustained funding supports adaptation efforts beyond impact assessments and planning is required to implement and sustain the recommendations based on their results (Ford, Labbé, Flynn, & Araos, 2017).

Fourth, climate change impacts are likely to continue to dampen or prohibit the feasibility of livelihoods that are dependent on stable environmental conditions (Larsen, et al., 2014), such as fishers and outdoor tourist operators (Dawson, Maher, & Slocombe, 2007; Keskitalo & Kuulyasova, 2009). In seeking to improve their financial safety, a household may change their livelihood practices to improve their economic stability (i.e., income). Critically, an adaptation focused on livelihood changes differs from an adaptation focused on financial safety improvements by seeking to maintain cultural place identity (Nuttall, 2017; Einarsson N. , 2009).

Indeed, some individuals consider a loss in their way of life and livelihood due to climate impacts an important determinant of their health (Healey, et al., 2011). Climate change impacts have also caused an increase in exploration, extraction industries, and shipping and transportation, which change and threaten the social-ecological dimensions of many Arctic communities (Huntington, Quakenbush, & Nelson, 2017; Cameron E. S., 2012).

Despite substantial exposure to the impacts of climate change, Arctic peoples have contributed little to the current climate crisis when compared to the rest of the world[9] (Trainor, Chapin, Huntington, Natcher, & Kofinas, 2007). Indeed, many Arctic communities have long engaged with energy efficiency and sound consumer practices that seek to minimize and reduce contributions to global climate change (Healey, et al., 2011). Public educational opportunities support these efforts and refer to adaptations that seek to improve collective knowledge. These educational opportunities may consist of informal knowledge sharing across social networks, the strength of which are a determinant of adaptive capacity (MacDonald, et al., 2015). For example, research outreach and sustained community engagement are educational opportunities that can benefit both parties (Baztan, Cordier, Huctin, Zhu, & Vanderlinden, 2017). The 7 adaptation types presented above were revealed through content analysis and situated within

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[9] Countries with Arctic territories such as the United States, Russia, and Canada face internal colonization (Trainor, Chapin, Huntington, Natcher, & Kofinas, 2007) that makes country-level per capita rates an unfair representation of true Arctic emissions.

broader resilience literature on social-ecological characteristics of adaptive capacity, governance, and sustainability.

Indicators of social-ecological change necessitating adaptation

It is important to understand the indicators of social-ecological change that necessitate adaptation to better identify and support viable future options. Case studies of adaptation discuss climate change impacts in relation to social systems or biophysical indicators that influence social systems. However, as confirmed in other studies, few adaptations are understood or enacted in response to climatic drivers alone (Labbé, Ford, Araos, & Flynn, 2017). Thus, I identified indicators of change from a social-ecological systems perspective as distilled from the systematic review. The 4 indicators are as follows:

- Degradation of Arctic ice,
- Changes in ecosystems,
- Changes in weather patterns, and
- Changes in hydro-geological risk

In what follows in this Section, these 4 indicators of change are discussed and supported by exemplary case studies from the broader Arctic climate change literature on adaptation, which evidence each emergent indicator presented, as revealed by content analysis.

Degradation of Arctic ice

The Arctic is experiencing climate change through impacts that result in the degradation of the cryosphere (IPCC, 2014). Reflecting this, the most common indicator in the literature, cited as necessitating adaptation, was changed land- and marine-based ice. Case studies cite degradations in the amount (Ignatowski & Rosales, 2013), extent (Kofinas, et al., 2010), depth (Wesche & Chan, 2010), and quality of ice (Fawcett, Pearce, Ford, & Archer, 2017), including reductions in the amount of shore-fast[10] and multi-year sea ice (Brubaker, Berner, Chavan, & Warren, 2011). Further, the seasonality of land- and sea-based ice is changing; case studies cite a delayed annual freeze-up (Ford, Smit, & Wandel, 2006) and an earlier annual break-up of ice (Pearce T. , Ford, Caron, & Kudlak, 2012).

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[10] Shore-fast ice is sea ice that has accumulated along a coastline and does not drift from its position.

The loss of shore-fast and multi-year ice diminishes natural protection from waves otherwise afforded to inlets and coastal areas (Fang, Freeman, Field, & Mach, 2018), resulting in an increase in storm waves and rougher waters, which pose direct risks to the health of Arctic peoples (Ford, et al., 2007). Other direct risks under less-predictable and less-reliable ice conditions include accidental drownings (Giles, Strachan, Doucette, Stadig, & Pangnirtung, 2013) and increased instances of off-roading and boating accidents (Loring, Gerlack, Atkinson, & Murray, 2011). Indirect risks to the health of Arctic peoples include the loss of species that require ice-dominated habitats, such as caribou, reindeer (Rattenbury, Kielland, Finstad, & Schneider, 2009), and marine mammals (Kovacs, Lydersen, Overland, & Moore, 2011; Burek, Gulland, & O'Hara, 2008), the loss of which can destabilize regional ecologies (Post, et al., 2013) and render existing food sources unviable (Bogdanova, et al., 2021).

The loss of ice and implications for health has spurred many Arctic communities' transition to imported, more expensive foods of lower nutritional quality than traditional sources (Rosol, Powell-Hellyer, & Chan, 2016). Ice loss poses barriers to food gathering, preparation, and storage process resiant on ice-dominated landscapes (Rosol, Powell-Hellyer, & Chan, 2016), which can lead to increased instances of food insecurity and food poisoning (Driscoll, Sunbury, Johnston, & Renes, 2013). The degradation of Arctic ice and resultant social-ecological changes implicated in these case studies reflect themes in the broader discourse of global health disparities (Trainor, Chapin, Huntington, Natcher, & Kofinas, 2007) and biodiversity (MEA, 2005) that forewarn the negative and unequally distributed impacts of climate change. Indeed, the Arctic is featured as home to many of the world's 'frontline communities'[11] in the environmental justice literature (Krupnik I. , 2019).

Changes in ecosystems

Changes to Arctic ecosystems are a strong indicator of climate change impacts that motivates or necessitates adaptation, with nearly 2 thirds of all case studies included in this review citing changes in wildlife (Goldhar, Bell, & Wolf, 2014; Huntington, Quakenbush, & Nelson, 2017; Trainor, Chapin, Huntington, Natcher, & Kofinas, 2007). This theme is also

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[11] Frontline communities are those that experience the impacts of climate change disproportionately sooner and more severely when compared to the rest of the world, such as rural communities of the Arctic.

reflected in the broader ecological literature, wherein climate change impacts and changes in land-use practices have collectively decreased the population of terrestrial animals in the Arctic by nearly a third since the industrial revolution (Larsen et al. 2014).

Concurrently, there is an overall observed decline in the health of mammals such as reindeer (Furberg, Evengård, & Nilsson, 2011) and caribou (Fawcett, Pearce, Ford, & Archer, 2017), and a decline in the health of native landscapes (Takakura, 2016; Ogden & Innes, 2009). These declines coincide with projections that much of the Arctic tundra will be replaced with new dominant ecosystems by the year 2100 under high-emissions scenarios (Myers-Smith, et al., 2011). Case studies also cite changes in species migration, habitats, and health (Keskitalo & Kuulyasova, 2009) and the appearance of new species, including biting or invasive species, such as mosquitos (Trainor, Chapin, Huntington, Natcher, & Kofinas, 2007) and the King crab (West & Hovelsrud, 2010).

As Arctic ecosystems change, so too do social systems, such as through the observed decline in the amount (Ogden & Innes, 2009) and quality of harvestable foods (Rosol, Powell-Hellyer, & Chan, 2016) that many communities rely on (Manrique, Corral, & Pereira, 2018). This trend is reflected in the broader literature on climate change impacts on nutrition (Borelli, et al., 2020) and food insecurity (Brubaker, Berner, Chavan, & Warren, 2011).

Amid changing environmental conditions, some Arctic species are becoming harder to find and are rendered physically or economically inaccessible through less safe and more costly transportation methods (Berkes & Dyanna, 2002; Giles, Strachan, Doucette, Stadig, & Pangnirtung, 2013). Further impediments are found in constrictive land-use practices (Rattenbury, Kielland, Finstad, & Schneider, 2009) and imposed hunting and fishing restrictions that fail to consider flexibility in the seasonal timing of migration patterns (Loring, Gerlack, Atkinson, & Murray, 2011). This justifies the need for inclusive and cross-scalar adaptations to sustain social-ecological processes tied to Arctic environments and their local uses (West & Hovelsrud, 2010; Keskitalo & Kuulyasova, 2009).

Changes in weather patterns

In addition to changes in Arctic ice and ecosystems, weather patterns throughout the Arctic are also changing. Over half of all case studies included in the systematic review cite an increase in unpredictable weather patterns (Pennesi, 2012) and more frequent extreme weather events (Labbé, Ford, Araos, & Flynn, 2017) as indicators of change necessitating adaptation. Nearly half of all case studies cite air-, land-, or marine-based temperature increases as an indicator of change (Ogden & Innes, 2009; Keskitalo & Kuulyasova, 2009). Indeed, the Arctic has already warmed by nearly 2ºC since the year 1990 (Jefferies, Overland, & Perovich, 2013). These observed increases in temperature often have coincided with changes in seasonality (Martin, et al., 2007; Tremblay, et al., 2008), which render it difficult to read the land using traditional environmental cues and place-making capacities (Loring, Gerlach, Atkinson, & Murray, 2011; Pearce T. , Ford, Willox, & Smit, 2015).

The loss of such ecological knowledge and traditional practices on the land has led to declines in the transmission of knowledge across generations (Pearce T. , Ford, Caron, & Kudlak, 2012). Indeed, climate change impacts can disrupt place-making processes (Baztan, Cordier, Huctin, Zhu, & Vanderlinden, 2017) and can erode the relationship between people and place (Masterson, Enqvist, Stedman, & Tengö, 2019). Increasing temperatures are particularly damaging to sense of place in the Arctic because the history and health of Arctic peoples is closely tied to cold environments and the identities and services these environments provide (Healey, et al., 2011). This theme was evident in articles throughout the systematic review (Kofinas, et al., 2010) and further justified the need for this dissertation research to examine the role of sense of place in climate change adaptation.

Youth and elders are particularly at-risk to the effects these changes could have on their mental health and well-being (MacDonald, et al., 2015; MacDonald, Harper, Willox, & Edge, 2013). This reflects a broader need for climate change adaptation research to include youth in the research process (Herman-Mercer, et al., 2016) and stresses the importance of retaining traditional values amid adaptation to change (Huntington, Quakenbush, & Nelson, 2017). Additional impacts to weather patterns gleaned from the systematic review included, for example, changes in the direction (Wesche & Chan, 2010) and strength (Ford, Smit, & Wandel, 2006) of wind and marine currents (Ignatowski & Rosales, 2013), and changes in the amount and timing of precipitation events (Furberg, Evengård, & Nilsson, 2011; Prno, et al., 2011).

Changes in hydro-geological risk

The above-noted changes in Arctic ice, ecosystems, and weather patterns are often linked to changes in hydro-geological risk that impact the health of Arctic peoples. Permafrost degradation, for example, was cited as an indicator of change motivating adaptation in nearly half of all case studies included in this review (Takakura, 2016; Healey, et al., 2011), often concurrent with coastal erosion (Berkes & Dyanna, 2002). Permafrost degradation and erosion have inherent implications for social-ecological risks, such as impacts on critical infrastructure (e.g., communication, energy, transportation, and water systems) and housing (Labbé, Ford, Araos, & Flynn, 2017). Historic cultural sites are also increasingly at risk to hydro-geological hazards (Pearce T. D., 2009), such as ground slumping (Trainor, Chapin, Huntington, Natcher, & Kofinas, 2007), mudslides (Gosselin, Bélanger, Lapaige, & Labbé, 2011), and landslides (Skrylnikova, Lozhnikova, Muravyov, Kirpotin, & Ozheredov, 2014). In severe cases, entire communities require relocation (Manrique, Corral, & Pereira, 2018).

As permafrost degrades and erosion continues, Arctic communities cite concerns over declines in the quality of available freshwater sources (Goldhar, Bell, & Wolf, 2014) and the need for improved water collection, treatment, storage, and distribution facilities (Gosselin, Bélanger, Lapaige, & Labbé, 2011). For example, water availability and quality are compromised in response to decreasing river levels (Martin, et al., 2007) and increasing instances of water-borne emergent disease vectors (Hughes-Hanks, et al., 2005). Permafrost degradation and warming temperatures have also allowed for a freer transport and accumulation of materials through ecosystems, resulting in increased exposure to harmful pollutants (e.g., bioaccumulation of metals) (Alexander, 1999; Larsen, et al., 2014). These hazard risks have spurred the need for tangible adaptations such as amendments to existing land use plans and building codes (Pearce T. , Ford, Caron, & Kudlak, 2012), support for enhancing emergency response capabilities (Labbé, Ford, Araos, & Flynn, 2017), and education on the risks of ‘raw’ water consumption (Martin, et al., 2007).

In review, climate change impacts are found to have altered Arctic ice, ecosystems, weather patterns, and hydro-geological risks, as revealed from content analysis of the literature in this systematic review. These 4 primary indicators of change contributed to the variables in this dissertation research's social-ecological framework that sought to measure local perceptions of broader trends in Arctic environmental change.

To illustrate the dimensions of climate change adaptation from a social-ecological systems perspective, I conclude by using an example of Northern fishing communities in Iceland. For example, Húsavík exhibits a strong sense of place and cultural resilience. Climate impacts caused changes to marine ecosystems that limited the viability of fishing practices. The resultant economic downturns caused residents of Húsavík to adapt by diversifying their economy to favor tourism and tourism development. Ultimately, whalers switched their livelihoods to whale-watching by viewing the activity as congruent with community well-being and traditional maritime culture, thereby successfully integrating a new activity into the existing culture and economy (Einarsson N. , 2009).

Gaps in the literature

Arctic case studies cited the need for research to better understand the local perceptions and mechanisms that enable people and communities to adapt to the impacts of climate change (Cameron E. S., 2012) and to use case studies to produce such generalizable knowledges and strategies (Keskitalo & Kuulyasova, 2009; Huntington, Quakenbush, & Nelson, 2017). This is supported by calls for more multi-scalar information (Ford & Smit, 2004) to combat scalar mismatches, which can inhibit examinations between case studies of how adaptation is encouraged by processes that operate across scales (Ford J. D., et al., 2012). Adaptation research needs to focus on examinations between, not just within, individual case studies such that research may be able to explain their differences and commonalities to guide sustainable place-based practices (Ostrom E. , 2007; Loring, Chapin, & Gerlach, 2008). This dissertation research helped to fill these knowledge gaps by focusing on the perceptions and social-ecological processes that enabled households to adapt while being mindful of the use of scale in analysis and representation.

Following the above, there is a long-standing need to examine how local adaptations are framed within broader scale processes (Wilbanks & Kates, 1999; Ford, McDowell, & Jones, 2014), including examination of the feedbacks between climate and non-climate stressors on social-ecological systems (McGovern, et al., 2007). Critically, studies on cultural aspects of adaptation are not as common as studies on aspects of risk and livelihoods (i.e., social and material well-being, respectively) (Ford & King, 2015). This oversight ignores how culture shapes how risk is interpreted and acted upon (Adger, Barnett, Brown, Marshall, & O'Brien, 2013; Beck, World at Risk, 2009). Indeed, the process of anticipatory adaptation remains a nascent area of research (Berrang-Ford, Ford, & Paterson, 2011; Tryhorn & DeGaetano, 2011), as evidenced by the relatively few guides and methods that exist for developing or reviewing adaptation plans (Schröter, Polsky, & Patt, 2005; Preston, Westaway, & Yuen, 2011).

Concurrently, there is little knowledge on institutional and governing factors that enable adaptation, including adaptation readiness and capacities to promote and develop adaptation strategies (Ford, Labbé, Flynn, & Araos, 2017). This is representative of broader research deficits on adaptation policy in the Arctic (ACIA, 2005), where there is little evidence of transboundary or cross-sectoral adaptation (Ford, McDowell, & Jones, 2014). This dissertation research helped fill these gaps by using a social-ecological perspective to examine what system variables enhance household adaptation outcomes. These results may inform future adaptation practices.

Such progress toward adaptations informed by cultural and place-based knowledge can be aided by engaging with communities and their knowledge (Tyler, et al., 2007). Beyond ensuring climate adaptations are congruent with local capacities, institutions, and values (Ford, McDowell, & Pearce, 2015), there are ethical responsibilities for engaging with communities that are the focus of research efforts (i.e., viewing communities as partners[12] , not subjects) (Giles & Castleden, 2008). There are also deep-seated differences between characteristics of Western and Indigenous epistemologies and ontologies[13]. In practice, this means culture is often overlooked in scientific research on adaptation (Labbé, Ford, Araos, & Flynn, 2017), which can lead to research fatigue and degradation of trust in community-researcher relations (Eriksen, Rautio, Johnson, Koepke, & Rink, 2021; Ford J. D., et al., 2012; Gearheard & Shirley, 2007).

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[12] Community engagement can be facilitated by involving community members in the research design and by providing local employment opportunities, for example (Pearce T. D., 2009), as I do in this dissertation research (see Chapter 3).

[13] Many Indigenous cosmologies view humans within a sentient ecology (Anderson, 2000; Natcher, et al., 2007) (e.g., 'human-in-nature' geographic traditions), whereas Western cosmologies view humans as outside of or separate from nature (Cronon, 1996; Nash, 1982).

This dissertation research engaged with communities and their knowledges by involving stakeholders in the research design and data collection, as described in Chapter 3, to avoid these pitfalls in community engagement practice.

Indigenous peoples, such as the Inuit and Saami, have inhabited the Arctic for thousands of years and have persisted through diverse social-ecological stressors (McCannon, 2013). For example, Arctic peoples have long contended with colonialism, calling for researchers to actively embrace and support Arctic decolonization through scholarship (Cameron E. S., 2012). There is a trend within Arctic literature to label local and Indigenous communities as having subsistence economies despite Arctic communities having long been integrated with and exposed to international market economies (Keskitalo & Kuulyasova, 2009; Cameron E. S., 2012), such as through reindeer husbandry (Keskitalo, 2004). Further, research needs to recognize the internal colonization within (developed) Arctic countries that comes from the unequal distribution of climate change burdens and benefits (Trainor, Chapin, Huntington, Natcher, & Kofinas, 2007).

There is also a great need expressed by the case studies included in this systematic review for the collaboration of climate and social scientists to address the issues of climate change from an integrated multidisciplinary approach (Prno, et al., 2011; Skrylnikova, Lozhnikova, Muravyov, Kirpotin, & Ozheredov, 2014). Indeed, the relationships between place-based knowledge and adaptation remain ill-defined in the climate change adaptation literature (Pearce T. , Ford, Willox, & Smit, 2015), and few studies connect or apply to the experience of local communities and their capacities (Huntington, Quakenbush, & Nelson, 2017). These incongruencies call for continued movement toward studying climate in connection with other social, cultural, and political conditions of communities (Nuttall, 2017; Ford, Smit, & Wandel, 2006). The social-ecological systems approach presents itself as a productive way forward, but researchers must consider the role of power and politics in place (Pelling M. , 2011; Thompson, 2006) and within dynamic historical contexts (Bennett, Blythe, Tyler, & Ban, 2016), which this dissertation research sought to do.

In many Arctic cultures, adaptation exists throughout local social-ecological contexts, rather than as a distinct body of knowledge (Krupnik & Jolly, 2002), and the scientific community may find informative and fruitful research directions under the guidance of such place-based knowledge (Ignatowski & Rosales, 2013; Bravo, 2009). For example, many public health adaptations require little innovation, relying primarily on the involvement of diverse stakeholders and improvements to the management efforts of healthcare authorities and systems (Gosselin, Bélanger, Lapaige, & Labbé, 2011). Despite scholarly attention on public health interventions (Bjerregaard, 2004), little is known about climate change impacts on the health of Arctic peoples (Ford J. D., et al., 2012) nor about community perspectives on these health effects (Healey, et al., 2011). Further, adaptation studies that consider the health impacts of climate change in the Arctic can fail to consider the nutritional implications of environmental change (Wesche & Chan, 2010). This dissertation research helped to fill these literature gaps by viewing adaptation from an integrated social-ecological perspective that solicits guidance from place-based knowledges.

In sum, this dissertation research helped to fill some of the aforementioned gaps in climate change adaptation research. First, the primary focus of this research is the need to better understand the local perceptions and mechanisms that enable people and communities to adapt to the impacts of climate change (**Research Question 1**). Second, this research addressed the relationships between place-based knowledge and adaptation by connecting to the experience of local communities and their capacities and by viewing climate in connection with the dynamic social-ecological conditions of communities and their histories (**Research Question 1**). Third, particular attention was paid to the cultural aspects of adaptation that shape how risk is interpreted and acted upon (**Research Question 2**). Finally, this systematic literature review accounted for cross-scalar social-ecological processes by examining commonalities within and between cases of adaptation to contribute to generalizable knowledges for guiding sustainable place-based adaptation practices (**Research Question 3**).

Conclusion

There is a globally recognized need to develop methods to identify pathways for climate change adaptation (UNFCCC, 1992). Climate change impacts have already altered Arctic ice, ecosystems, weather patterns, and hydro-geological risks, as revealed by a systematic review of the literature. Thus, there is a need to identify what social-ecological processes are most supportive to households' ability to implement adaptive action(s) within the context of rapid environmental change and what variables can reliably measure those processes (**Research**

Question 1). The social-ecological systems approach provided a sound theoretical basis for examining the mechanisms that may support adaptation, such as sense of place and ecosystem services (**Research Question 2**). In particular, the SESF presented a promising framework methodology for creating a social-ecological model to examine system dynamics (**Research Question 3**).

In Chapter 3, the theory and concepts presented and justified in this methodological Chapter are translated into methods. In Chapter 4, the results from the application of these methods are presented to test the research hypothesis. Namely, that when facing rapid environmental changes, the ability of households to implement adaptive action is regulated by place-based experiences within a framework of social-ecological relationships, such as the availability of ecosystem services and individuals' sense of place, and that the distribution of these place-based experiences will be uneven across space, producing clusters of social-ecological characteristics, each resulting in tendencies to particular outcomes of adaptation processes. Finally, Chapter 5 summarizes this dissertation research, including a discussion of study limitations and future research plans.

Chapter 3

Modeling Methods and Data Analysis Plan

Improved understanding of the extent and severity of the impacts of climate change (Stocks, et al., 1998) has spurred research on social and ecological adaptation practices (Chatzidaki & Ventura, 2010; Sheremata, Tsuji, & Gough, 2016). That research demonstrated a need to develop spatial methods to aid in identifying adaptation interventions that are community-backed and ecologically sound. This chapter describes the methodological approaches I developed to enable my proposed spatial social-ecological analysis of adaptation to climate change. I draw from studies that apply the SESF to analyze social-ecological system processes and outcomes. The social-ecological approach is situated within the disciplines of geography and ecology as outlined in Chapter 2.

In this Chapter, I develop methods and describe data collection procedures that enabled testing and analysis of the theoretical concepts within Chapter 2, in which I proposed a framework that integrates biophysical features with social-ecological systems modeling. Thus, in this Chapter, I describe how to implement the framework with empirical measures. I used data generated from an online survey and online participatory mapping exercises with households in North Central Iceland. Together, these methods and data enabled the testing and evaluation of the extent that social-ecological processes were associated with successful household adaptation behavior (**Research Question 1**), viewed here as the adoption of greater numbers of household adaptations. Examples of associated social-ecological processes include the valuation of ecosystem services and the role of sense of place (**Research Question 2**). Finally, I end this Chapter by briefly describing the statistical and spatial data analysis plan, which emphasized using a Geographic Information System (GIS) (**Research Questions 3**). The results from the application methods and data discussed in this Chapter will be presented in the following Chapters.

Mixed-Methods Data Collection

In this Section, I describe my use of a mixed-methods approach to data collection, analysis, and visualization. A mixed-methods approach integrates qualitative and quantitative research designs when research questions cannot be answered from either of the 2 approaches on their own (Creswell & Clark, 2017). Specifically, I used an online data collection format (Qualtrics, 2020) with a survey and participatory mapping exercises as supported by local mail and web-based recruitment efforts. In Chapter 4, I present the results of my use of descriptive, exploratory, and spatial statistics to analyze the data collected, as outlined in this Chapter.

This research included research approval from the Institutional Review Board (IRB) at Penn State University. Approval was given in December of 2020 (STUDY00015730), and data collection occurred from March through May of 2021. Ballot-stuffing was prevented by restricting the survey access to once per IP address. The collected data were anonymized to protect participants' privacy, including the removal of IP addresses from the dataset (Nayak & Narayan, 2019). I included an informed consent form under the General Data Protection Regulation (GDPR) because I stored identifiers from participants in a European Economic Area (EEA). While the data collected were anonymous, self-disclosed identifiers were stored for compensation via a random lottery drawing of $25 Visa gift cards and participants who indicated an interest in contributing to follow-up research.

Online Survey

The lack of adequate secondary data sources for addressing my research questions required a survey to generate the necessary data. I used an online survey questionnaire hosted through Qualtrics to conduct data collection. I chose an online survey delivery format because it was more effective than in-person researcher-led survey delivery formats at minimizing researcher influence on survey response (National Research Council, 2013; Brown G. , 2017) and because I sought to reach many households at a time when travel bans were in place due to the COVID-19 pandemic. The survey was available in English and Icelandic and solicited numerical, categorical, text, and spatial information using multiple-choice, multi-select, Likert, and matrix question formats. Some questions encouraged participants to elaborate on their responses via open-ended text entries. Due to travel bans put in place in 2020, 2 planned field seasons of data collection were canceled, so I sought the assistance of an on-site research assistant to coordinate local outreach.

Local outreach methods were deployed to encourage awareness of the research and solicit participation with a two-part approach using invitational survey mailers and strategic media outreach. I sent invitational survey mailers to every household in the Eyjafjörður area, that is, approximately 10,121 households across 7 municipalities, encompassing 4,300 square kilometers or approximately 1,650 square miles. The color A5 postal mailer had 2 sides; one side was in English and the other Icelandic (see Figure 3 at the end of this Chapter). The mailers featured a map of the local study area and offered a brief description of the research aim with a QR code linking the survey. I also included a link to my website, where participants could open the survey and learn more about my background, qualifications, and research motivations. Supplemental media outreach consisted of communications through social media (i.e., Facebook posts and messages) and informal academic networks (i.e., emails with social networks at the University of Akureyri and the University of the Westfjords). Collectively, I sought to encourage a broad-reaching and lasting conversation around this dissertation research through my outreach efforts. I also included my contact information in the survey and in all modes of outreach to promote transparency and open communication.

Before data collection began, I tested and improved survey questions based on the feedback of colleagues. I also improved and finalized survey questions in consult with a small team of Icelanders, which occurred over regular meetings throughout the research process beginning in August 2020. This collaboration provided me with valuable friendships, on-site research efforts, and effective and appropriate linguistic and cultural translations, including the detailed re-working of survey questions and local outreach methods.

Participatory Mapping for Local Knowledge Production of Social-Ecological Systems

Methods of participatory mapping emphasize processes that build and generate social capital and empowerment (Dunn, 2007). Similar approaches exist. For example, public participation GIS (PPGIS) focuses on supporting public engagement in the production of knowledge (Sieber, 2006), and volunteered geographic information (VGI) focuses on the tools used to collect and disseminate geographic information (Goodchild, 2007). Participatory mapping methods, including PPGIS and VGI, are helpful because they can make visible that otherwise unseen (by the researcher) (Baker, Cullen, Debevec, & Abebe, 2015). Importantly for this research, participatory mapping placed value on the situated knowledges of actors embedded within the local social-ecological system (Robinson, Maclean, Hill, Bock, & Rist, 2016), which enhanced the scientific understanding of the system to produce a more holistic representation of the study area. Nearly every social-ecological variable has explicit space-time attributes, but they are difficult to measure and visualize due to their dynamism in relation to societal perceptions of space (Cronon, 1996).

For this research, mapping exercises used a standardized set of base maps created in ArcGIS Pro to highlight the biophysical and political features of the study area (see Figure 4 at the end of this Chapter). These mapped featured included municipal boundaries, wetlands, urban areas, and hydrology networks, as presented in the following sections of this Chapter. To identify sites during the participatory mapping exercise, participants placed points on a map. Points could overlap, but no more than 2 points could be placed. Each additional point placed erased the first point. The latitude and longitude of each point were recorded. However, the post-processed results of these points were displayed as buffered polygon features. I did this to minimize the effects of the spatial discounting present in participatory mapping practices that can skew the spatial distribution of mapped attributes (Pocewicz & Nielsen-Pincus, 2013) and maintain participant anonymity.

Creating a Social-Ecological Framework for Analyzing Climate Change Adaptation

This research used a social-ecological systems approach based on the SESF (Ostrom E. , 2009) to construct a nested framework of components, offering a hierarchal structure from which to analyze social-ecological processes over space and in relation to adaptation outcomes. The 4 top tiers of the SESF are the resource system (RS), resource units (RU), actors (A), and governance system (GS). I represented 2 of these 4 tiers of the SESF as biophysical features (RS) and individuals and households (A). Like the SESF, my framework's components are connected by social-ecological processes representing human-environment relationships (I). In this Section, I describe and justify the variables I use in my framework. As noted above, the social-ecological framework used in this research consists of the following major components: 1) adaptation outcomes (O); 2) biophysical features (RS); 3) system actors (A); and 4) human-environment relationships (I) (see Figure 5 at the end of this Chapter). These framework components and their measures are discussed in turn.

Household Adaptation Outcomes

The first step in constructing this dissertation's framework was to develop a set of adaptation actions that yielded successful adaptation outcomes. Adaptation actions sought to reduce social-ecological risks (IPCC, 2012) and resulted from actions that sought to ensure household health and safety in the context of hazardous environmental changes or conditions. This research focused on 7 common categories of behavioral household adaptation actions, in line with best practices for understanding household adaptation (Pelling M. , 2011; Smit B. , Burton, Klein, & Wandel, 2000), and particularly those in the Arctic (Ford, McDowell, & Jones, 2014). As argued in Chapter 2, behavioral changes are the most common adaptation implemented at the household level and can inform broader adaptation goals and policy. Indeed, analyzing the characteristics of adaptation within and between households can inform soft and hard policy approaches beyond the boundaries of the social-ecological system (UNFCCC, 2011).

Based on the literature, I selected 7 categories of adaptation actions, which were described in Chapter 2, as follows:

1. Structural safety improvements,
2. Emergency preparation,
3. Financial safety improvements,
4. Livelihood changes,
5. Practicing energy efficiency,
6. Changing consumer practices, and
7. Educational opportunities.

To gauge the implementation of household adaptation actions in the study area, survey participants indicated whether they implemented each of the 7 types of adaptations described above. By collecting this information, statistical analysis revealed how system variables related to adaptation outcomes, particularly for those households that implemented greater numbers of adaptation actions. Participants were encouraged to elaborate on the adaptation action(s) that their household implemented via text entry, which provided local qualitative context for the quantitative results.

Biophysical Features

The biophysical features of place create the foundational components of an ecological system, calling for their continued integration in social-ecological systems models such as the SESF (Agrawal, 2003; McGinnis & Ostrom, 2014). Indeed, the size and distribution of the biophysical features of a system can determine the abundance, range, and health of wildlife species (Legagneux, et al., 2014). Moreover, the size and distribution of biophysical features can also structure the human-environment dynamics of their use, as seen in the variation of fishers' recreational activity by lake size (Kaemingk, Chizinski, Allen, & Pope, 2019).

Many social-ecological analyses that use the SESF tend to underrepresent the importance of biophysical features of the system, despite 2 of the framework's 4 top-tier categories focusing on these system resources (Epstein, Vogt, Mincey, Cox, & Fischer, 2013). I sought to fill this gap by integrating biophysical features in social-ecological system modeling. Guided by best practices (Partelow, 2018), I represented the resource system using biophysical features as measured by the composition of the landscape (RS) in the context of local climate characteristics (ECO). In the next Section, I describe these biophysical system components and their measures.

The representative landscape of the social-ecological system was a composite of land use and land type classifications informed by best practices in GIS modeling (Simensen, Halvorsen, & Erikstad, 2018) and by the qualitative results of the systematic literature review presented in Chapter 2. Together, these characterized the biophysical features that were important for the functioning and management of the ecosystem. From this foundation, 5 primary landscape classifications were created—urban areas, wetlands, grasslands, water features, and glaciers—using data from the National Land Survey of Iceland. These data were displayed as a polygon layer using data from the CORINE Land Cover (CLC) inventory, produced using satellite data from Sentinel-2 and Landsat-8.

I follow the CLC nomenclature to define these 5 landscape classifications (Kosztra, Büttner, Hazeu, & Arnold, 2019). Namely, urban areas refer to geographic areas such as town centers, residential building developments, and road network infrastructure. To be considered urban, these features must dominate 80 percent or more of the land surface area. Wetlands refer to inland and coastal wetlands, such as intertidal zones, salt meadows and marshes, bogs, and riparian vegetation. Water features refer to areas of lakes, lagoons, rivers, and streams. Finally, glaciers refer to areas of permanent ice and snow that retain snowpack throughout the year. Alongside municipal boundaries, road networks, and place names, the resulting map of landscape classifications was used for this dissertation's participatory mapping exercises (see Figure 4 at the end of this Chapter).

Climate Characteristics

A climate characteristic refers to a state of atmospheric or weather conditions, whereas climate change refers to long-term trends in the climate, typically over thirty or more years, in the observable features of local climate systems. This research focused on 3 such climate characteristics in line with best practices for monitoring the climate, whose features contribute to local weather patterns. These values were needed because climate systems can define the boundaries of ecosystems (Drinkwater, et al., 2010; Smol, et al., 2005), and global changes in climate dynamics are impacting ecosystems (MEA, 2005). Based on the literature, I selected the following climate characteristics: temperature, wind speed, and cloud cover.

Temperature refers to the surface air temperature of an area. Wind speed refers to the average speed of the wind at the time of the observation. Cloud cover refers to the amount of cloudiness an area receives. These climate characteristics were chosen because they contribute to prevailing weather patterns, local data were readily available, and initial field site visits in 2019 pointed to their local importance. Other climate characteristics such as air pressure and humidity also contribute to weather patterns (Barry & Chorley, 2009), but these data were not consistent across the study region nor discussed locally in the area when compared to the chosen climate characteristics.

The proposed climate characteristics of the social-ecological system were documented based on data from 3 of the Icelandic Meteorological Office's (IMO) *in situ* human-crewed and asynchronous synoptic weather stations in Akureyri, Grímsey, and Ólafsfjörður, of North Central Iceland (IMO, 2020). Aside from these measurements, local historical climate observations are sparse (Jónsson & Garđarsson, 2001). *In situ* temperature measurements are disseminated by the

IMO as average monthly and annual observations. The observational record for Akureyri dates back the farthest to 1950, potentially providing a longitudinal baseline to qualitatively analyze the change in the context of local climate characteristics over time. Minimal statistical processing was required to define baseline annual climate characteristics using these data. I calculated the annual climate characteristics of these weather observations by averaging monthly values of each year. Together, these baseline measurements of climate characteristics provided the context for understanding the early indicators of Arctic environmental change.

Early indicators of Arctic environmental changes

The results of the systematic literature review presented in Chapter 2 suggested that I include a third dimension of biophysical features—early indicators of Arctic environmental change—based on their importance in translating climate change impacts to contexts of local social-ecological changes. These indicators are based on Arctic case study evidence and reveal that adaptation is tied to different—sometimes multiple—environmental triggers or early impacts of climate change. I defined the 4 early indicators of Arctic environmental change as follows: degradation of Arctic ice, changes in ecosystems, weather patterns, and changes in hydro-geological risk.

As elaborated in Chapter 2, degradation of Arctic ice is the loss or degradation of sea- and land-based ice (IPCC, 2014). Changes in ecosystems include new or more plentiful plant, insect, and other marine and terrestrial species (Burgiel & Muir, 2010), and an overall decline in the range, abundance, or health of native wildlife (Larsen, et al., 2014; Myers-Smith, et al., 2011). Changes in weather patterns include warmer land and sea temperatures and more frequent or intense storm events (Jefferies, Overland, & Perovich, 2013). Changes in hydro-geological risk refer to climate change impacts that result in permafrost degradation and erosion, more frequent or intense avalanche events, mud, debris, or rockslide events, and flooding events (Manrique, Corral, & Pereira, 2018; Hovelsrud, Karlsson, & Olsen, 2018).

To measure the relevancy of each Arctic indicator of change to the local social-ecological system, participants indicated statements that were relevant to their personal experience *in situ* and then again in a second prompt in relation to their historical knowledge of the area. I identified the temporal dimensions of adaptation practices by distinguishing between experience and historical knowledge, which may aid in differentiating between responsive and anticipatory adaptation. I used 8 statements to represent the 4 early indicators of Arctic environmental change presented in Chapter 2. Participants identified the statements they agreed with. Participants also had the option to note if none of the indicators (i.e., statements) applied to the study area, and they could include additional indicators by marking 'other' and elaborating via text entry. I included this additional opportunity for indicators because system actors and their situated knowledges were necessary for holistic representations of the study area, the impacts of climate change on the households within it, and actors' solutions.

Temporally, climate change adaptation strategies were either enacted proactively in anticipation of change (e.g., by planned adaptation) or reactively in response to current or past changes (e.g., by autonomous adaptation) (IPCC, 2012). The timing of adaptation action in relation to environmental change is important because it implies an underlying behavioral process in relation to system triggers (Clayton, et al., 2015). Understanding when adaptation is enacted in relation to a system trigger may point to commonalities in the perceived 'temporal suitability' of adaptation actions, which may, in turn, reveal avenues for supporting existing adaptation pathways (Sadiq, Tharp, Graham, & Tyler, 2019). Thus, it was fruitful to determine if adaptations were implemented by households proactively or reactively. In Chapter 4, I present the results of the analysis of the types of early change indicators experienced historically and at present in relation to households with greater numbers of implemented adaptation outcomes.

System Actors

The system actors—those who were eligible for survey participation—resided within the boundaries of the social-ecological system (i.e., study area) for some part of the year and were over 18 years old. While I accounted for youth in household counts and local demographic statistics, they were excluded from primary survey participation, a potential limitation reflected in the broader under-representation of youth in climate change adaptation studies and is worthy of future research (Herman-Mercer, et al., 2016). In what follows in this Section, I describe the components of this research framework that represent system actors, namely, demographic and household characteristics; lived experience and historical knowledge of the social-ecological system; and concern for risk from local to global levels.

Demographic and household characteristics

Consistent with variables from best practices in social-ecological modeling (Partelow, 2018), I included social and demographic information about participants and their households. Participants identified their gender and age from pre-defined categories. Participants also identified basic household information by indicating their response from pre-defined categories of the highest education completed, the average monthly income on a typical year, and the type of household occupancy (i.e., rent or own). In Chapter 4, I present the results from the analysis of survey responses.

Concern for current and future risk across scales

I engaged with the cross-scalar nature of participants' concern for hazard risk, building on the psychometric paradigm (Renn, 2008), from 2 temporal dimensions—the present and the future. Here, concern is an emotion representative of solastalgia, or existential distress caused by environmental change, and may provide a proxy measure for general levels of distress in response to environmental loss (Phillips & Murphy, 2021). Critically, risks are increasing due to climate change, and are increasingly deterritorialized as they move from the local to the global scale, which may create a bifurcation in concern across scale (Beck, 2002; Wachinger, Renn, Begg, & Kuhlicke, 2013; Van der Linden, 2014). I used 2 temporal measures to understand the concern for risk. First, participants identified their level of concern on a Likert scale from no concern to extreme concern for current and future risks. Participants did this at 5 scales—the household, the municipality, the study area, the nation, and the world—to situate their risk concerns along a spectrum from local to global.

I used the above measures of concern for risk to represent a dynamic space-time snapshot of risk perception that builds on calls for research to account for the role of emotion and public perceptions of climate change (Van der Linden, 2014; Marx, et al., 2007). Indeed, an individual's level of concern or distress for impacts of environmental change and hazard risks can influence their behavior (Kates R. W., 1978), further justifying the need to understand the role of risk perception in climate change research (Van der Linden, 2015). In addition, addressing the temporal nature of participants' concern for risk also expands the potential for analysis on the temporal nature of adaptation behavior (Sadiq, Tharp, Graham, & Tyler, 2019).

Social-Ecological Processes

To answer the research questions elucidated in Chapter 1, I measured social-ecological processes of sense of place and the valuation of ecosystem services to test for associations with households' total amount of adaptation actions implemented. Indeed, sense of place can account for variations in the environmental risk perceptions that help govern adaptation practices (Quinn, Bousquet, & Guerbois, 2019; Adger, Brown, Cervigni, & Moran, 1995), and ecosystem services can account for social-ecological system interactions (Daily, 1997) by identifying flows from ecological to social values and from social to ecological values (Munange, Thiaw, Alverson, Mumba, & Liu, 2013). As such, adaptation actions need to be considered in relation to social-ecological processes, that is, from the social context in which ecological change takes place (Moser S. C., 2013). I describe the components and measures of sense of place and the valuation of ecosystem services for the remainder of this Section.

Sense of place

Following best practices (Jorgensen & Stedman, 2001; Hay, 1998) described in Chapter 2, I engaged with sense of place (Tuan, 1977) from 3 aspects—place attachment, place dependence, and place identity (Fresque-Baxter & Armitage, 2012). These 3 aspects of sense of place are positioned within attitude theory (Ajzen & Fishbein, 1975; Greenwald, 1968) by cognitive, behavioral, and affective functioning processes, respectively. Here, affect is interpreted as a reactive feeling that indicates positive or negative stimulus (i.e., perceived benefits and risks) (Slovic & Peters, 2006; Tuan, 1990). Following this logic, I used 2 measures for each of the 3 aspects of sense of place; participants rate their level of agreement with a set of 6 statements on a Likert scale from strong disagreement to strong agreement. Participants did this at 2 scales—their immediate lived-in surroundings and the study area. I assigned the 3 aspects of sense of place for each scale the average score of its 2 component measures. Using the average of 2 measures for each aspect of sense of place, I aimed to reduce question bias present in single-measure analyses.

Sense of place is increasingly important in analyses of climate change risk at the individual level related to place disruption (Clarke, Murphy, & Lorenzoni, 2018; Jorgensen & Stedman, 2006). For example, the perceived (future) or actual loss of species, ecosystems, and landscapes can be highly disruptive to sense of place. This can sometimes degrade sense of place in response to the emotional pain of ecological loss (e.g., ‘reef grief’) or in response to the loss of cultural place values (Marshall, et al., 2019). As such, sense of place is increasingly important in social-ecological systems theory and application to understand the motivations (i.e., values and behaviors) needed to solve sustainability issues (Masterson V. A., et al., 2017; Dawson, Maher, & Slocombe, 2007; Masterson V. A., et al., 2017).

Since place attachment is shown to vary by length of residence and homeownership (Lewicka, 2011), I engaged place attachment beyond the measures of sense of place outlined in the paragraph above by asking participants to identify how much time they spend in the study area on an annual basis and how many years they have resided in place. Participants also indicated if their household owns or rents their residence. In Chapter 4, I present the results of the analysis of these aspects of sense of place and the potential moderators of place attachment in relation to households that implemented greater numbers of adaptation actions.

Valuation of ecosystem services

Ecosystem services are the benefits people freely obtain from the environment they live in, such as clean air and water, habitat for wildlife species, and areas for outdoor recreation (MEA, 2005; CBD, 2009). For this research, I engaged participants in evaluating the study area’s ecosystem services (Busch, La Notte, Laporte, & Erhard, 2012). First, participants rated their level of agreement with a set of statements using a Likert scale from strongly disagree to strongly agree. I used 6 statements to represent the categories of ecosystem services. Supporting services were identified using biophysical surface features of the landscape in a GIS; thus, measures for supporting ecosystem service were excluded from the survey. In total, 2 statements reflected cultural ecosystem services, provisioning ecosystem services, and regulating services, respectively. If participants strongly agreed with a statement, they were encouraged to elaborate on their choice via text entry. I assigned the 3 categories of ecosystem services the average score of their 2 component measures. As above, I aimed to reduce question bias by using the average of 2 measures for each ecosystem service.

To further engage participants with the concept of ecosystem services, I used a spatially explicit approach to engage with ecosystem values and risk perception by including 2 participatory mapping exercises in the survey (Klain & Chan, 2012; Spyra, et al., 2019). There are relatively few ecosystem services assessments that include participatory spatial approaches, further justifying their use in this research to fill this need (Cadag & Gaillard, 2012). The first mapping exercise presented participants with a map of the study area and prompted them to identify 2 places that would benefit from natural conservation or preservation activities, such as sites of historical or cultural significance or areas with important habitats for non-human species. In doing so, participants contributed to the creation of a map that identified areas where ecological value was perceived to be the highest. Participants were encouraged to describe the places they identified via text entry, which assisted in accurate analysis of the produced maps, as presented in Chapter 4.

A second mapping exercise then presented participants with the same base map of the study area. This time, participants identified 2 places that were prone to hazard events or hazardous conditions, such as frequently flooded roads or sites prone to avalanches or point-source pollution. Again, participants were encouraged to describe the places they identified via text entry. Collectively, participants contributed to the creation of a map that identified areas of social-ecological value where the need for risk reduction activities in response to hazard risk were perceived to be the highest.

Model Use and Validation

This research used the SESF and literature review to guide the construction of components of a social-ecological system model that incorporates biophysical features, as described above. The SESF approach has been proven effective in the literature for assessing complex human-environment interactions, including those that rely on mixed methods data guided by *in situ* observational and survey data (Asah, 2008; Masterson, Enqvist, Stedman, & Tengö, 2019). Thus, I can infer the validity of my application of a social-ecological framework (Tasantab, Gajendran, Von Meding, & Maund, 2020).

Many studies that applied the SESF focused on the governance of institutions and the collective management of common-pool resources (Partelow, 2018; Herrero-Jáuregui, et al., 2018). My application of the SESF broadly aligned with these prior studies by focusing on adaptation strategies that benefit both people and the environment. Here, however, I improved on the use of social-ecological modeling approaches by developing a spatial mixed-methods approach to social-ecological modeling. I based my methods of data collection and methodology of analysis on appropriate theory (de Vos, Biggs, & Preiser, 2019) and on the ethics of representation (Bassett & O'Riordan, 2002), rigor, and replicability (Thiel, Adamseged, & Baake, 2015).

One common critique of using the SESF approach is that local knowledge often is not included in the decision-making processes that determine the research questions and suggest what system variables to include in the analysis (Partelow, 2018). Geographic research also reminds us that spatial mismatch occurs when inconsistencies exist between the data resolution and the scale at which generalized claims are aggregated and derived (Folke, L, Berkes, Colding, & Svedin, 2007). The mixed-method approach outlined in this Chapter allowed for information collected at the household level to represent the social-ecological system. Further, I included local knowledge to the extent possible in all aspects of the research process, given temporal and mobile constraints, to avoid this common pitfall.

A second common critique of using the SESF approach is that it is challenging to avoid panaceas for solving social-ecological issues. It is also difficult to avoid overly context-specific situations in representing study results and their implications (Ostrom E. , 2007). Despite this, the strength of the SESF is in its design for detail in the specification of social-ecological variables, whose interactions may influence system outcomes (Partelow, 2018). This framework of system components offers a nested structure from which to analyze coupled social-ecological system characteristics (Eisenack, Lüdeke, & Kropp, 2006). This is important because coupled characteristics may identify pathways for promoting and implementing adaptation to climate change in social-ecological systems.

In addition to the steps noted above and throughout this Chapter, I evaluated my use of the SESF by continually assessing the appropriateness and validity of paired theories and methods (i.e., ontological consistency) (Thiel, Adamseged, & Baake, 2015). For example, I explicitly acknowledged and justified the inclusion of each system variable, particularly those that diverged from traditional categories of SESF variables, to maintain external validity. I also explicitly defined the meanings and measures of these variables and how they were representative of the concepts underpinning social-ecological systems.

Data Analysis Plan

In the following Chapter (4), I present and discuss the results of the empirical framework put forth above, including the results of spatial and statistical analyses in R (R Core Team, 2020), to accept or reject my hypothesis and answer the research questions proposed in Chapter 1, which are revisited below.

> *RQ1: What social-ecological processes are most supportive to households' ability to implement adaptive action(s) within the context of rapid environmental change, and what variables can reliably measure those processes? How do these processes and their variables vary across the local social-ecological system?*

To answer **Research Question 1**, I first analyzed local climate characteristics using descriptive statistics and Welch's *t*-test to identify a change in variables over time. I then analyzed the survey sample dataset. Namely, I determined the confidence level of the sample using Slovin's formula, the dataset's variable normality using the Shapiro-Wilk test (Razali & Wah, 2011), and the dataset's variance using Spearman's test. I then described the adaptation outcomes of participants using descriptive statistics. Finally, I tested for associations between households with more implemented adaptation actions and social-ecological variables using ridge regression. Together, these tests enabled me to model the dependent variable (i.e., household adaptation outcome) in relation to the set of exploratory independent variables (i.e., social-ecological processes) to test if any of the variables lead to significant differences in the number of adaptation actions that a household implemented.

> *RQ2: To what extent do the valuation of ecosystem services and sense of place play a role in supporting adaptive behavior? Are there associations between these variables?*

To answer **Research Question 2**, I conducted an exploratory analysis of the associations within and between social-ecological processes of sense of place and ecosystem services using a series of linear regression models. I first tested for associations between participants' adaptation level and their sense of place and valuation of ecosystem services. I then tested for associations between the valuation of ecosystem services and sense of place.

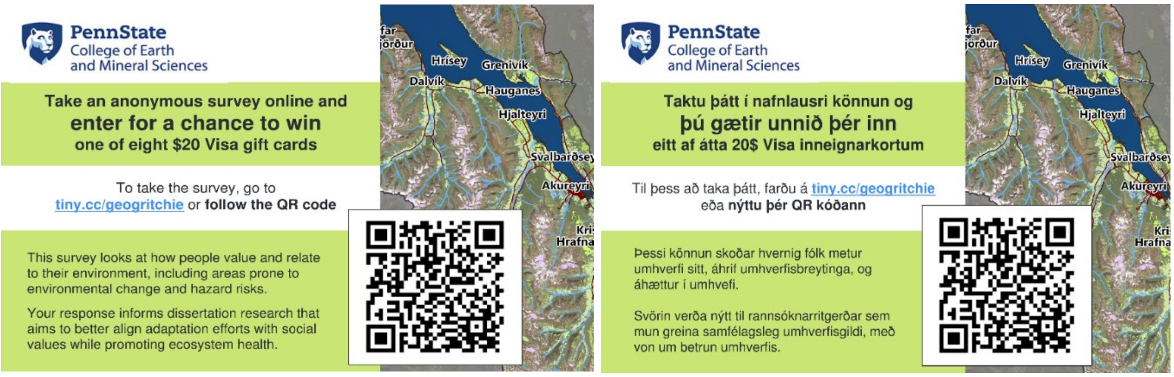
RQ3: *How can human-environment relationships within a social-ecological system be modeled spatially, using adaptation to climate change as an example? What might we learn about adaptation from such modeling?*

To answer **Research Question 3**, I used a spatial approach to visualize human-environment relationships in the social-ecological system. As described above, participatory mapping exercises engaged with participants' social-ecological system interactions and local knowledge. Ultimately, the maps focused on identifying participants' evaluation of areas most in need of risk reduction efforts to sustain valued ecosystem services.

Participants placed a total of 4 points or 2 points per map. To visualize the collective results of participants' input, I used an optimized hot spot analysis within a GIS. This executes the Getis-Ord Gi tool and automatically adjusts for multiple testing and spatial dependence using the False Discovery Rate correction method. The execution of this tool yields area hot spots based on the input data. The results of these hot spot analyses were then interpreted with the aid of narrative information provided in participants' survey responses.

In sum, the goal of this Chapter was to describe the methods used to answer the research questions put forth in Chapter 1. I described the data collection methods and tools, study participants, and social-ecological system variables and their measures. I then presented the data analysis plan. Collectively, this Chapter presents a social-ecological systems methodology for the development of a framework to analyze climate change adaptation using mixed methods. In the following Chapter (4), I present social-ecological variables that are facilitative of more numerous positive households adaptation outcomes, as identified by descriptive statistics, regression analysis, and hot spot analysis of the sample datasets. Chapter 4 combines the theoretical discussion of Chapter 2 with the methodological discussion of this Chapter through a presentation of the results of the framework as it was applied in North Central Iceland.

Figure 3. An image of the A5 double-sided survey mailer that was sent to households in the Eyjafjörður study area, written in English (left) and Icelandic (right).



PennState
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and Mineral Sciences

Take an anonymous survey online and
enter for a chance to win
one of eight $20 Visa gift cards

To take the survey, go to
tiny.cc/geogritchie or **follow the QR code**

This survey looks at how people value and relate to their environment, including areas prone to environmental change and hazard risks.

Your response informs dissertation research that aims to better align adaptation efforts with social values while promoting ecosystem health.

PennState
College of Earth
and Mineral Sciences

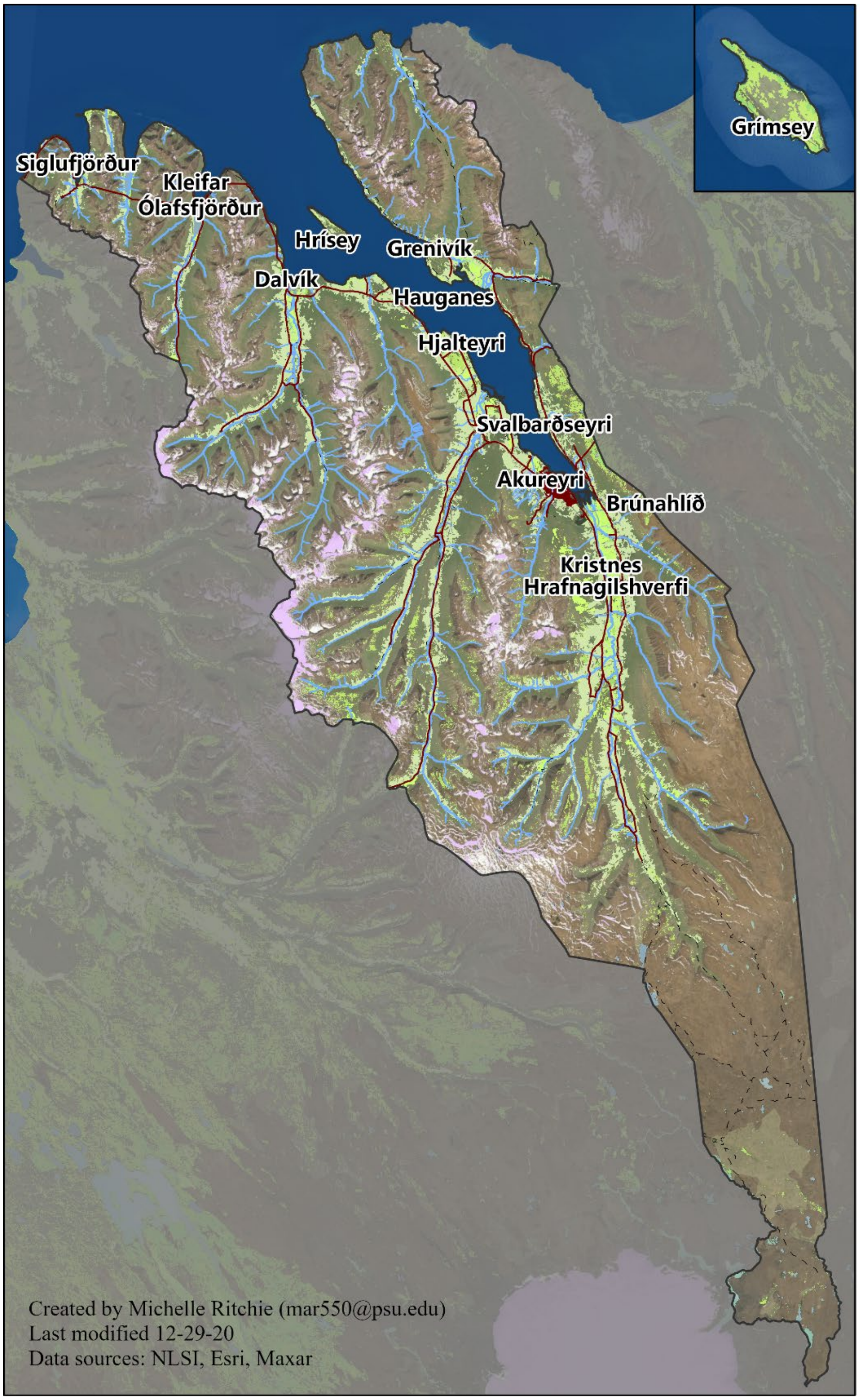
Taktu þátt í nafnlausri könnun og
þú gætir unnið þér inn
eitt af átta 20$ Visa inneignarkortum

Til þess að taka þátt, farðu á tiny.cc/geogritchie
eða **nýttu þér QR kóðann**

Þessi könnun skoðar hvernig fólk metur umhverfi sitt, áhrif umhverfisbreytinga, og áhættur í umhvefi.

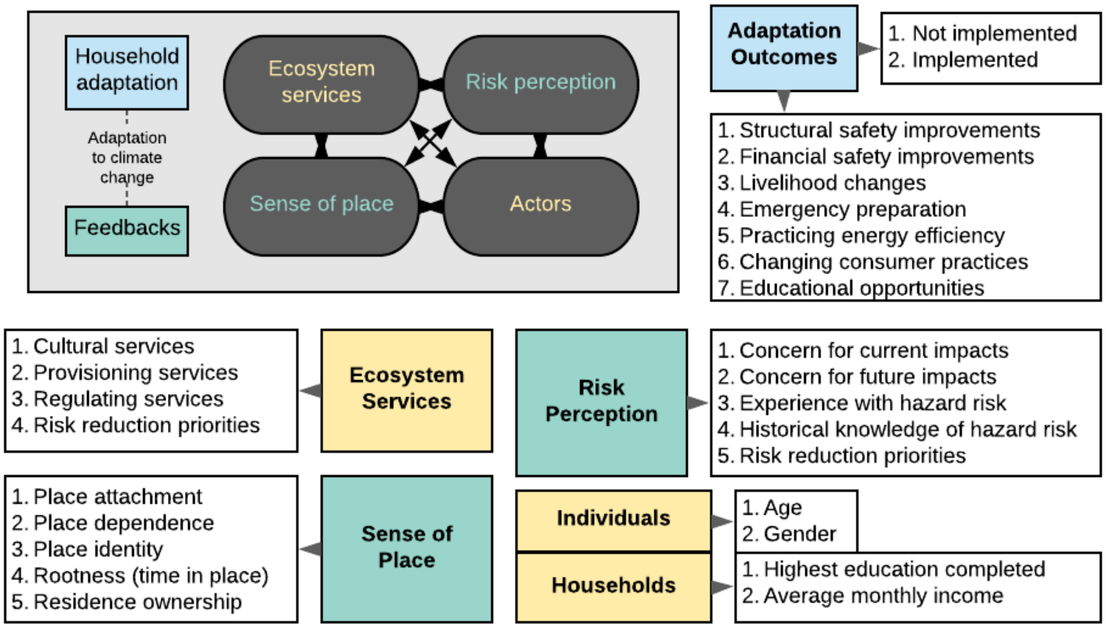
Svörin verða nýtt til rannsóknarritgerðar sem mun greina samfélagsleg umhverfisgildi, með von um betrun umhverfis.

Figure 4. A base map of the Eyjafjörður study area with biophysical features and political boundaries, used in the online participatory mapping exercises.



Created by Michelle Ritchie (mar550@psu.edu)
Last modified 12-29-20
Data sources: NLSI, Esri, Maxar

Figure 5. A conceptual diagram of the social-ecological systems model that was developed and applied in this dissertation research, which builds on the right-hand panel of Figure 2.



Chapter 4

Application of a Social-Ecological Systems Framework Approach to Advance Analysis of Climate Change Adaptation in the Arctic

Climate change impacts are not projected to diminish in intensity over the short or long term (IPCC, 2014). Environmental change is occurring rapidly in the Arctic (Larsen, et al., 2014), which has influenced hazard risk throughout the Arctic (ACIA, 2005), as outlined in Chapter 2. Amid changes in the Arctic environment, there is a pressing need to cultivate guides and methods to identify pathways for adaptation actions that are community-backed and ecologically sound (UNFCCC, 1992; IPCC, 1996; Preston, Westaway, & Yuen, 2011). To address this methodological gap and contribute to current knowledge on the factors that support adaptation at the household level, I developed a social-ecological systems framework approach (outlined in Chapter 3) and applied it in North Central Iceland.

The application of the social-ecological framework was guided by 3 research questions, put forth in Chapter 1. To answer the research questions, this Chapter (4) presents the results of the application of the framework for analysis of adaptation to climate change. The results of the framework's application are presented within the context of the research questions put forth. Each subsection to follow builds on the results presented in the previous subsections. To conclude, I present a summary of the results discussed throughout the subsections in the context of the social-ecological system framework.

Determining survey sample size confidence level and managing data quality

My initial challenge was to determine whether my survey sample size was large enough to ensure adequate statistical inference to the population. I used Slovin's formula to determine what sample sizes, n, were needed for survey participation at 98, 95, 90, and 85 percent confidence levels. Slovin's formula is as follows, where *N* is the number of households, and the confidence interval is measured at 0.02, 0.05, 0.10, and 0.15, respectively.

$$n = N/(1 + N \times confidence\ interval^2)$$

Slovin's formula is appropriate here because I sought to make inferences about a randomly sampled population with unknown distributions of behavior (Tejada & Punzalan, 2012). There are approximately 10,121 households in the study area (Statistics Iceland, 2020). As such, Slovin's formula indicates that a sample size of 2,005 households is required to reach a 98 percent confidence level. A sample size of 385 households is required to reach a 95 percent confidence level. A sample size of 99 is required to reach a 90 percent confidence level. A sample size of 44 is required to reach an 85 percent confidence level.

After data collection, incomplete and falsified survey responses were removed. In sum, there were 76 samples used[14] in this study, which translates to an 88 percent confidence level. This sample size represented approximately 3 percent of the total households within each municipality of the area, as seen in Table 1, at the end of this Chapter. While statistically significant, Slovin's formula is less effective when used below a 95 percent confidence level (Tejada & Punzalan, 2012), indicating that future applications of this dissertation's framework should include a larger sample size to produce results that more accurately reflect the population being sampled with greater confidence.

Testing for normality, variance, and correlation

To ensure the use of the correct statistical models, I first tested the normality of variable samples in the dataset. To do this, I ran a Shapiro-Wilk test on appropriate variables, such as scaled ranks (e.g., strongly agree to strongly disagree) that have some degree of granularity (i.e., more than 4 dimensions) (Razali & Wah, 2011). The Shapiro-Wilk test is necessary to ensure that assumptions of normality are met among independent and dependent variables in further statistical procedures.

The null hypothesis of the Shapiro-Wilk test states that the sample being tested is of a normal distribution. Thus, for variables with significance levels less than 0.05, I rejected the null

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[14] The initial sample size was 216 households. After removing noise from the dataset (e.g., blank responses, partial responses, and forged responses) the new sample size was 117 households. A further 37 responses that did not include demographic and household information were removed for consistency across analyses, though multiple datasets may be used in near-future studies to account for these participants.

hypothesis that the sample was of a normal distribution (see Table 2 at the end of this Chapter). The variable that exhibited the most normality was participants' adaptation level, which, as the dependent variable, meant the sample dataset might lend itself well to further statistical analyses. Ultimately, however, the results of the Shapiro-Wilk test revealed that the statistical models I chose needed to account for non-normality within the dataset's independent variables.

Following the Shapiro-Wilk test, I used Spearman's rank correlation coefficient to measure the strength of the social-ecological system variables' association with the number of adaptations a household implemented. Spearman's test allowed me to account for non-normality within the data. Unlike the Pearson's correlation that evaluates a *linear* relationship, Spearman's test measures the correlation between the ranking of 2 or more variables by evaluating any *monotonic* relationship. That is, Spearman's test measures the strength of association between 2 variables, including the direction of the relationship (i.e., positive/direct or negative/inverse association) (Zar, 1972; Spearman, 1906). Coefficients are scored from -1 to 1, with a score of -1 or 1 indicating a perfect association to understand the strength of the relationships presented in the Spearman's test,

The resulting Spearman's correlation indicated a significant positive association between participants' level of adaptation and their valuation of provisioning and regulating ecosystem services, with p-values of 0.032 and 0.011, respectively, as seen in Table 3 at the end of this Chapter. Spearman's correlation also indicated that none of the social-ecological system variables were adequate as stand-alone predictors of the number of household adaptations implemented since no other variables were considered significant.

Collectively, using the results from the Slovin's, Shapiro-Wilk, and Spearman's rank correlation coefficient tests, I determined that regression analysis was warranted to examine further the relationships between the number of household adaptations implemented and the independent social-ecological system variables. Slovin's test confirmed that, while not within the 95 percent confidence level, the sample size used in this dissertation still allows for high confidence. Thus, the data were deemed appropriate for further statistical analysis. The results of the Shapiro-Wilk test determined that approximately one-third of the sample data variables were not normally distributed. The number of total adaptations a household implemented exhibited the most normalcy. Finally, Spearman's correlations emphasized the need to examine the role of participants' valuation of provisioning and regulating ecosystem services more closely and show that no single variable can sufficiently explain the variation in households' total adaptations implemented.

Analyzing recent changes in local climate characteristics

I used descriptive statistics to summarize monthly weather station observations to quantify change and variability across the region. A Welch's *t*-test was used to test for any significant differences in the mean of climate characteristics over time. I used Welch's *t*-test because the data have unequal variances and unequal sample sizes, as stated in the above Section. These data were then used to run a series of linear regressions to test for any associations between mean wind speed, temperature, and cloud cover changes. These variables were chosen due to their observational consistency and availability across the study area weather stations, as described in Chapter 3. The results are presented in turn and in the context of downscaled climate reanalysis data for Icelandic summer and winter temperatures by the year 2100.

Firstly, the mean temperature in the Eyjafjörður study area over the last 70 years ranged from approximately 2.5ºC in Grímsey to 3.7ºC in Akureyri and 4.1ºC in Saudanesviti (or 36.5-, 38.6, and 39.4 degrees Fahrenheit (ºF), respectively), as shown in Tables 4, 5, and 6. These climate observations, as revealed from descriptive statistical analysis on *in situ* weather stations, show that the mean annual temperature in Akureyri and Saudanesviti has increased over this time period, while the mean annual temperature in Grímsey—a small island to the north of the Eyjafjörður fjord—has decreased slightly over this same time period (see Figures 6, 7, 8, and 9 at the end of this Chapter).

In Akureyri, the mean annual temperature rose from 3.4ºC in 1950 to 4.5ºC in 2020. This equates to a 1.1-degree Celsius increase in temperature (or nearly 2ºF) over 70 years. The results of a Welch's *t*-test, presented in Table 4 at the end of this Chapter, show a significant change in mean annual temperature for Akureyri between 1950-1984 and 1985-2020. In Saudanesviti, the mean temperature increased by 0.76ºC over 30 years, from 3.76ºC in 1990 to 4.52ºC in 2020. However, the results of Welch's *t*-test show that these trends were not significant.

The mean wind speed in the Eyjafjörður study area over the last 70 years ranged from 3.80 meters per second (m/s) in Akureyri to 7.13 m/s in Saudanesviti, and 7.19 m/s in Grímsey[15]. In Akureyri, the mean wind speed slightly decreased over time, by approximately 0.56 m/s. The wind speed in Grímsey and Saudanesviti increased over time, by approximately 2.17 m/s and 1.88 m/s, respectively, as seen in Figure 10. The results of Welch's *t*-test showed that these changes in wind speeds were significant for each weather station. However, the only instance of increasing wind speeds noted by participants in this dissertation research was in the context of the increasing severity of winter storms.

The mean cloud cover in the study area over the last 70 years ranged from 6.14 oktas[16] in Akureyri to 6.49 oktas in Saudanesviti and 6.55 oktas in Grímsey. Based on these observations, the study area experienced an approximately 76-82 percent daily cloud coverage on an annual basis. The mean annual cloud cover in Akureyri remained relatively stable over time, while the annual cloud cover in Grímsey and Saudanesviti decreased over time, as seen in Figure 11. The Welch's *t*-test showed that these trends in changing cloud cover were significant for Grímsey but not for Akureyri or Saudanesviti.

Collectively, the results of the analyses on these 3 observational datasets from *in situ* weather stations confirm that there is significant change occurring in the characteristics of the local climate. Namely, in Akureyri, temperatures have significantly increased, and wind speeds have significantly decreased since 1950. Simultaneously, wind speeds have significantly increased in Grímsey and Saudanesviti, and cloud cover has significantly decreased in Grímsey.

Recent reports from the IMO confirm this observed change in local climate characteristics (Björnsson, et al., 2018). Namely, downscaled climate reanalysis data show that temperatures in Iceland will continue to rise, with the most pronounced warming in the North and areas of high elevation, including throughout the Eyjafjörður study area (Gosseling, 2017).

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[15] The difference in wind speed between Akureyri and the other locations is readily explained, given that Akureyri is located at the mouth of a long, deep fjord. Meanwhile, the small island of Grímsey is located approximately 40 kilometers beyond the northwesternmost point of the Eyjafjörður fjord in the Greenland Sea. Saudanesviti is a coastal weather station and lighthouse on the Northwest point of the fjord. Like Grímsey, Saudanesviti is not afforded the protections from strong oceanic winds that Akureyri is.

[16] Oktas refer to eighths of sky, when viewed from a single point on the ground up, that are covered by cloud. Here, oktas are a measure of mean cloud cover rated on a scale between 0-8, indicating a clear sky at 0 and an overcast sky at 8.

Indeed, the average expected surface temperature warming for RCP 4.5 and 8.5 is most evident across the Eyjafjörður fjord study area (see Figure 12 at the end of this Chapter).

Many participants' survey responses in this dissertation research reflected temperature change in the study area experienced within the social-ecological system. A steady increase in temperature was noted through related hazard impacts, including an increase in the extremity of weather events and the degradation of Arctic ice. Social-ecological memory may play a key role in understanding participants' stated observations of climatic and environmental change related to weather observations. Social-ecological memory, similar to collective memory, is a concept that connects social identities with historical memories (Colten & Sumpter, 2009; Cooper, 2012). For example, participants stated,

> "We are thrown back [into colder temperatures] every few years with extreme winters, and we forget about the few years that seem hotter.
>
> Temperatures used to be much more stable. We had some storms, some whiteouts, but now we get weeks of storms and whiteouts or days of heavy rain.
>
> My mother remembers the fjord freezing over and people skating on the ice.
>
> The snow came in late fall and went in late springs, lakes were frozen, but now the snow is coming and going many times each winter, and the lakes are no longer frozen."

These comments represent the participant's lived experience in the context of historical knowledge, such that social memory can situate weather observations of temperature change in the context of the local social-ecological system. Indeed, many participants have noticed an emerging pattern of harsher winters and warmer summers, which may coincide with the sustained observed warming of temperatures and their projected continuation in time throughout the Eyjafjörður area.

Describing household adaptation outcomes

In the survey, participants identified adaptation actions that they or their households implemented. I used simple descriptive statistics to examine these adaptations. In total, there were 209 adaptation actions implemented or approximately 3 adaptations per household. As presented in Table 5, over 30 percent of adaptations focused on changes to consumer practices, and over 20 percent focused on changes to financial practices.

A range of specific adaptation actions was noted by participants who focused on adjusting their consumer practices. For example, participants noted reusing, recycling, and upcycling items; choosing to walk, bike, or carpool more often; preventing and reducing food waste; and reducing their overall consumer consumption. Further, many participants noted their efforts to be “environmentally aware” when shopping or their efforts to practice more “mindful shopping,” that is, to only buy what is deemed essential. Participants who made financial safety improvements most commonly cited the securities afforded by insurance as an adaptation to cover for “whatever the world throws [at them].” Together, changes to consumer practices and financial safety improvements accounted for over 50 percent of the total adaptations implemented by participants.

Of the remaining adaptations implemented, over 16 percent focused on educational practices, and 11 percent focused on ensuring the safety and security of physical structures. In complement to these efforts, educational practices most often included informal knowledge sharing, such as with neighbors, friends, and family members. Additional educational practices included visiting museums to learn about place history and learning about alternative energies (e.g., solar, wind) and methods for growing food (e.g., hydroponics, permaculture). Finally, a few participants elaborated on their improvements to physical structures and cited actions such as the reapplication of building insulation, replacing old windows, and sealing rooflines. Together, educational practices and structural safety improvements accounted for over 25 percent of the total adaptations implemented by participants.

Less than 10 percent of adaptations focused on changing energy practices or changing livelihoods. Most often, participants noted changing their energy practices by using home energy and water more efficiently and using solar energy. However, this may be a less popular adaptation option as renewable geothermal, and hydropower energy currently supplies much of Iceland’s energy demands. Finally, less than 4 percent of adaptations focused on emergency preparations. For example, a participant noted already having the equipment needed to cope with local seasonal weather conditions, such as a plow for heavy snow, which negated their perception of a need for further emergency preparation. Overall, participants exhibited an average of fewer than 3 adaptations per household, and over half of all adaptations made by participants focused on changes to consumer and financial practices.

Modeling the associations between household adaptation and social-ecological processes

Identifying significant associations and remaining multicollinearity

Based on the results of the analyses presented in the above Sections, I assumed non-normality to be present in this dissertation's sample dataset of variables. This may be due, in part, to the fact that some social-ecological system indicators comprise multiple variables that may be collinear. For example, local sense of place comprises 3 variables—place attachment, place dependency, and place identity. This meant a traditional linear regression would be inadequate for use on this dissertation's dataset due to the model's underlying assumption that dependent variables exhibit no multicollinearity.

Instead, I conducted a ridge regression, also known as an L^2 parameter regularization, to minimize model complexity (i.e., number of independent variables) and test for associations between households with a greater number of adaptations implemented and the variables within the social-ecological system framework. Ridge regression is based on ordinary least squares (OLS) but adds a penalty for the number of features in the model (Wu & Vos, 2018). This produces greater degrees of freedom than an analysis of OLS coefficients, which also improves the adjusted R^2 value of the model.

Ridge regression penalizes by the sum-of-squares of the parameters, like a weight decay in neural networks, until the coefficients converge to least squares (James, 2017). This means a ridge regression builds on the principal components of the input data by projecting a monotone decreasing function onto them, resulting in a proportional shrinkage to the coefficients of the components with low variance (Hastie, 2009). Like other statistical approaches, such as a principal component analysis (PCA) and partial least squares (PLS), the components of the ridge regression depend on the scaling of the input data and so are typically standardized.

Further, in ridge regression, coefficients of the principal components are shrunk dependent on the size of their eigenvalue, while in PCA and PLS approaches, the coefficients of the components with the smallest eigenvalues are truncated. As a result, PCA and PLS can be more unstable and have higher prediction errors than ridge regression (Frank and Friedman 1993). Thus, I chose a ridge regression over other standard statistical techniques due to its statistical power. The results of a ridge regression model depend on the order of variables' testing, so a two-way analysis was used to prevent model bias. The null hypothesis was that there was no significant linear relationship between the independent and dependent variables.

The ridge regression results provided an R^2 value of 0.4582, which means that approximately 46 percent of the variance of the dependent variable (i.e., adaptation level) could be explained by the variance of the independent variables. However, because the ridge regression included several independent variables, the R^2 value was adjusted to compensate for additional variables (that otherwise increase a model's R^2 value, even if the additional variables do not enhance the model). As a result, the ridge regression results provided an adjusted R^2 value of 0.2699. This means that the independent variables in the model account for approximately 27 percent of the variability in the dependent variable. The ridge regression results also showed that 6 independent social-ecological variables had a significant relationship with the number of adaptations that a household implemented. The direction and strength of these relationships are explored in the following Section.

Before further examining the variables presented in the ridge regression model, I checked the remaining multicollinearity within the model's independent variables. I did this because, under instances of unresolved multicollinearity, coefficient estimates can vary widely with only minor changes in the model (García, García, López Martín, & Salmerón, 2015). Thus, the presence of multicollinearity reduces the statistical power of regression models by diminishing the precision of coefficients.

I tested the multicollinearity of independent variables by identifying the variance of inflation factor (VIF). This identifies the remaining correlations between independent variables (and their strength) in a regression. The VIF score starts at 1, which signifies no correlation, and as the VIF score increases, multicollinearity increases. Scores between 1-5 indicate that variables are somewhat correlated. Scores over 5 indicate that a strong correlation is present. The results of the VIF test on the ridge regression model results indicated that the independent variables have low to moderate levels of collinearity with one another, with scores lower than 2.

Only 2 variables exhibited a high level of multicollinearity, namely, concern for current and future impacts of climate change at the global scale with scores of 6.17 and 5.72, respectively.

Research Question 1

> RQ1: *What social-ecological processes are most supportive to households' ability to implement adaptive action(s) within the context of rapid environmental change, and what variables can reliably measure those processes? How do these processes and their variables vary across the local social-ecological system?*

To answer **Research Question 1**, I determined the relationship between social-ecological variables and the number of adaptations that a household implements by applying descriptive statistics and conducting statistical tests on local weather observation datasets and on the local survey dataset. Namely, on the survey dataset, I used a Shapiro-Wilk test, Spearman's rank correlation coefficient, a ridge regression, and a VIF test to examine the associations between the social-ecological variables in the system framework, proposed in Chapter 3, and households with greater numbers of adaptations implemented. The results of these tests are discussed in turn.

The 6 most significant independent variables as determined by the ridge regression were (1) concern for current climate change impacts at the scale of the nation, (2) concern for future climate change impacts at the scale of the social-ecological system, (3) historical knowledge of ecosystem change, (4) sense of place attachment to the municipality, (5) high valuation of provisioning ecosystem services, and (6) risk reduction priorities favoring mitigation efforts. These 6 variables all have p-values of less than 0.01, which indicated strong evidence to reject the null hypothesis that there was no significant relationship between the independent social-ecological variables and the dependent variable (i.e., a greater number of household adaptations implemented) (see Table 6 at the end of this Chapter).

While these 6 variables were all significant, they did not have equal effects on how many adaptations a household implemented. First, as participants' concern for *current* climate change impacts on Iceland increased, the number of adaptations their households implemented decreased. Here, it appears that the more concerned participants were about the current impacts that climate change is having at the national level, the fewer adaptations their household implemented. Specifically, for every increase in participants' concern for climate change impacts on Iceland, the total number of adaptation actions their household implemented decreased by an estimated model weight of 0.49, indicating a 2:1 relationship between the variables. This value is referred to henceforth as the model weight of each variable. A potential explanation for this may be found in the experience and consequences of climate anxiety (Clayton S. , 2020), such that an increased sense of concern may erode participants' perceived ability to act, in this case, at the national level to adapt to the impacts of climate change.

Second, as participants' concern for *future* climate change impacts on the local social-ecological system (i.e., the study area) increased, their total number of adaptation actions implemented increased (estimate model weight of 0.63). Here, it appears that the more concerned participants were about the future impacts that climate change will have on the study area, the more adaptation their household implemented. This reflects an anticipatory approach to adaptation and highlights the role of feelings and scale in the household adaptation process. Further, participants' concerns varied over time and across space reinforced the idea that concern for climate change is a scale-dependent process (Janssen, Anderies, & Ostrom, 2007).

Third, participants who expressed historical knowledge of changes in ecosystems, and fourth, who gave a high valuation of provisioning ecosystem services, implemented more adaptations within their household. Thus, as one of these independent variables increased, so did the total number of implemented adaptations, with estimated model weights of 0.40 and 0.35, respectively. That households with historical knowledge of changes in the local ecosystem implemented more adaptation actions indicate this knowledge may have enabled participants to take a *responsive* approach to adaptation. Here, adaptation is situated within the context of the area's ecological history (Epstein, Vogt, Mincey, Cox, & Fischer, 2013). Additionally, participants who gave provisioning ecosystem services a high valuation implemented more adaptation actions. This indicates that values-based processes play a role in adaptation and may be explained, in part, by the recognition of the tangible benefits provided by the local social-ecological system (i.e., ecosystem services).

Fifth, conversely to the relationships above, as the strength of participants' sense of place attachment to their municipality increased, their household implemented fewer total adaptation actions, with an estimated model weight of -0.44. This may indicate that sense of place attachment is scale-sensitive, and that a strong local affection for sense of place may inhibit adaptation, such that changes to the current system are not desired. It could be that people are averse to implementing adaptation actions that could alter the places familiar to and revered by them (Eyles, 1989). On the other hand, it could also be that a sense of place attachment has already strained or eroded participants' relationship with place at the municipal scale due to changing climate conditions or otherwise, preventing adaptation actions from being implemented (Nielsen & Reenberg, 2010).

Finally, a strong valuation on mitigation efforts for local risk reduction was negatively related to the number of adaptation actions a household implemented, with an estimated model weight of -0.38. Thus, as participants' preference for mitigation efforts increased, the fewer adaptation actions their household implemented. This may be due to participant desires to prevent change rather than adapt to change, such that a strong preference for mitigation efforts may serve to inhibit household adaptation. This is troubling, as the impacts of climate change are complex, increasing, and require a blend of mitigation and adaptation efforts to sustain social and ecological systems alike.

In sum, I rejected the null hypothesis that there was no significant relationship between the 6 independent social-ecological variables presented above and the number of adaptations that a household implemented. The social-ecological variables found to be most supportive to participants' household adaptation included (1) feeling concern for future local impacts of climate change, (2) having historical knowledge of ecosystem change, and (3) placing a high valuation on provisioning ecosystem services. Based on these results, the promotion of household climate change adaptation may be most effective when it addresses feelings of concern for the future of local areas. Here, feeling and scale are important elements in implementing adaptation actions and so must be engaged with care.

The results presented above also reveal inhibitive effects on household adaptation, such as concern for the current impacts of climate change on Iceland. An additional 2 social-ecological variables were inhibitive of household adaptation, including a strong municipal place attachment and risk reduction that favor mitigation. Mitigation is vital and complementary to adaptation efforts, so further investigation into this phenomenon is needed to address the mitigation-adaptation dichotomy.

Secondary significant associations

Secondary significant variables revealed by the ridge regression model, those with p-values between 0.01-0.05, include (1) a strong local sense of place identity, (2) concern for future impacts of climate change at the global scale, (3) the lived experience of ecosystem change, and (4) a strong valuation of cultural ecosystem services. The direction and strength of association between these variables are discussed in turn.

First, as the strength of participants' local sense of place identity increased, their household implemented more adaptation actions, with an estimated model weight of 0.40. This meant a strong local sense of place identity was facilitative of household adaptation. This may be due, in part, to participant desires to maintain the place identity of where they live. Second, in contrast to the above variable, as participants' amount of concern for future climate change impacts at the global scale increased, their household implemented fewer adaptation actions, with an estimated model weight of -0.65. Thus, high levels of concern for *current local* climate change impacts may support household adaptation. In contrast, high levels of concern for *future global* climate change impacts may inhibit household adaptation.

The remaining 2 social-ecological system variables identified by the ridge regression model also negatively related to household adaptation outcomes. For example, as participants indicated having lived experience with ecosystem changes, their household implemented fewer adaptation actions, with an estimated model weight of -0.34. This may be due to participants experiencing an erosion of place and its ecosystems, such that this experience inhibits their household from implementing adaptation actions. Finally, as participants' valuation of cultural ecosystem services strengthened, their household implemented fewer adaptation actions, with an estimate of -0.38. As discussed above, this may be due to participant desires to maintain the current social-ecological system rather than adapt to changes. However, further research is still needed to understand better why strong ties to the landscape of the social-ecological system, such as the aesthetic and recreational attributes it provides, may inhibit household adaptation.

In sum, the 4 variables presented above all had p-values between 0.01-0.05, indicating strong evidence to reject the null hypothesis that there was no significant relationship between them and the number of adaptation actions that households implemented. The strength of the participant's local sense of place identity was supportive of household adaptation. Conversely, participants' concern for future climate change impacts at the global scale, participants' lived experience of ecosystem changes, and the strength of participant's valuation of cultural ecosystem services was inhibitive of household adaptation.

Reflecting on the Analytical Results and Implications for Research Question 1

Each household sampled in the Eyjafjörður study area implemented an average of nearly 3 adaptation actions, with over 200 total adaptations implemented across the sample of 70 households. Over half of all adaptation actions focused on changes to household consumer and financial practices, such as reducing household consumption of goods and purchasing or expanding insurance coverage.

Collectively, the results of the descriptive statistics and statistical tests (i.e., Slovin's test, Shapiro-Wilk tests, Spearman's rank correlation coefficient tests, ridge regression, and VIF) on the datasets used in this dissertation (i.e., local climate and survey data) indicated that there were significant relationships between the social-ecological variables (i.e., the independent variables) in the system framework and the number of adaptation actions a household implements (i.e., the dependent variable). Slovin's test confirmed that the sample size used in this dissertation allows for high confidence. Thus, these variables may serve to reliably measure the social-ecological processes most supportive of a household's ability to implement greater numbers of adaptive actions within the context of rapid environmental change (**Research Question 1**).

Namely, the 4 variables found to be most facilitative to greater numbers of household adaptation actions implemented were (1) feeling concern about the future local impacts of climate change, (2) having a strong local sense of place identity, (3) having a strong valuation of provisioning ecosystem services, and (4) having historical knowledge of ecosystem change. Collectively, these results show that household climate change adaptation may be most supported in North Central Iceland if it addresses local feelings of concern for the future of the local area and its place identity, including how adaptation actions are situated within local ecological histories and how they promote the continuation of provisioning ecosystem services. Thus, the application of the social-ecological system framework presented in this dissertation highlighted the importance of feeling and scale, which can be supportive or inhibitive of household adaptation.

Research Question 2

RQ2: To what extent do the valuation of ecosystem services and sense of place play a role in supporting adaptive behavior? Are there associations between these variables?

To answer **Research Question 2**, I used a series of linear regressions to determine if there were any (1) associations between these ecosystem services or sense of place and participants' adaptation level, (2) associations within ecosystem services and sense of place, or (3) associations between ecosystem services and sense of place. The results of these analyses are presented in turn.

Testing the relationships between and within social-ecological processes

The results of a series of linear regressions, as seen in Table 7, indicated no statistically significant associations between the number of household adaptations and any stand-alone, independent social-ecological variable. However, there were significant positive associations within the variables that constitute cultural, provisioning, and regulating ecosystem services, within the variables that constitute sense of place, and within participants' preferences for the focus of risk reduction efforts.

Ecosystem services were a particularly strong predictor of sense of place, exhibiting a close 1:1 relationship. In future studies, the number of variables in the social-ecological system can be reduced for model efficiency if the strength of these predictors holds in applications to other social-ecological systems.

The only significant negative relationship between social-ecological processes was found between participants' local sense of place and their valuation of cultural ecosystem services. Here, a high valuation of cultural ecosystem services was a negative predictor of local sense of place, with an estimated weight of -1.58. This inverse relationship between the valuation of cultural ecosystem services and the strength of local sense of place must be further examined, particularly as these 2 bodies of literature continue to merge.

Collectively, these results indicated that evaluations of cultural ecosystem services and sense of place must test for the direction and scale (not just the strength) of any observed associations. In a few cases, the strength of participants' sense of place was tied to a negative emotion, not a positive emotion. In sum, to answer **Research Question 2**, no single independent variable within the valuation of ecosystem services or sense of place can explain the adoption of more numerous adaptation actions within households, and there are significant associations between these variables.

Research Question 3

RQ3: How can human-environment relationships within a social-ecological system be modeled spatially, using adaptation to climate change as an example? What might we learn about adaptation from such modeling?

To answer **Research Question 3**, I used a spatial approach to visualize human-environment relationships within the social-ecological system. Namely, 2 participatory mapping exercises engaged with participants' social-ecological system interactions and local knowledge. These exercises focused on identifying participants' evaluation of areas most in need of risk reduction efforts to sustain valued ecosystem services. Incorporating participatory mapping exercises moved beyond the data formats provided by traditional survey questions. Collecting spatial and narrative data enabled the sharing of situated knowledges and priorities, which are increasingly used to improve community disaster risk reduction efforts (White, Kingston, & Barker, 2010; Cadag & Gaillard, 2012).

Participants placed 4 points, or 2 points per map, which resulted in a total of 280 points across both maps. In a GIS, these 280 locations were reduced using a hot spot analysis and given a buffer to protect participant anonymity and improve the visual interpretability of the results. In both maps, the areas identified appeared well-dispersed compared to the concentration of the population within Akureyri (nearly 75 percent of the total population in the study). The 2 resulting participatory maps revealed sense of place as an individual experience that, collectively, constitutes place meanings and descriptive cognitive factors of the types of places in question (e.g., "natural paradises," "hazardous environments"), which can aid in identifying how household adaptation is facilitated in response to rapid environmental and climate change impacts.

The results of the first participatory mapping exercise revealed areas perceived by participants as having high value for potential natural conservation and preservation efforts. The second participatory mapping exercise results revealed areas perceived by participants as most in need of risk reduction efforts. Together, these maps and the narrative descriptions provided by participants enabled spatial modeling of human-environment relationships within the social-ecological system. The results of these participatory mapping exercises are presented and discussed in turn.

Identifying areas of high social-ecological value

Figure 13 offers a visualization of areas that participants identified as most worthy of natural conservation or preservation efforts. As noted above, these hot spot areas represent the locations and frequencies of points placed by participants. The map revealed 6 clearly defined hot spot areas of high social-ecological value, consisting of 2 primary and 4 secondary locations. Additional areas were identified and should be incorporated in future analyses. There is a marked absence of noted value along the riparian corridor that accompanies Route 1, the “Ring Road”, which runs Northeast-Southwest from Svalbarðseyri.

Collectively, participants expressed a desire to protect a variety of social-ecological places and features. These include biophysical features such as lakes and natural habitat areas and social features such as historic cultural sites and outdoor recreational areas. The 2 primary areas perceived by participants to have the highest natural conservation and preservation value were the islands of Grímsey and Hrísey.

Grímsey is located over 40 kilometers North of the Eyjafjörður fjord’s northernmost landmass. The island is under 6 square kilometers in size and extends above 66.5 degrees north latitude, which makes Grímsey Iceland’s northernmost territory. Less than 100 people occupy the island. Participants referenced Grímsey’s natural habitats and the species they support, including puffins and Arctic Terns. Participants also reference the island's social and cultural value, including a small historic church, Miðgarðar.

Hrísey is an island located in the Eyjafjörður fjord less than 4 kilometers from Árskógssandur, where the ferry to and from Hrísey is located. The island covers approximately 8 square kilometers in size. A small community of fewer than 200 people lives on the island of Hrísey year-round. Participants referenced Hrísey as "the pearl of nature" and "the pearl of Eyjafjörður." It is valued for its "pristine" and unique "wonders of nature." The island is minimally inhabited and is valued for its natural habitat that supports an array of bird species, including the Ptarmigan, Arctic Tern, and Common Eider. In addition to its natural habitat, Hrísey is also valued for its community and cultural heritage. The island was settled in the 10th Century and now hosts a lighthouse, a few hiking trails and small farms, a small town with a restaurant, a geothermal swimming pool, and a school. The northernmost portion of the island is a private nature reserve that protects bird species during their nesting seasons.

Secondary areas perceived to have the highest natural conservation and preservation value were the areas within and around Kristnes, Akureyri, Hjalteyri, Hauganes, and Siglufjörður. These 5 locations range from the southerly to the most northerly reaches of the western side of the Eyjafjörður fjord, respectively. These areas and the mountains to the west are known as the Troll Peninsula, or Tröllaskagi. Here, the highest peak is Kerling, which reaches over 1,500 meters above mean sea level. Tröllaskagi, and the Eyjafjörður fjord, are endued with a rich cultural history, which is represented in Icelandic sagas.

Kristnes is less than 10 kilometers to the south of Akureyri. It has a population of approximately 50 people and sports a hospital and mixed-use museum and café. This area is well-known for its productive farming. Akureyri has a population of over 18,000 people (Statistics Iceland, 2020). It is the second-largest city in Iceland, sporting an airport, a harbor, a university, and numerous residential homes, restaurants, museums, and stores.

Hjalteyri is approximately 17 km to the north of Akureyri and has just over 40 residents (Statistics Iceland, 2020), sporting a restaurant, accommodations, and whale watching and diving centers, such as to Strýtan, an underwater formation of silica off the coast of Hjalteyri. Strýtan is the only known geothermal chimney in the world that is accessible by diving and is one of the only known vents to be alkaline, providing a supportive habitat for a variety of unique microbial life (Marteinsson, et al., 2001). Indeed, these underwater formations and their hydrothermal chimney vents were the first underwater areas protected by the Environmental Agency of Iceland

(Ministry for the Environment, 1999). Other similar underwater formations can be found throughout the Eyjafjörður fjord study area.

Finally, Hauganes is approximately 17 km to the north of Hjalteyri and has approximately 140 residents (Statistics Iceland, 2020). Like other coastal towns of the Eyjafjörður fjord, Hauganes is centered on the fishing industry and sports a restaurant, accommodations, and whale watching tours. Overall, the areas perceived by participants to have the highest natural conservation and preservation value were the islands of Grímsey and Hrísey. Secondary areas perceived to have the highest natural conservation and preservation value were within and around Kristnes, Akureyri, Hjalteyri, and Hauganes.

Many participants reportedly chose these locations because they “feel good there”, using terms including “outdoor paradise” and “natural gem” to describe the location’s social-ecological value. These statements were indicative of participants’ sense of place attachment. Further, participants noted that these sites provide space for activities that are not provided elsewhere, which reinforces the importance of sense of place dependency in social-ecological processes (Masterson V. A., et al., 2017) of the region that influences the valuation of the environment and its ecosystem services. Finally, participants noted the importance of community-buildingn these spaces—such as by meeting friends at a park so that their children can play (Hahn, Schultz, Folke, & Olsson, 2008).

Identifying areas of high hazard risk

Figure 14 offers a visualization of the areas perceived by participants as most in need of risk reduction efforts. As noted above, these areas represent the locations and frequencies of points placed by participants. The resulting map revealed 2 primary hot spot areas and 3 secondary areas needing risk reduction efforts. Collectively, participants expressed a desire to reduce hazard risk by protecting a variety of social and biophysical features, with many centered on improving public health and safety and on coastal and transportation infrastructure. These included physical structures like residential buildings and transportation networks, such as roads and tunnels.

The hot spots perceived by participants to have the highest need for risk reduction efforts were the areas of Siglufjörður and Ólafsfjörður. Siglufjörður is a historic fishing village of approximately 1,200 people (Statistics Iceland, 2020). It is the northernmost town in Iceland, second only to the island of Grímsey. Ólafsfjörður, another fishing village, is located approximately 14 kilometers to the southeast of Siglufjörður. Ólafsfjörður and Siglufjörður are connected by Route 76 that runs through 2 mountain tunnels. The tunnels, Héðinsfjarðargöng, were completed in 2010, and run a total length of 10.6 kilometers (or approximately 6.5 miles).

Participants noted choosing these 2 locations because snowstorms and avalanches make the roads difficult or impossible to navigate in the winter season, including the tunnel noted above. A recent occurrence of this was reported in the Iceland Review:

> Yesterday, an avalanche fell on the road to Ólafsfjörður, effectively closing it to traffic, and today, large avalanches fell in Ósbrekkufjall mountain, one reaching all the way down to the sea. All roads to and from the Fjallabyggð municipality, containing the towns of Siglufjörður and Ólafsfjörður, are impassable due to the snow (Einarsdóttir, 2021).

The hazardous characteristics of these areas are portrayed beyond news media, such as in the entertainment crime-drama series *Trapped* (Kjartansson, 2015). Participants suggested constructing avalanche defenses and updating or creating new tunnels to adapt to the increasing severity and occurrence of avalanches and snowstorms. These sentiments were expressed with urgency.

Participants perceived secondary hot spots as most in need of risk reduction efforts to be the areas in and around Akureyri, Dalvík, and Hrísey. Dalvík is a coastal town with approximately 1,400 residents (Statistics Iceland, 2020). Participants fear that coastal areas such as these may one day become uninhabitable. These fears are not unfounded. Indeed, habitation in some parts of the social-ecological system, such as Fjörður and Flateyjardalur (Flateyjarskagi), ceased in the early 20th century due to coastal erosion. “The barrage of the ocean” is noted, in this and other terms for coastal erosion, as negatively impacting historical relics throughout the social-ecological system, such in Akureyri and on the island of Hrísey. Participants expressed concern about the future of these areas under the influence of severe weather events and coastal erosion, notably exposed locations of historical and daily use-values. Participants also noted earthquakes as posing a continued risk throughout the social-ecological system, which can trigger, for example, further erosion or avalanche events.

Identifying spaces of high social-ecological value and hazard risk for adaptation

Akureyri and Hrísey were the only 2 hot spot locations that featured prominently in participatory maps of areas that would benefit from natural conservation *and* risk reduction efforts, as shown in Figure 15. Both locations sport areas of social-ecological value, including historical-cultural sites and unique ecological and marine habitats. Both areas also face hazard risks, including the effects of coastal erosion and severe storms. Due to their perceived high value and high hazard risk, it may be beneficial to introduce climate change adaptation efforts in these locations.

Participatory mapping enabled climate change adaptation to serve as an example of how human-environment relationships can be modeled spatially within a social-ecological system (**Research Question 3**). Further, the spatial modeling approach results showed that identifying areas perceived as having both high natural value and high hazard risk can, thus, enable identification of locations within the social-ecological system where adaptations may most co-benefit social and ecological components while maintaining community values.

Reflecting on the Results of the Application of a Social-Ecological Framework in North Central Iceland for Analyzing Household Climate Change Adaptation

In conclusion, the results of the application of the spatial social-ecological systems framework of adaptation to climate change that I presented in this dissertation were described above to answer the research questions put forth in Chapter 1. Here, I summarize these findings and present them within the context of the social-ecological system.

For this dissertation research, the SESF was adapted to expand its use to analyze climate change adaptation, though only 2 of the 4 SESF tiers were included in this dissertation research, the actors and the resource system (Ostrom E. , 2009). The feedback and interactions among the variables within and between these tiers connect the system variables by accounting for the flows between social and ecological components (Folke, 2006). External factors, such as the characteristics of the climate, also work to influence the variables within the framework. Together, these system dynamics create a nested framework to analyze adaptation outcomes (Ostrom E. , 2007; Thiel, Adamseged, & Baake, 2015).

In identifying sets of social-ecological processes that influence households to implement adaptation actions, this dissertation research has contributed to the development of the social-ecological systems approach for use as an analytical tool of climate change adaptation. In future research, these methods may be used to identify adaptation typologies in other social-ecological systems (Eisenack, Lüdeke, & Kropp, 2006).

Household adaptation actions focused on changing consumer practices and improving financial security

Participants implemented a total of 209 adaptations or slightly fewer than 3 adaptations per household on average. Of these adaptations, over 30 percent focused on changes to consumer practices, and over 20 percent focused on changes to financial practices. Participants commonly noted reusing and recycling items more often, effectively preventing and reducing food waste, and purchasing or upgrading their insurance. The least common adaptation action implemented was emergency preparation.

There are observed, lasting changes in local climate characteristics

Observational datasets from 3 *in situ* weather stations collectively spanned the last 70 years. Their analysis, alongside downscaled climate reanalysis data (Gosselin, Bélanger, Lapaige, & Labbé, 2011), confirmed a sustained change in the characteristics of the local climate. Wind speeds increased in Grímsey and Saudanesviti, and cloud cover decreased in Grímsey and Saudanesviti. The temperature increased in Akureyri and Saudanesviti and was also referenced by participants in relation to hazard impacts, including more severe weather events and the degradation of local permafrost and glacial ice. Participants also experienced increasingly harsher winters and warmer summers, coinciding with the observed warming of temperatures throughout the area. When corroborated with participant narrative information, these results show that social-ecological memory may play a key role in understanding and acting on local observations of climate change. This is because participants' lived experience and historical knowledge acted to situate observations in the context of the local social-ecological system.

Three key social-ecological system variables were supportive of household adaptation

The social-ecological system variables found to be most supportive to or facilitative of household adaptation were (1) feeling concern for future local impacts of climate change, (2) having historical knowledge of ecosystem change, and (3) highly valuing provisioning ecosystem services. Here, feeling and scale are important elements in adaptation implementation at the household level and must be engaged with care. Conversely, a high valuation of mitigation efforts for risk reduction was inhibitive of households' total number of adaptation actions implemented. Mitigation is vital to combat further climate change, but these efforts should not inhibit adaptation from co-occurring.

Spatial methods can aid in identifying areas suitable for adaptation

Participants expressed a desire to protect a variety of social-ecological places, including natural habitat areas and historic cultural sites. The areas that participants perceived to have the highest social-ecological value and the highest hazard risk were Akureyri and the island of Hrísey. These locations have historical-cultural sites and unique ecological and marine habitats, and both face hazard risks, including severe storms and coastal erosion. These areas may be ideal places to begin climate change adaptation efforts due to their perceived values and risks (Folke, Colding, & Berkes, 2003). In sum, spatial methods can aid in modeling human-environment relationships within a social-ecological system and can lead to the identification of areas perceived to be most valued and most at-risk to the impacts of climate change.

In this Chapter, I sought to contribute to current knowledge on the factors that support adaptation by presenting the results of the application of a social-ecological systems approach as applied in North Central Iceland. I presented the results of the application of the framework within the context of the research questions put forth, with each subsection building on results presented in the previous subsections. I concluded by presenting a concise summary of the most formative results discussed in the context of the social-ecological system. In the following

Chapter (5), I summarize this dissertation research, including an overview of study limitations. I also offer the next steps for advancing the research framework and application.

Figure 6. A graph depicting the annual mean temperature in ⁰C over time based on monthly weather station observations in Akureyri, Iceland. Points represent annual mean temperatures. The dotted line is a trend line (linear regression model) of the relationship between annual temperature and years (IMO, 2020).

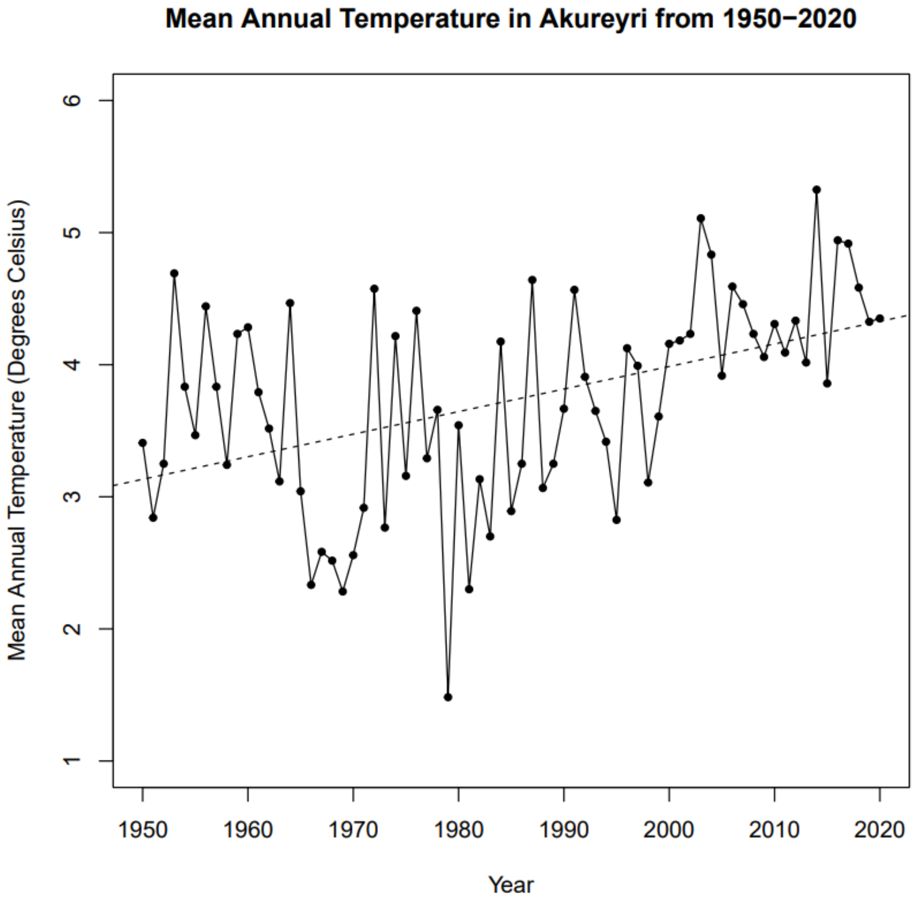


Figure 7. A graph depicting the annual mean temperature in ⁰C over time based on monthly weather station observations in Grímsey, Iceland. Points represent annual mean temperatures. The dotted line is a trend line (linear regression model) of the relationship between annual temperature and years (IMO, 2020).

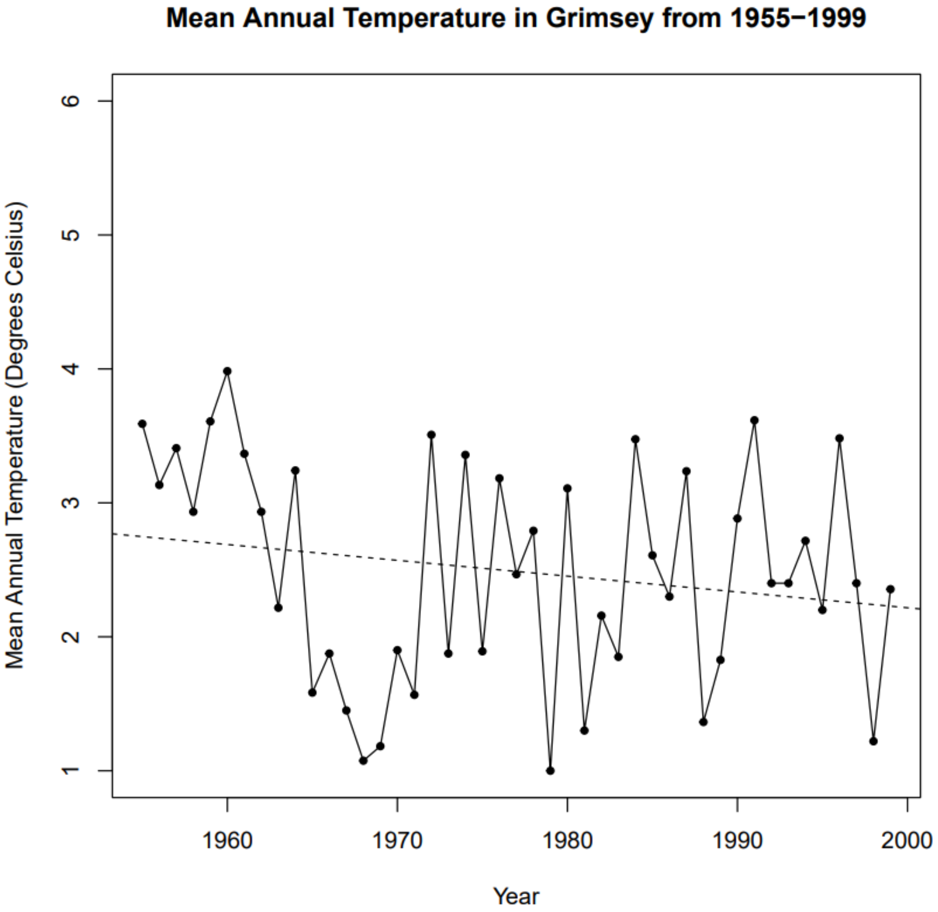


Figure 8. A graph depicting the annual mean temperature in ºC over time based on monthly weather station observations in Saudanesviti, Iceland. Points represent annual mean temperatures. The dotted line is a trend line (linear regression model) of the relationship between annual temperature and years (IMO, 2020).

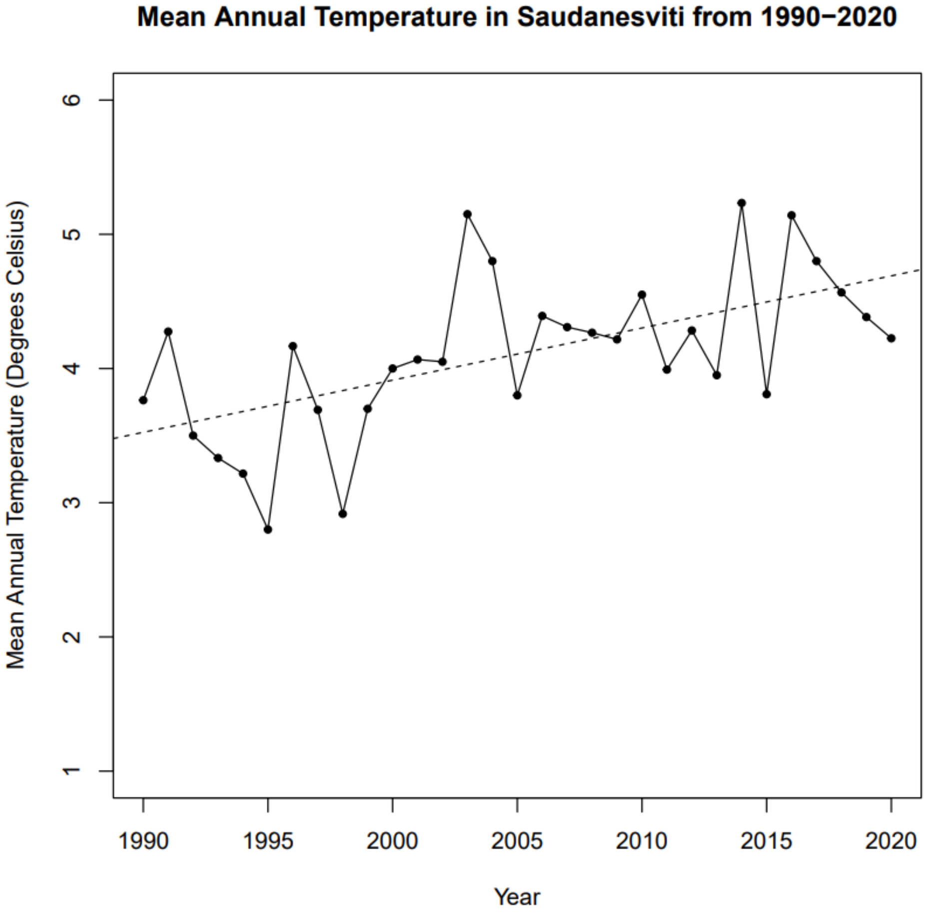
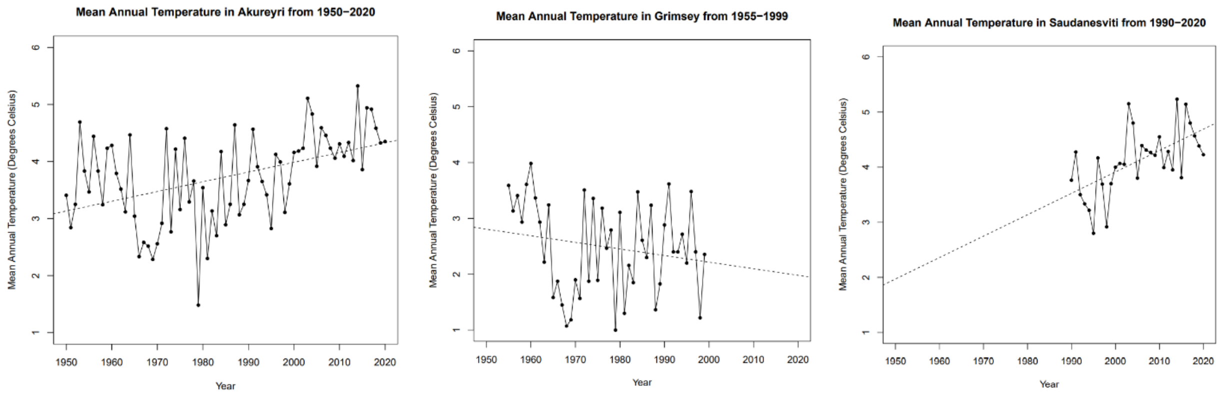


Figure 9. Side-by-side graphs depicting the change in annual mean temperature over time based on monthly weather station observation in Akureyri, Grímsey, and Saudanesviti, Iceland. Note that the x- and y-axis are standardized across the graphs. These graphs show that the mean annual temperature in Akureyri and Saudanesviti have increased, while the mean annual temperature in Grímsey has decreased slightly (IMO, 2020).



Mean Annual Temperature in Akureyri from 1950−2020

Mean Annual Temperature in Grimsey from 1955−1999

Mean Annual Temperature in Saudanesviti from 1990−2020

Figure 10. Side-by-side graphs depicting the change in annual wind speeds over time based on monthly weather station observation in Akureyri, Grímsey, and Saudanesviti, Iceland. Note that the x- and y-axis are standardized across the graphs. These graphs show that the mean annual wind speeds in Akureyri decreased slightly from 1950-2020, while the mean annual wind speeds in Grímsey and Saudanesviti have increased (IMO, 2020).

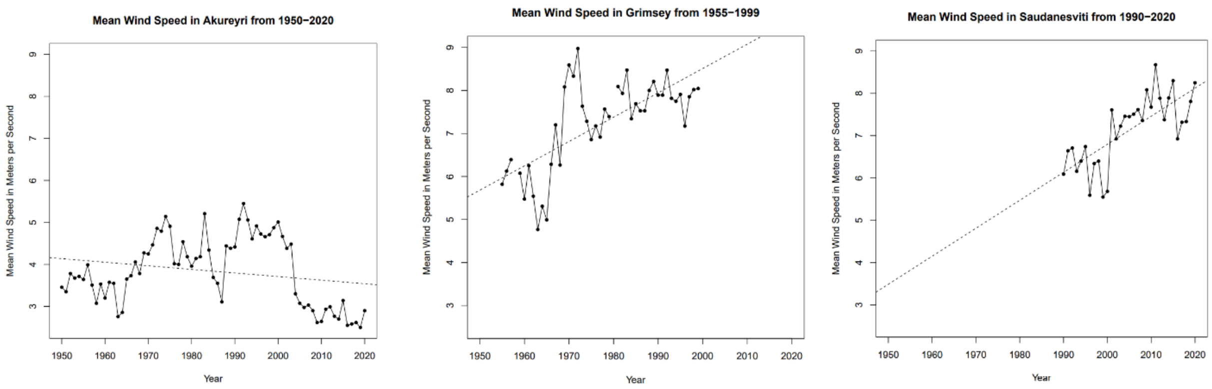


Figure 11. Side-by-side graphs depicting the change in annual cloud cover over time based on monthly weather station observation in Akureyri, Grímsey, and Saudanesviti, Iceland. Note that the x- and y-axis are standardized across the graphs. These graphs show that the mean annual cloud cover in Akureyri remained relatively constant from 1950-2020, while the mean cloud cover in Grímsey and Saudanesviti has decreased (IMO, 2020).

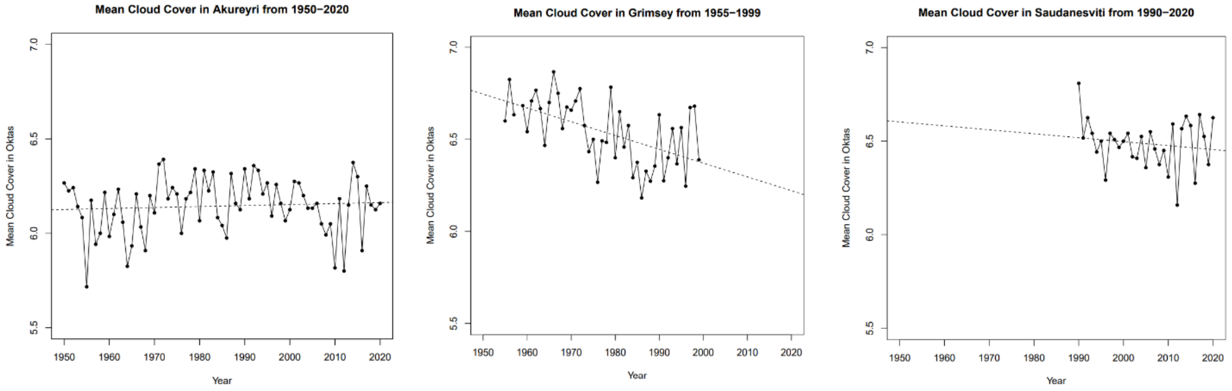


Figure 12. A visualization of the average expected surface temperature warming for RCP 4.5 and 8.5 (Gosselin, Bélanger, Lapaige, & Labbé, 2011).

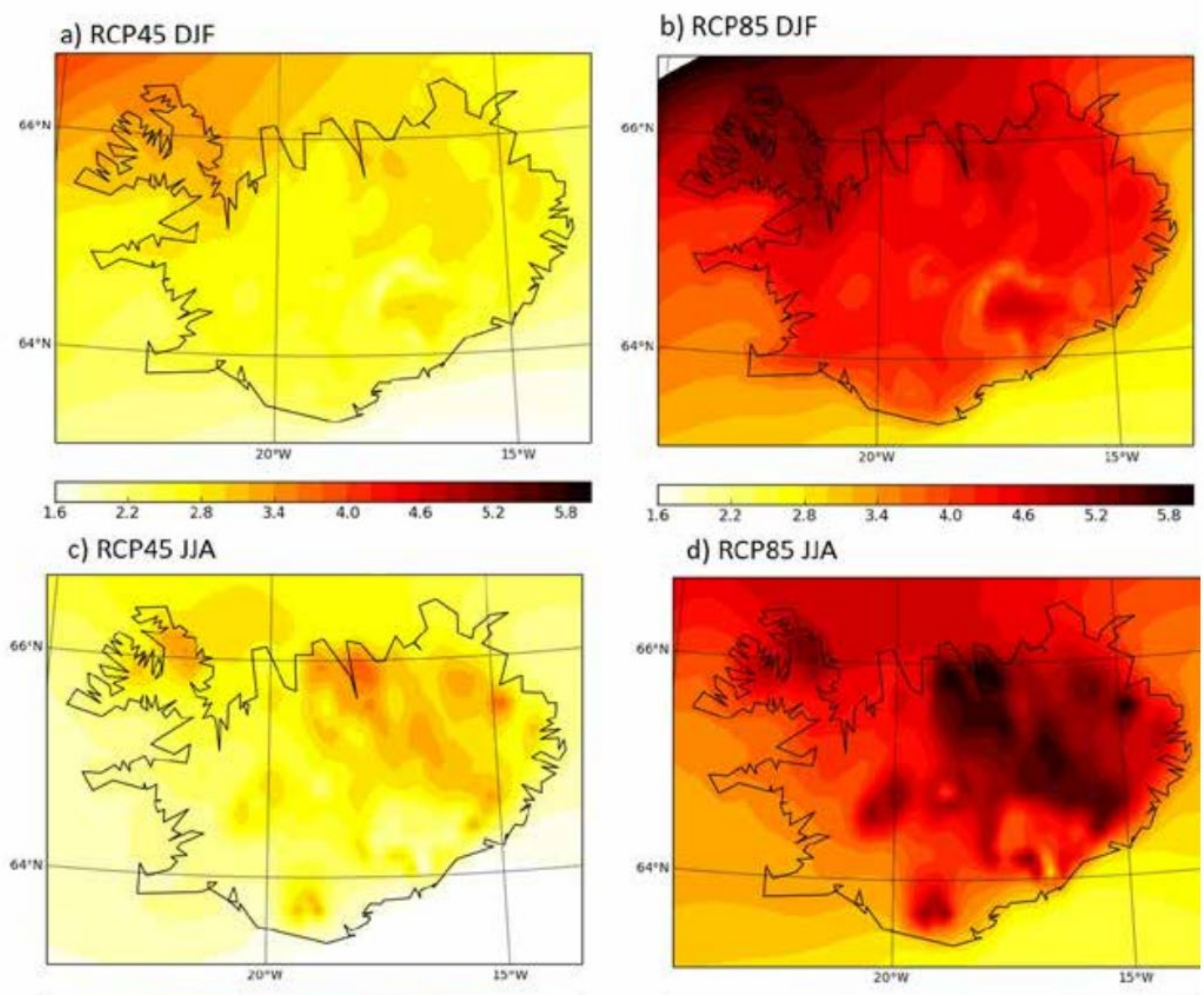
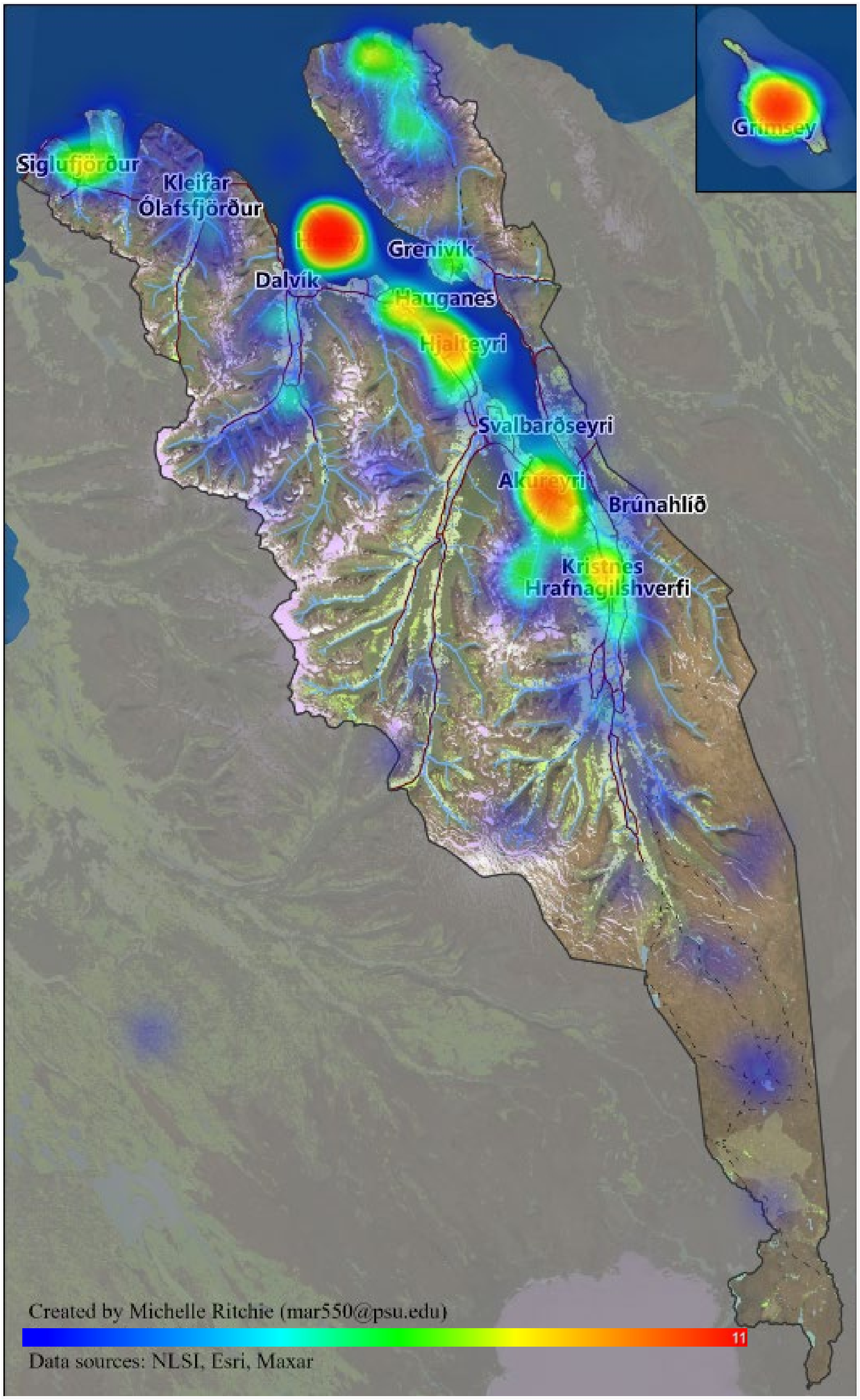


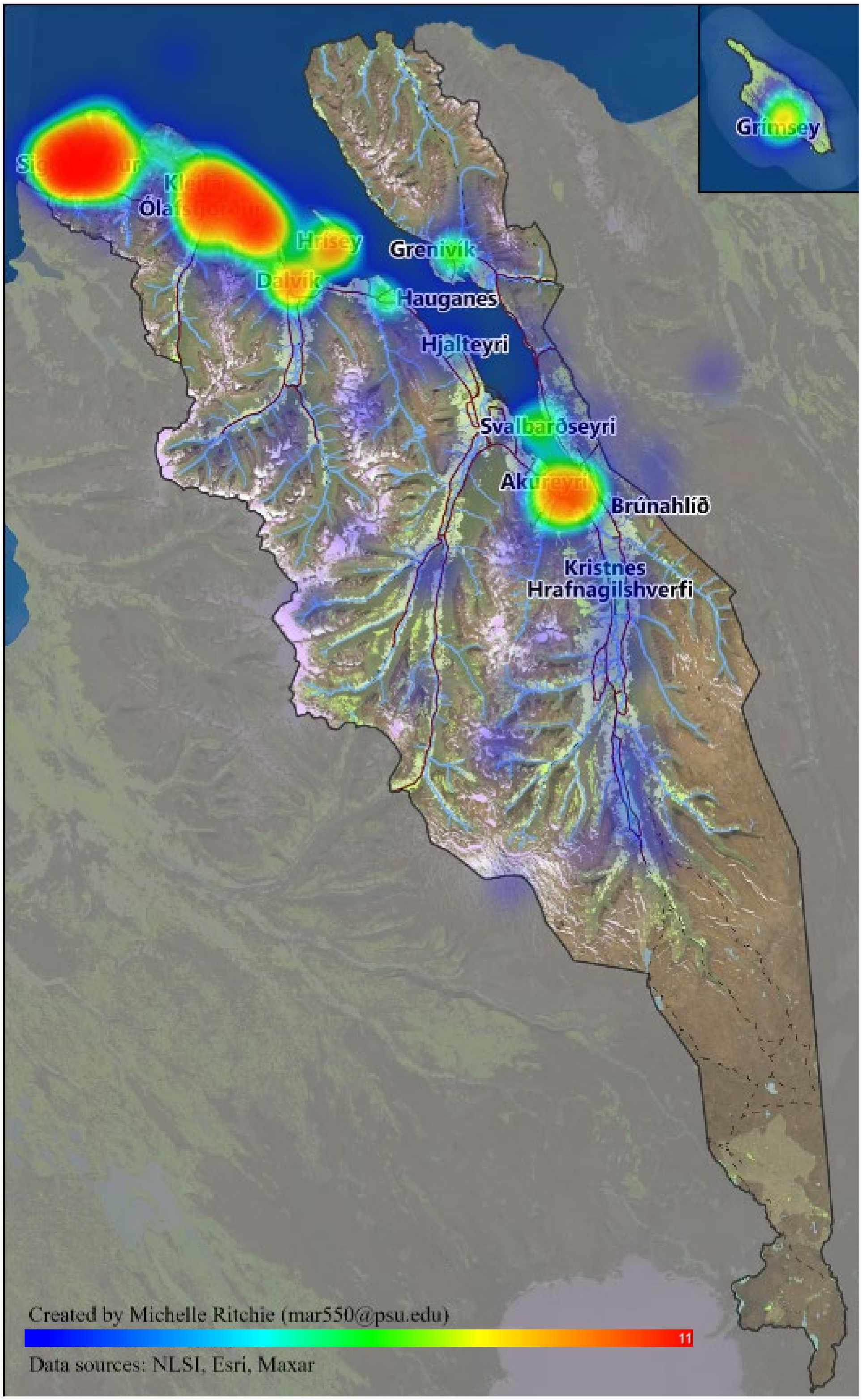
Figure 13. A participatory map that highlights hot spots of perceived social-ecological value in the study area. As seen in the map, the 2 primary areas of value are the islands of Grímsey and Hrísey. Secondary areas of value center on Kristnes, Akureyri, Hjalteyri, and Hauganes.



Created by Michelle Ritchie (mar550@psu.edu)

Data sources: NLSI, Esri, Maxar

Figure 14. A participatory map that highlights hot spots of hazard risk in the study area. As seen in the map, the 2 primary areas of hazard risk are Siglufjörður and Ólafsfjörður. Secondary areas of risk center on Akureyri, Dalvík, and Hrísey.



Created by Michelle Ritchie (mar550@psu.edu)

Data sources: NLSI, Esri, Maxar

Figure 15. A side-by-side comparison of hot spots of social-ecological value in the left panel and hot spots of hazard risk in the right panel (Figures 13 and 14, respectively).

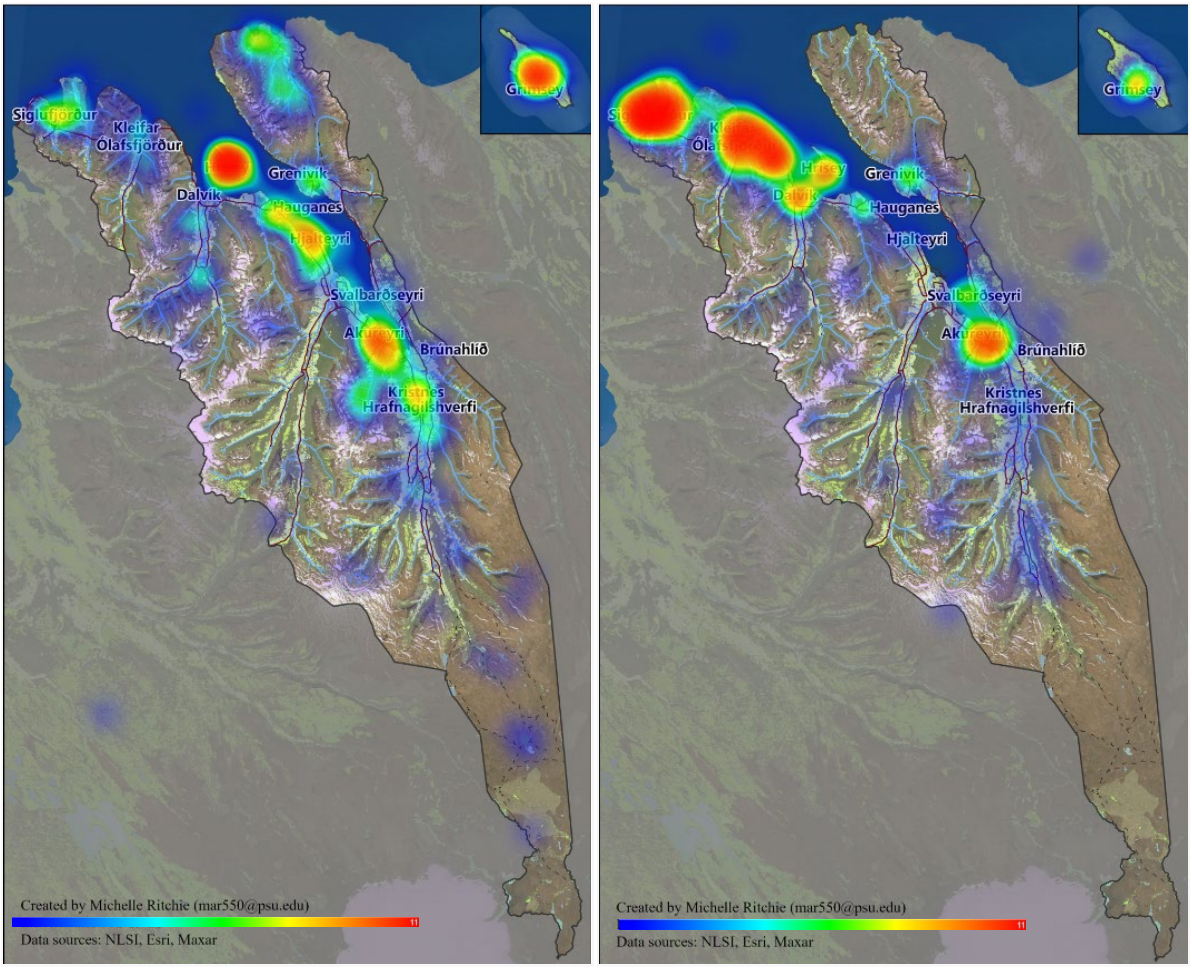


Table 1. Number of sampled households and total number of households in the Eyjafjörður study area.

Municipality	**Total Households in Municipality**	**Total Households Participating**	**Percent of Municipality Households Sampled**
Akureyrarkaupstadur	7,570	40	0.53
Dalvíkurbyggð	762	8	1.05
Eyjafjarðarsveit	417	3	0.72
Fjallabyggð	803	11	1.37
Grýtubakkahreppur	127	1	0.78
Hörgársveit	246	2	0.81
Svalbarðsstrandarhreppur	196	5	2.55
Total	10,121	70	**7.82**

Note: As of 2019, Iceland had an average household size of 2.5 people (Statistics Iceland, 2020).

Table 2. Results of the Shapiro-Wilk test of sample normality.

Variable	**Shapiro-W**	**Significance of Normality**
Total concern about current changes	0.94602	**
Total concern about future changes	0.93596	**
Concern about future changes at the household level	0.92261	*
Concern about future changes at the municipal level	0.91561	*
Age	0.95019	**
Total sense of place	0.93472	**
Total sense of place at the municipal level	0.91957	*
Sense of place dependence at the municipal level	0.94162	**
Total sense of place at the local level	0.91732	*
Dense of place dependence at the local level	0.91854	*
Dense of place attachment at the local level	0.9288	*
Valuation of provisioning ecosystem services	0.94717	**
Preference for mitigation as risk reduction	0.92781	*
Preference for preparedness as risk reduction	0.91354	*
Preference for adaptation as risk reduction	0.94673	**
Total household adaptations	0.95462	***

Table 3. Results of the Spearman's correlation coefficient test as variables relate to the total number of household adaptation actions implemented.

Variable	**Spearman's Rho**	**P-Value and Significance**
Total valuation of ecosystem services	0.2855002	0.01506*
Valuation of provisioning ecosystem services	0.2531034	0.03194*
Valuation of regulating ecosystem services	0.2991197	0.0107*

Table 4. Results of Welch's *t*-tests on the 3 climate characteristics.

Weather Observation	**Variables**	**T-Value**	**P-Value and Significance**
Temperature	Akureyri 1950-1984 and 1985-2020	-2.098	0.0362*
Wind speed	Akureyri 1950-1984 and 1985-2020	3.0627	0.002264**
	Grímsey 1955-1977 and 1978-1999	-6.9845	9.077e-12***
	Saudanesviti 1990-2009 and 2010-2020	-5.1471	5.202e-07***
Cloud cover	Grímsey 1955-1977 and 1978-1999	4.0924	4.954e-05***

Table 5. Total count and percent of each type of adaptation action that was implemented in the Eyjafjörður study.

Variable	**Total Count**	**Percent**
Total adaptation actions implemented	209	100
Structural safety improvements	23	11.0
Financial safety improvements	43	20.6
Livelihood changes	17	8.1
Emergency preparation	8	3.8
Practicing energy efficiency	20	9.6
Changing consumer practices	63	30.1
Educational opportunities	35	16.7

Table 6. Results of the ridge regression analysis on the independent social-ecological system variables, showing those significantly related to the breadth of participants' adaptation portfolios.

Independent Variables	**Slope Estimate and Significance**
Concern for current changes at the national level	-0.49**
Concern for future changes at the regional level	0.63**
Concern for future change at the global level	-0.65*
Lived experience of ecosystem change	-0.34*
Historical knowledge of ecosystem change	0.42**
Sense of place attachment at the municipal level	-0.44**
Sense of place identity at the local level	0.40*
Valuation of cultural ecosystem services	-0.39*
Valuation of provisioning ecosystem services	0.36**
Preference for mitigation as risk reduction	-0.39**

Table 7. Results of a series of linear regressions conducted to explore the correlations within and between variables representing social-ecological processes.

Variables Tested	**Slope Estimate**	**P-Value**	**Significance**
SOPL~SOPM	0.82442	<2.2e-16	***
SOPLA~SOPMA	0.70796	6.76e-16	***
SOPLD~SOPMD	0.89366	<2e-16	***
SOPLI~SOPMI	0.75813	4.05e-16	***
SOPLA~SOPLD	0.75025	1.22e-14	***
SOPLA~SOPLI	0.80275	8.79e-12	***
SOPLD~SOPLI	0.7486	1.63e-09	***
SOPMA~SOPMD	0.83073	2.9e-13	***
SOPMA~SOPMI	0.7771	2.26e-09	***
SOPMD~SOPMI	0.81093	6.01e-14	***
SOPCOMB~ESCOMB	0.9696	1.51e-11	***
SOPL~ESCOMB	0.97317	5.05e-13	***
SOPL~ESC	-1.5822	1.01e-11	***
SOPL~ESP	0.4784	3.03e-05	***
SOPL~ESR	0.77047	5.96e-11	***
SOPM~ESCOMB	0.92379	2.49e-10	***
SOPM~ESC	0.8052	4.77e-09	***
SOPM~ESP	0.4877	4.67e-05	***
SOPM~ESR	0.7014	6.171	***
SOPCOMB~RRPRE	-0.02375	0.0698	.
SOPM~RRPRE	-0.02975	0.0218	*
SOPMA~RRPRE	-0.03346	0.0366	*
SOPMD~RRPRE	-0.03015	0.0341	*
ESC~ESP	0.36388	0.000117	***
ESC~ESR	0.59259	1.54e-09	***
ESP~ESR	0.6353	3.07e-07	***
RRMIT~RRPRE	-0.4404	0.0191	**
RRMIT~RREVL	-0.9343	3.71e-09	***
RRMIT~RRAPD	-0.8522	1.63e-07	***
RRPRE~RREVL	-0.2037	0.0699	.
RRPRE~RRADP	-0.2862	0.0101	*

Chapter 5

Summary of Problem Statement and Research Objective

In review, this dissertation research was guided by 3 research questions. **Research Question 1** sought to understand what social-ecological processes were most supportive to households' ability to implement greater numbers of adaptive actions within the context of rapid environmental change and what variables could reliably measure these processes. **Research Question 2** sought to understand to what extent the valuation of ecosystem services and sense of place played a role in supporting adaptive behavior and any associations within or between these variables. **Research Question 3** explored how human-environment relationships within a social-ecological system could be modeled spatially, using adaptation to climate change as an example.

There is a globally recognized need to reduce the risks posed by climate change and variability impacts through adaptation policies and strategies that are informed by research (Smith & Lenhart, 1996; UNFCCC, 1992; IPCC, 1996). Sustained climate impacts continue to affect people and places worldwide (Stocks, et al., 1998), spurring research on both social and ecological adaptation practices (Chatzidaki & Ventura, 2010; Sheremata, Tsuji, & Gough, 2016). However, there remain relatively few guides or methods for developing adaptation plans (Schröter, Polsky, & Patt, 2005; Preston, Westaway, & Yuen, 2011) or for assessing the presence of existing capacities that support adaptation (Ford, Labbé, Flynn, & Araos, 2017). While the effects of climate change are global in reach, the Arctic is experiencing these effects at a rate of change roughly double that of the global average (Serreze, Barrett, Stroeve, Kindig, & Holland, 2009; Larsen, et al., 2014; ACIA, 2005).

Since 1990, temperatures in the Arctic have warmed by approximately 2°C versus the global mean of 1 degree (Jefferies, Overland, & Perovich, 2013). The effects of this warming are expansive. By the year 2100, much of the Arctic tundra may be replaced by new dominant ecosystems (Myers-Smith, et al., 2011). The first evidence of this is seen in observed changes to species migrations, habitats, diet, and health (Keskitalo & Kuulyasova, 2009; Fawcett, Pearce, Ford, & Archer, 2017), including the appearance of new species (Trainor, Chapin, Huntington, Natcher, & Kofinas, 2007; West & Hovelsrud, 2010).

Additional early evidence of Arctic climate change impacts includes the degradation of Arctic ice, changes in weather patterns, and changes in permafrost with associated hydrogeological risks. Indeed, there is a sustained reduction in terrestrial- and marine-based ice, including ice depth, extent, duration, and quality (Fang, Freeman, Field, & Mach, 2018), throughout the Arctic. Concurrently, weather patterns are becoming less predictable (Pennesi, 2012), and extreme weather events are increasing (Labbé, Ford, Araos, & Flynn, 2017). Ultimately, the need remains for research to better understand local perceptions and mechanisms that enable social-ecological systems to adapt to these impacts of climate change (Cameron E. S., 2012). This understanding is also needed to produce generalizable adaptation knowledges and strategies (Keskitalo & Kuulyasova, 2009; Huntington, Quakenbush, & Nelson, 2017).

Following the above, this dissertation research responded to the need for the development of methods to aid in identifying adaptation interventions that co-benefit social and ecological systems. To achieve this objective, I developed a spatial social-ecological framework for the analysis of climate change adaptation in the Arctic. To construct the framework, I drew from best practices in social-ecological system modeling (Folke, 2006; Thiel, Adamseged, & Baake, 2015) and from studies that applied the SESF (Ostrom E. , 2007; Loring, Chapin, & Gerlach, 2008; McGinnis & Ostrom, 2014) to analyze social-ecological system interactions and outcomes, particularly those that related to adaptation in the Arctic, as presented in Chapter 3. The framework was then applied to the social-ecological system of North Central Iceland.

The implementation of the SESF enabled 3 major sets of findings. First, the results of the application of the social-ecological framework in North Central Iceland revealed that over 200 adaptations were implemented by the 70 households included in this dissertation research. Of these adaptations, over 30 percent focused on making changes to household consumer practices, and over 20 percent focused on changing household financial practices. For example, participants noted reusing and recycling items more often, more effectively preventing and reducing household food waste, and purchasing or upgrading household insurance, as discussed in Chapter 4. Securing peoples' household safety in the face of changing climate risk is among their top priorities.

Second, analysis of *in situ* observational weather datasets confirmed a sustained change in the characteristics of the local climate. Namely, the average annual temperature has increased in Akureyri and Saudanesviti and decreased slightly in Grímsey. Furthermore, downscaled climate reanalysis data corroborates sustained warming in Iceland, and particularly in the Eyjafjörður study area. When corroborated with additional narrative information provided by participants, these results showed that social-ecological memory might play a key role in understanding the local observations of climate change. For example, increasingly harsher winters and warmer summers were noted by participants and may coincide with this sustained warming of temperatures. Thus, lived experience and historical knowledge acted to situate changes in weather in the context of the local social-ecological system.

<u>Third</u>, the results of the ridge regression analysis, presented in Chapter 4, revealed that the social-ecological system variables most supportive to households implementing greater numbers of adaptation actions were (1) feeling concern for future local impacts of climate change, (2) having historical knowledge of ecosystem change, (3) having a strong local sense of place identity, and (4) valuing provisioning ecosystem services. Collectively, these variables play a significant positive role in facilitating the implementation of household adaptation actions (**Research Question 1**). In the context of North Central Iceland, adaptation may be most effective if it addresses participants' feelings of concern for the future of their local area and its place identity, including how adaptations are situated in local ecological histories and how they promote the continuation of provisioning ecosystem services. In other words, the scale of concern about impending climate change impacts is local and tied to peoples' affinity for the place in which they live. These conclusions imply that perception of potential future change and focus on a local scale are important elements in adaptation and must be engaged with care.

Following the above, no statistically significant associations were found between participants' adaptation level and any single independent social-ecological variable. However, associations were found within and between the variables that constitute sense of place and ecosystem services indicators (**Research Question 2**). Collectively, the indicators of ecosystem services were a powerful predictor of sense of place, exhibiting a near 1:1 relationship. There were also significant positive associations within indicators. Namely, between the valuation of cultural, provisioning, and regulating ecosystem services, between factors of sense of place, and between participants' preferences for risk reduction efforts. From this, I conclude that multiple social-ecological processes may be working in concert to support households' adaptation.

Therefore, there is merit in further exploring the links between ecosystem services and sense of place. These results also suggest that the social-ecological variables used in this dissertation research can be reduced if these significant associations hold after application in other social-ecological systems.

Finally, this dissertation research contributed to the development of spatial methods for identifying pathways for climate change adaptation. Namely, participatory mapping served as a method to model the human-environment relationships within the social-ecological system, which led to the identification of areas perceived to be most valued and most at-risk to the impacts of climate change (**Research Question 3**). Akureyri and Hrísey were the only 2 hot spot locations featured prominently in participatory maps of areas that would benefit from natural conservation *and* risk reduction efforts. Only by using participatory mapping was this additional spatial component of the analysis revealed. Namely, in North Central Iceland's social-ecological system, Akureyri and Hrísey may be ideal locations to begin climate change adaptation efforts due to their perceived social-ecological value and hazard risk.

Contribution to the Literature on Climate Change Adaptation

In sum, this dissertation research contributed to the development of a social-ecological systems approach to analyze climate change adaptation. This included the identification of social-ecological processes that potentially will enable adaptation. Thus, these methods may be further developed and ultimately used to identify adaptation typologies in other social-ecological systems throughout the Arctic (Eisenack, Lüdeke, & Kropp, Construction of archetypes as a formal method to analyze social-ecological systems, 2006).

The results of the application of the framework also reinforced the idea that progress toward adaptations informed by cultural and place-based knowledge can be aided by engaging with communities (Tyler, et al., 2007). Namely, the framework enabled the representation of the cultural aspects of adaptation that shape how risk is interpreted and acted upon. Thus, the framework developed and applied in this dissertation presents as a productive method for studying climate in connection with other social, cultural, and political conditions of communities (Nuttall, 2017; Ford, Smit, & Wandel, 2006; Bennett, Blythe, Tyler, & Ban, 2016).

Study Limitations

The application of the social-ecological systems framework proved fruitful for analyzing climate change adaptation. However, there were limitations in the development and application of the framework. First, while the study sample size allowed for confidence that the sample accurately reflected the population, garnering a larger sample size in future applications of the framework will result in a higher level of confidence. Travel bans due to the ongoing COVID-19 pandemic resulted in unforeseen mobility and time constraints that impacted the design and implementation of the research, which may have inhibited participant involvement.

Second, since this dissertation research focused primarily on system actors and social-ecological processes related to adaptation outcomes, the governance system and resource units of the SESF were not represented in the development of the framework. Indeed, the only governance variable included, home ownership, was not significant to the number of adaptation actions that a household implemented. Despite this, homeownership is considered a variable of the SESF governance system because it can shape participants' land use (Sharma, et al., 2016). Thus, the governance system should be further incorporated in the next phase of the framework's development. This may enable, for example, an examination of the role of existing land use policy practices on adaptation, such as those imposed through land use plans, building codes, and industry and commercial regulations.

Third, the model developed in this dissertation research is complex and flexible, making it ideal for studying human-environment relationships and making it difficult to explain, justify, and implement. This complexity can inhibit the use of the framework by broader audiences and calls for further methodological development, such as to make the model more efficient to use and easier to understand and apply.

Finally, the results presented in Chapter 4 showed that the independent social-ecological system variables account for approximately 30 percent of the variability of how many adaptation actions a household implemented. While the model accounts for a limited amount of variability, it can be improved to account for a more considerable amount of the variability in the dependent variable, that is, how many adaptation actions a household implements. For example, further development and testing of the model can reduce the number of variables to reflect only the most influential ones, and additional variables can be added and tested. This may allow for the independent variables in the model to account for a larger amount of the variability in the dependent variable.

Next Steps and Future Research

There are many potential opportunities to advance the research presented in this dissertation. A few such opportunities are offered here. First, further collaboration with participants is required to support (or invalidate) current results and direct future research attention in North Central Iceland. Many participants expressed an interest in participating in future research efforts. These participants will be contacted and included in future research development. Indeed, in the survey, many participants presented solutions to local problems that should be supported by examining their potential viability. Further, to advance collaboration, future research efforts should explicitly engage with youth and the elderly. As noted in Chapter 2, these demographic groups are often overlooked in research efforts on climate change adaptation (MacDonald, et al., 2015).

It is also worth noting that Iceland's population and the study area in North Iceland are largely homogenous. The literature shows that adaptation and other activities for managing common-pool resources or collective problems may be easier to implement and reach consensus on within a homogenous population (Pelling, O'Brien, & Matyas, 2015). This again brings into focus the role of agency within social-ecological systems, as the majority may override some participants' opinions. This homogeneity may be due, in part, to outreach methods that were not effective at reaching and retaining rural or seasonal households. Nevertheless, we know that much of the transformational adaptation often comes from the margins of societal norms and expectations (Pelling M. , 2011). Thus, future studies need to consider how results vary between sites with largely homogenous and largely heterogenous populations.

Second, future analyses should explore how the model's independent variables relate to adaptation outcomes that did *not* result in the household implementation of adaptation actions. I used Spearman's correlation coefficient to garner the fruitfulness of such an exercise to test the relationship between adaptations not considered and not implemented with the social-ecological system's independent variables. Initial results are promising and warrant further investigation, as shown in Table 8. For example, the implementation of adaptation actions was considered less of a concern as participants' concern about the future impacts of climate change decreased. Future analyses on the survey dataset should also include a cluster analysis to identify social-ecological characteristics beyond that revealed by the analyses conducted for this dissertation research. The results of a cluster analysis may reveal subsets of system configurations that lead to differing adaptation outcomes.

Third, this dissertation research's changes in climate observations were corroborated with downscaled climate reanalysis data under different RCPs. However, additional climate change analysis must be conducted to supplement and corroborate the social-ecological system framework developed and applied in this dissertation research. For example, a deeper analysis of changes to Arctic ice is warranted, including by use of satellite imagery to determine changes in the extent and depth of permafrost and glaciers.

Fourth, future research should examine how sense of place, particularly place attachments, may transfer across regions. Scalar differences in responses to questions about the current and future impacts of climate change indicate that there may be a bifurcation or other change between the local and global scales. Additional research is also needed to examine the low amount of emergency preparation conducted by households and how risk is accounted for in adaptation, such as through minimizing or transferring risk. For example, participants noted the securities provided by their insurance as an adaptation, which has implications for the role of insurance in managing climate change risks.

In summary, this dissertation research made steps toward advancing methods for identifying climate change adaptation pathways. Sustained efforts are necessary. The 4 areas of focus presented above offer promising pathways for continued development of the social-ecological systems framework presented in this dissertation for analyzing climate change adaptation. Indeed, the need for adaptation is globally recognized (UNFCCC, 1992; ACIA, 2005; IPCC, 1996), yet the methods and guides for conducting or analyzing adaptation remain in their infancy (Ford, Labbé, Flynn, & Araos, 2017).

Table 8. This table presents the results of Spearman's correlation coefficient as variables related to participants' adaptations not implemented and not considered.

Variable	**Spearman's Rho**	**P-Value**	**Significance of Correlation**
Total concern about current changes	-0.2491575	0.03481	**
Concern about current changes at the municipal level	-0.2503862	0.03389	**
Total concern about future changes	-0.2441123	0.03878	**
Concern about future changes at the household level	-0.232639	0.04924	**
Concern about future changes at the municipal level	-0.2768495	0.01856	**
Concern about future changes at the regional level	-0.2795203	0.01741	**
Age	0.2350595	0.04686	**

Appendix A:

Systematic Literature Review Protocols and Methods

The review presented in Section 2 centers on the following research questions:

1. What is the working definition of adaptation in the context of Arctic climate change?
2. Who is adapting what, and are there common social-ecological changes necessitating climate change adaptation?
3. Where is research needed?

These research questions relate to the goals of this dissertation research by identifying common social-ecological indicators of change that necessitate adaptation in the Arctic.

First, a search string was developed to identify peer-reviewed case studies of climate change adaptation in the Arctic of relevance to the research questions ("adaptation" AND "climate change" AND ("Arctic" or "arctic" or “Alaska” or “Canada” or “Finland” or “Iceland” or “Norway” or “Sweden” or “Russia” or “Siberia”)). The search string was applied to titles and abstracts and expanded to full texts when possible. Temporally, the search was constrained to articles published over the last thirty years (01/01/1990-01/01/2021) to reflect current adaptation responses to climate change, and because studies on climate change adaptation grew tremendously over this time period (Larsen, et al., 2014; Carson & Peterson, 2016), calling for a focused review effort. Indeed, over the last thirty years, the Arctic warmed by over .05^{o}C per decade (Jeffries, Richter-Menge, & Overland, 2012) and is amplifying (IPCC, Climate Change 2013: The Physical Science Basis, 2014), thus increasing the need for adaptation.

These search constraints were applied to 7 databases and Google Scholar to find articles relevant to the research objectives. Databases were accessed through the Penn State University library system, one of North America’s most extensive library collections (Morris & Roebuck, 2019). 7 databases were selected because, collectively, they encompass a wide range of social and environmental sciences. The databases are as follows:

- Academic Search Complete
- Directory of Open Access Journals
- ScienceDirect
- Taylor & Francis Journals
- Wildlife & Ecology Studies Worldwide
- Wiley Online Library
- Web of Science

The same constraints were applied to Google Scholar to find relevant literature that may be located outside of these databases, such as peer-reviewed ‘grey literature’. After this initial search, the relevancy and quality of the articles found were determined using a set of exclusion criteria. These exclusion criteria were developed following best practices and in support of the research objectives. Namely, articles were excluded if they were published before 1990, if they were not a peer-reviewed journal article, if they were not written in or translated to English, if they were irrelevant to the study area or did not define a geography, and if they did not discuss outcomes of relevance to climate change adaptation. Future studies should be conducted with more time, funding, and personnel to include articles written in languages other than English to draw a more inclusive representation of adaptation.

All duplicates were removed following the search and exclusion processes, and the full-text PDF versions of articles were downloaded[17], stored, and organized. The data collection process took place from December 2019-February 2020 and again from February-April 2021 to catch the remaining articles published since the last collection process. The analysis took place from March-May 2021.

Ultimately, following the methods above, 56 articles were chosen for inclusion out of 351 articles found. In support of answering the research questions put forth, a bibliometric analysis was conducted by recording objective article information in a database using Microsoft Excel, including the following information:

- Abstract and article title,
- First author name and country of institutional affiliation,
- Journal and year of publication,

A codebook was created to guide the secondary, more subjective data collection process around specific themes (Franzosi, 2008) to classify and analyze information drawn from diverse case studies systematically. Articles were reviewed one at a time in alphabetical order by the first author's last name. After an initial assessment was complete, articles underwent a second review, and data were updated and iteratively compared across studies for evaluation consistency (Srivastava & Hopwood, 2009). Articles were reviewed, and data collection was conducted until a saturation point in themes was reached, wherein no new information is gleaned by additional data collection (Crabtree & William, 1999; Baxter & Eyles, 1997). Following this systematic review process allowed information presented in case-level studies to produce more generalizable knowledge claims, such as the archetype approach seeks to do (Eisenack, Lüdeke, & Kropp, 2006).

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[17] Some articles were only accessible through inter-library loan services, which speaks to the broader need for research to be more accessible beyond academia.

Appendix B:

Survey Questions

1. How long have you resided in the Eyjafjörður area?
   - ○ Less than 1 year
   - ○ 1 to 4 years
   - ○ 5 to 9 years
   - ○ 10 to 14 years
   - ○ 15 to 19 years
   - ○ 20 or more years

2. What municipality do you reside in? (Note: If you reside in more than one municipality, please choose the one you spend the most time in.)
   - ○ Akureyrarkaupstadur
   - ○ Dalvíkurbyggð
   - ○ Eyjafjarðarsveit
   - ○ Fjallabyggð
   - ○ Grýtubakkahreppur
   - ○ Hörgársveit
   - ○ Svalbarðsstrandarhreppur

3. How much time of the year do you typically reside here?
   - ○ All year (12 months)
   - ○ Most of the year (7-11 months)
   - ○ About half of the year (6 months)
   - ○ Less than half of the year (1-5 months)
   - ○ Almost none (1 month or less)

4. This question asks about your level of agreement with statements about where you live and about the greater Eyjafjörður area. Please rate your level of agreement with the following statements. [2 questions are displayed]

	Strongly disagree	Disagree	Somewhat disagree	Somewhat agree	Agree	Strongly agree
This place is a reflection of me; I strongly identify with this place.	○	○	○	○	○	○

	Strongly disagree	Disagree	Somewhat disagree	Somewhat agree	Agree	Strongly agree
I feel I can be myself when I am here.	○	○	○	○	○	○
This is the best place for doing what I like to do.	○	○	○	○	○	○
I feel happiest when I am here.	○	○	○	○	○	○
I get more satisfaction out of being here than I do from being in any other place.	○	○	○	○	○	○
I miss being here when I am away for too long.	○	○	○	○	○	○

5. This question is about ecosystem services. Ecosystem services are the benefits nature provides to society. Please rate your agreement with the following statements about the greater Eyjafjörður area.

	Strongly disagree	Disagree	Somewhat disagree	Somewhat agree	Agree	Strongly agree
This region has a rich cultural history, aesthetic beauty, or spiritual meaning (such as historical sites, burial grounds, ruins; locations connected to mythology; historical accounts of people, events).	○	○	○	○	○	○
This region is known for producing raw materials and products (such as freshwater; food from gardens, farmland, cropland; timber; gravel, minerals, metals).	○	○	○	○	○	○

	Strongly disagree	Disagree	Somewhat disagree	Somewhat agree	Agree	Strongly agree
This region has clean air, water, and soil.	○	○	○	○	○	○
This region has habitats for plants and animals (such as protected land areas; diverse terrestrial/marine species; migration corridors).	○	○	○	○	○	○
This region has outdoor education and recreation (such as picnicking, hiking, bird-watching, skiing; school trips; educational signs or tours).	○	○	○	○	○	○
This region has sources of energy (such as geothermal, hydroelectric, wind).	○	○	○	○	○	○

6. Have you or another member of your household experienced or witnessed any of the following changes or learned about historical occurrences of changes in the greater Eyjafjörður area? If so, which ones? Check all that apply.

☐ Loss or degradation of glaciers or permafrost; more frequent or intense avalanche events or mud/debris/rockslides

☐ More frequent or intense storm events (such as rain, snow, ice); warmer temperatures or less extreme cold temperatures

☐ More frequent or intense flood events

☐ New or more plentiful species (such as plants, insects, birds); decline in abundance, range, or the health of native wildlife

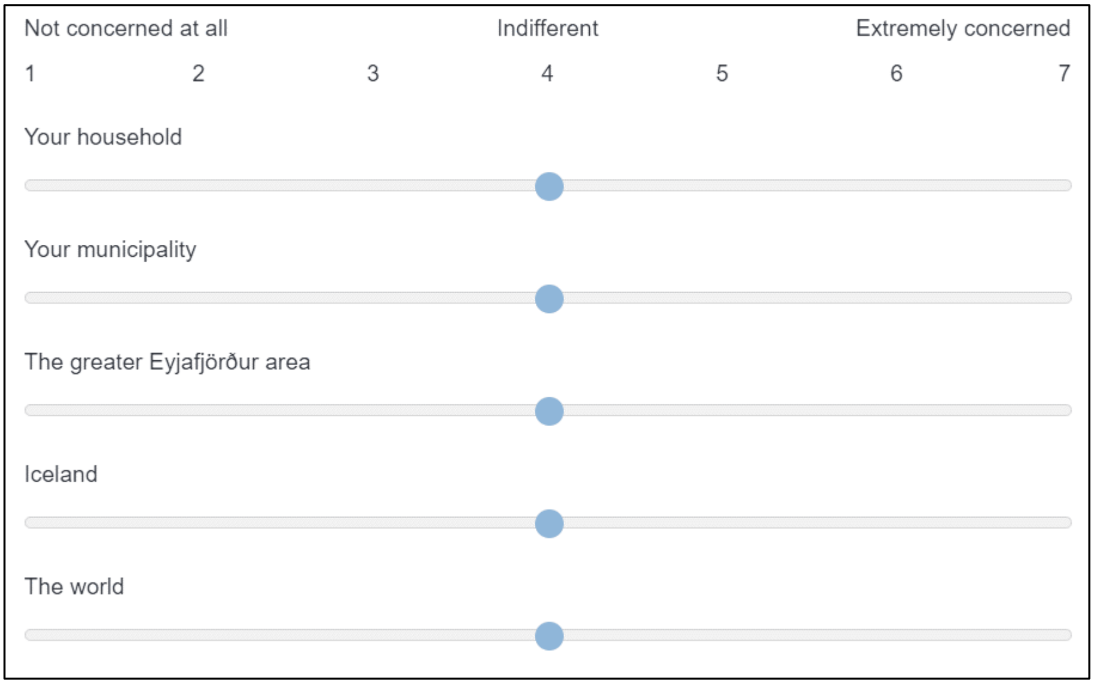
☐ Other ☐

7. In the greater Eyjafjörður area, what level of attention should be given to the following types of risk reduction activities? For each type of activity (for each row), enter a number between 0-100. The higher the number you assign, the higher the importance of that type of activity. The sum of the rows must total 100 and is automatically calculated.

Mitigating or preventing hazard risks
Planning and preparing for hazard risks
Monitoring and evaluating hazard risks
Responding and adapting to hazard risks

Total

8. This question asks about your level of concern regarding current and future impacts of environmental change and hazard risks. In addition, this question asks about your level of concern for your household, your municipality, the greater Eyjafjörður area, Iceland, and the world. Please click the slider bar in each row to verify your choice. How concerned are you about current and future impacts of environmental change and hazard risks?



Not concerned at all
Indifferent
Extremely concerned

1 2 3 4 5 6 7

Your household

Your municipality

The greater Eyjafjörður area

Iceland

The world

9. To ensure their health and safety, households worldwide are taking action by preparing for and responding to local environmental changes and hazards (such as extreme weather events). Which of the following actions, if any, has your household considered or implemented? Check all that apply.

	Considered, but not implemented	Implemented
Structural safety improvements (such as installing a new roof; weather-proofing windows and doors)	○	○

	Considered, but not implemented	Implemented
Financial safety improvements (such as purchasing insurance)	○	○
Livelihood changes (such as seeking new income sources; changing investments)	○	○
Emergency preparation (such as making an emergency plan or go-bag; buying a generator)	○	○
Practicing energy efficiency (such as carpooling; reducing home energy use)	○	○
Changing consumer practices (such as reducing food waste; shopping less; recycling, or upcycling)	○	○
Educational opportunities (such as knowledge sharing; visiting a museum; attending a class)	○	○

10. What type of structure does your household currently reside in?
    - ○ Owned single-family or multi-family home (such as a condo, duplex, townhouse)
    - ○ Rented single-family or multi-family home (such as an apartment unit)

11. What is the highest level of education completed within your household?
    - ○ Compulsory (primary and lower secondary) education
    - ○ Upper secondary education
    - ○ Technical degree or certificate
    - ○ Higher education degree (Bachelor’s, Master's, etc.)

12. What is your household's average monthly income before taxes? (i.e., combine monthly earnings of each working household member then divide the total by number of working household members)
    - ○ Less than 200.000 ISK
    - ○ 200.000 - 299.999 ISK
    - ○ 300.000 - 399.999 ISK
    - ○ 400.000 - 499.999 ISK
    - ○ 500.000 - 599.999 ISK
    - ○ 600.000 - 699.999 ISK

○ 700.000 - 799.999 ISK
○ 800.000 - 899.999 ISK
○ 900.000 - 999.999 ISK
○ 1.000.000 - 1499.999 ISK
○ More than 1.500.000 ISK

What gender do you most identify with?

○ Male
○ Female
○ Transgender
○ Genderqueer or genderfluid
○ Other ☐

What age range do you fall in?

○ 18-24
○ 25-29
○ 30-34
○ 35-39
○ 40-44
○ 45-49
○ 50-54
○ 55-59
○ 60-64
○ 65-69
○ 70-74
○ 75+

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