Resilience and Adaptation to Climate Change Among Organic Farmers in the United States:
A Mixed Methods Investigation

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Abstract

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Farmers around the world are adapting to less predictable seasons and more frequent extreme weather events. This challenge is no less for organic farmers, who contribute to social well-being and ecological regeneration through their food production practices. This thesis employs a mixed-methods approach to explore resilience and perceived adaptive capacity to climate change among organic farmers in western Washington and the United States, more broadly. Chapter 2 uses qualitative methods to explore the relationship between climate resilience and crop diversity among organic vegetable farmers in western Washington. Findings contribute to academic debates around diversity and climate resilience by offering (i) a grounded perspective of how diversity confers socio-ecological resilience by those who enact it; (ii) an explanation for how climate interacts with social contexts to shape diversity; and (iii) an analysis of the limits of diversification and benefits of specialization to confer resilience. Chapter 3 uses Bayesian structural equation modeling to assess the relationship between land access and perceived adaptive capacity to climate change among certified organic farmers in the United States. Beyond the specific associations reported, the Chapter signals how Bayesian approaches can integrate qualitative and quantitative analyses, while accounting for uncertainty inherent in complex socio-ecological systems.

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Introduction

Background and context

As people who earn their livelihoods from the land, farmers and farmworkers are among the most impacted by climate change. Across the globe, climate-related hazards such as droughts, flooding, wildfires and heat are becoming more frequent, alongside increasingly variable and unpredictable weather patterns (Bezner-Kerr et al., 2022). In the United States, climate change is disrupting agriculture through more frequent and extreme heat and precipitation events, drought, and less predictable seasonality (Bolster et al., 2023). These physical effects of climate change interact with the social and ecological dimensions of agricultural systems in complex ways. The ability of farmers to adapt to weather extremes and unpredictability is critical. Understanding the factors that influence resilience and adaptation can inform agricultural and broader livelihood practices under an increasingly variable climatic context.

Chapter 2 uses approaches from resilience to explore how organic vegetable farmers may use crop diversification to cope with the impacts of climate change. A socio-ecological systems (SES) approach understands a resilient system as one that can absorb disturbance, reorganize itself, and learn and adapt to dynamic conditions (Folke, 2006; Walker et al., 2004). Generally, agroecosystems with more ecological complexity are understood as better able to adapt to changing conditions (Lin, 2011), and reductions in complexity or variation can increase vulnerability (Berkes et al., 2002). Despite diversification's connection with resilience and its prevalence in organic agriculture, little attention has been paid to the relationship between organic agriculture, crop diversity, and resilience. Chapter 2 explores the relationship between climate resilience and crop diversification among organic vegetable farmers in the western Washington, U.S.A.

Informed by the Sustainable Livelihoods Approach (SLA), Chapter 3 uses a Bayesian structural equation modeling approach to assess the relationship between a farmer's access to land and perceived capacity to adapt to climate change. The SLA offers a well-established and empirically-grounded framework to understand how and why farmers may be differentially vulnerable to climate change. A sustainable livelihood is defined as one that can cope with gradual and sudden disruptions, maintain capabilities and assets, and provide opportunities for future generations (Chambers & Conway, 1992). As such, a farmer is considered vulnerable when they are unable to mobilize their assets to adapt to changing conditions (Knutsson & Ostwald, 2023), such as climate change. While past studies have measured adaptive capacity to climate change as a reflection of the resources one can access, recent research has emphasized the importance of cognition (Grothmann & Patt, 2005; Mortreux & Barnett, 2017). One's self-assessment of the ability to act in response to threats—their 'perceived adaptive capacity'—can influence their propensity to take adaptive action, regardless of the actual resources available to them. Chapter 3 explores perceived adaptive capacity to climate change and its relationship with land access among organic farmers in the United States.

This thesis takes organic farmers in the United States as its empirical context for exploring resilience and adaptation to climate change. Organic agriculture is a rapidly growing sector in the United States, having doubled in acreage since the turn of the 21^{st} century – despite constituting a small percentage of total cropland (Raszap Skorbiansky et al., 2023). Because organic agriculture provides numerous environmental and social benefits, including biodiversity conservation, increased soil quality, and healthy and resilient rural livelihoods (Seufert & Ramankutty, 2017), it is important to understand organic agriculture's resilience and adaptability to a changing climate. Relatedly, many studies assessing agricultural resilience, vulnerability, and adaptability to climate change are situated in the Global South—and further empirical research to assess the theories and claims of current literature can benefit from broader geographical and empirical content.

Aims

This thesis aims to:

1) Explore the dynamic relationship between crop diversity and climate resilience among organic farms in western Washington;
2) Investigate the role of land access on perceived adaptive capacity to climate change among organic farmers in the United States; and
3) Exemplify the value of using Bayesian modeling approaches for mixed-methods research on climate resilience and adaptation.

Methods

This thesis takes a mixed-methods approach to achieving its research objectives. It uses qualitative methods through semi-interviews with vegetable farmers using organic practices in western Washington, and quantitative methods through building a Bayesian structural equation model for perceived adaptive capacity among organic farmers in the United States. Qualitative findings from Chapter 2 informed model variables, structure, and priors of Chapter 3.

To collect data for Chapter 2, the author conducted and analyzed semi-structured interviews with twenty-eight vegetable farmers using organic practices in western Washington. Eligible farmers made decisions about seed selection on their farms, including vegetable in their cropping systems, and self-identified as using organic practices. Participants were asked a range of questions about how they make decisions around seed and crop selection, how they are impacted by and adapt to climate change, and how they think about crop planning in the context of climate change. Farmers were offered complimentary soil testing as compensation for participation. Interviews were auto-transcribed using a combination of NVivo and Trint softwares and subsequently corrected line-by-line for accuracy. They were then thematically analyzed using NVivo software using an inductive, structural coding method (Saldaña, 2009).

For Chapter 3, a Bayesian structural equation model was built to estimate perceived adaptive capacity among U.S. organic farmers, using a combination of secondary survey data and climatic data. One thousand fifty-nine (n = 1059) certified organic farmers in the United States were surveyed in 2019 and 2020 about their farm products and practices, production challenges, non-production challenges, market channels and more. The survey data was collected for the National Organic Research Agenda report by the Organic Farming Research Foundation in tandem with the Organic Seed Alliance. Climatic data from ERA 5 – Land (Muñoz-Sabater et al., 2021) were processed to create metrics for temperature variability, precipitation variability, and extreme heat, while moderate and severe drought data were provided by the U.S. Drought Monitor (Svoboda et al., 2002). Survey results were joined with data representing climate extremes and variability at the zip code level. Multiple imputation was used to fill in missing survey data for explanatory variables the 'mice' package in R (v3.13.0; van Buuren & Groothuis-Oudshoorn, 2011), while mean-based imputation was used for climate variables. A Bayesian structural equation modeling approach was used to estimate perceived adaptive capacity—represented by a question in the survey asking farmers to rate their challenges adapting to climate change. Based on previous research and the author's data from Chapter 2, explanatory variables were selected representing land access, market strategy, financial capital, and climate exposure. A Bayesian approach was used because it allows the integration of qualitative findings into the model through the use of priors and can reflect uncertainty inherent in complex socio-ecological systems. A structural equation model was created to estimate direct effects of variables representing natural capital, financial capital and climate exposure on perceived adaptive capacity, as well as indirect effects through the construction of a latent variable representing land access and future land needs. Models that only estimated direct effects, and those that estimated both direct and indirect effects with different priors for the land access latent variable were assessed. Comparing fitness among models with different priors allowed an assessment of how well the prior beliefs fit the data.

Chapter 2 was approved by the University of Washington's Institutional Review Board (IRB) as an Exempt Determination (STUDY#00020369). The University of Washington Human Subjects Division determined that the methods involved in Chapter 3 did not involve human subjects and did not require approval from the IRB (STUDY#00020424).

Significance and Contributions

Understanding how crop diversity matters to the people who are enacting it is important for efforts that aim to increase agricultural resilience. Thus, Chapter 2 contributes to academic debates around the role of crop diversity in socio-ecological resilience to climate stressors. It offers a grounded perspective on the role of diversity in resilience: the Chapter presents farmers' narrations of how diversity in *which* seeds they plant and *when* they plant them contributes to the ecological notions of response and functional diversity. Chapter 2 further offers a nuanced vision of diversification which is not at odds with specialization, but rather complementary in achieving farmers' market strategies while maintaining climate resilience. Finally, the Chapter offers a refined understanding of climate adaptation, suggesting a framework for climate change interacts with other social, economic, and ecological factors to shape seed selection.

Chapter 3 contributes a conceptual understanding of the factors influencing perceived adaptive capacity, as well as methodological contributions about the value of Bayesian modeling for mixed-methods investigations. In order to support farmers in coping with climate change, it is critical to understand the factors that influence their perceived capacity to adapt. Thus, Chapter 3 offers a unique assessment of perceived adaptive capacity to climate change among U.S.

organic farmers at the national, population scale—a first of its kind, to the author's best knowledge. Chapter 3 finds that at the population level, land access is only weakly associated with perceived adaptive capacity, while financial capital factors and climate exposure variables like precipitation variability and extreme heat have more moderate associations with less accompanying uncertainty. Furthermore, the Chapter provides a methodological contribution of the value of Bayesian approaches for incorporating local, qualitative findings into population-scale, quantitative models that reflect uncertainty inherent in attempts to measure dynamics of complex systems.

Chapter 2: Resilience in Diversity—Seed Selection and Climate Adaptation Among Organic Farmers in Western Washington

Abstract

Farmers around the world are adapting to less predictable seasons and more frequent extreme weather events. Socio-ecological systems (SES) approaches posit that "diversity" serves resilience in so far as it enables agricultural systems to withstand disturbance and maintain critical functions. Crop diversification is one such adaptation strategy that can strengthen on-farm resilience to climate change and variability. This study contextualizes and grounds SES resilience theory by exploring how crop diversity is shaped and how it contributes to practices of climate resilience among organic vegetable farmers in western Washington, U.S.A. Twenty-eight vegetable farmers using organic practices were interviewed about their seed decision-making practices and their experience with, and adaptation to, weather and climate-related extremes and unpredictability. Findings indicate that market strategies and farmer preferences affect crop and seed selection, within the broader social and environmental contexts of their farm. Through continued adaptive management, farmers devise strategies of "specialized diversification", specializing in particular crops to satisfy market niches while maintaining broad levels of diversity that contributes to practices of resilience. Such resilience practices include learning through experimentation and maintaining high levels of flexibility, culminating in an adaptive management approach. These findings contribute to academic debates around diversity and climate resilience by offering (i) a grounded perspective of how diversity contributes to resilience practices, ii) an analysis of the limits of diversification and benefits of specialization, and iii) an explanation for how climate interacts with social contexts to shape diversity.

Introduction

Climate change poses a major threat to farms and food systems worldwide, disrupting agriculture in the United States through more frequent and extreme heat and precipitation events, drought, and less predictable seasonality (Bolster et al., 2023). These climate risks have complex effects on agricultural livelihoods and production systems, including in the Pacific Northwest region of North America (Chang et al., 2023). There, observed average temperature increases can lengthen the growing season and enable warmer-weather crops (Chang et al., 2023). However, temperature increases can expand pest ranges, expose workers and crops to extreme heat, increase crop demand for irrigation, and reduce water availability, all with adverse risks for agricultural systems (Eigenbrode et al., 2014; Bezner Kerr et al., 2023, Chang et al., 2023). Further, precipitation from atmospheric rivers is intensifying during the wet season (Warner et al., 2015), increasing the incidence of wintertime flooding in the Pacific Northwest. To these ends, climate change is associated with increased inter-annual variability in both temperature globally and precipitation in mid-latitude areas (Pendergrass et al., 2017; Vargas Zeppetello & Battisti, 2020).

Farmers make regular decisions around farm management that present opportunities to respond to changing conditions. In the United States, farmers have been documented to change their irrigation infrastructure, shift planting dates, reduce tillage, manage nutrients, purchase crop insurance, adopt soil moisture sensors, and more in order to adapt to climate impacts (Ishtiaque, 2023). Seed selection and crop planning are also areas of decision-making that farmers revisit at least annually, and often more frequently, providing regular opportunities to adapt to climate change through variety selection, crop diversification, and shifting planting timings (Ishtiaque, 2023). However, competing narratives among international efforts to drive seed system development offer differing perspectives on how farmers can leverage seeds to adapt to climate change (Kilwinger et al., 2025). While market-driven approaches emphasize the importance of genetic improvement to develop stress-tolerant varieties that can increase food security under changing climatic conditions, conservation-oriented approaches highlight the role of increasing agricultural biodiversity through community-based solutions to broaden the array of crops for which quality seed is accessible (Kilwinger et al., 2025). This Chapter assesses how crop diversity contributes to practices of socio-ecological resilience among organic vegetable farms in western Washington in the context of climatic change and variability.

Resilience in Diversification? An Overview

Socio-ecological systems (SES) is a key intellectual research tradition that has informed the study of resilience—including how and when agricultural systems are "resilient" to climate change (Cabell & Oelofse, 2012). SES approaches foreground complex interactions and feedbacks across multiple scales aiming to understand how agricultural systems experience change, and how they may be adapting to such dynamics (Cabell & Oelofse, 2012). Accordingly, SES scholars emphasize change as inherent to, and not an aberration from, coupled human-nature systems (Berkes et al., 2002; Folke, 2006). The concept of resilience has become an organizing principle in rural and agricultural development in recognition of the inherency of dynamic change: if the world is constantly changing, then what does it mean to be able to cope with these changes? As global climate change upsets local expectations around existing weather patterns, socio-ecological resilience is a useful lens to focus on elements and processes of a system that enhance a farm's capacity to adapt to climate change through an iterative process of experimentation, learning, and reorganization. In this Chapter, practices associated with socio-ecological resilience (described below) are understood to contribute, broadly, to climate resilience.

Intellectual streams of thought emphasize different heuristics of resilience. These include "engineering resilience," "ecological resilience," and "socio-ecological resilience" (Folke, 2006 for overview). Resilience as understood from an engineering discipline reflects how efficiently a given system can return to a single, stable pre-stress state and is evaluated by metrics of return time (Folke, 2006). Emerging in the 1960's and 1970's, C.S. Holling's (1973) research found ecological systems can have multiple "stable equilibria" characterized by particular relationships and feedbacks between ecosystem components and processes (Folke, 2006; Holling, 1973). Developed from this paradigm, ecological resilience reflected the capacity of a system to absorb change and maintain key structures, functions, and relationships that govern a particular stable state (Holling, 1973). The integration and interdisciplinarity between the sciences produced the recognition that any separation between social and environmental systems did not reflect their mutual interactions (Berkes et al., 2002). The SES lineage has, since, emphasized the governance and management of coupled human-nature systems through operationalizing resilience theory (Berkes, 2002). SES approaches have emphasized the complexity and multi-scalar nature of human-nature interactions, clarifying the practical importance of "complex adaptive systems" (CAS) in managing socio-ecological systems. CAS characterizes systems as open and dynamic with individual components that self-organize across scales with the potential for producing emergent patterns that are sudden and surprising (Folke, 2006). When considering socio-ecological systems, resilience reflects the degree to which "components," such as institutions, resource-users, and other actors (Ostrom, 2009), exhibit learning and the capacities to manage change (Berkes et al., 2002). From these perspectives, a resilient human-nature system is one with the capacity to (i) self-organize, (ii) absorb disturbance while maintaining the same structure and functions, or (iii) learn and adapt to create "desirable" socio-ecological conditions (Folke, 2006; Walker et al., 2004). It indicates the need for "[…] not pushing the systems to its limits but [for] maintain[ing] diversity and variability, leaving some slack and flexibility, and not trying to optimize some parts of the system but retaining redundancy" (Berkes et al., 2002, pp. 15). Practically, managing for SES resilience moves away from controlling change and even simply reacting to, and instead emphasizes proactive capacity-building for navigating surprise and uncertainty (Folke, 2006). Accordingly, Folke et al. (2002) argue for managing human-natural systems through “adaptive management”—viewing management behaviors as experiments to learn from and building a certain degree of flexibility to change into a system. Learning from experimentation is an important component of adaptive capacity (Folke et al. 2002). In this context, adaptation refers to how actors manage change to create particular visions and outcomes for “resilience” (Walker et al., 2004).

One way in which resilience has been operationalized in natural resource management and policymaking in sectors around the world has been through the concept of “diversity” or “diversification” (Brock & Carpenter, 2007; Meybeck et al., 2024; Reckling et al., 2023). Diversification has often grafted classical ecological concepts onto understanding resilience in socio-ecological systems—likely owing to how conventional SES applications of resilience have borrowed strongly from its ecological conceptualization (Cote & Nightingale, 2012; Leslie & McCabe, 2013). For example, “functional” and “response diversity” are ecological concepts used in social-ecological systems analysis of agricultural livelihoods.

In order to examine how diversity has been operationalized in relation to socio-ecological resilience, it is important to understand its ecological roots. In ecology, diversity contributes to resilience not only through the number of species that is present, but also the diversity in the roles they play in the ecosystem, such as fixing nitrogen, decomposing organic matter, or providing shade (Folke, 2006). In other words, functional diversity can enable resilience when features of an ecosystem system serve different roles (Folke, 2006). For example, functional diversity associated with complex crop rotations can buffer against water stress, likely owing to the way that different crops rotating across the same field play different ecological roles to support increases in soil organic matter and water storage capacity (Bowles et al., 2020). Relatedly, response diversity is said to exist with different responses or reactions to environmental disturbance among species that serve the same function in an ecosystem (Elmqvist et al., 2003). Elmqvist et al. (2003) advocate for using an insurance metaphor for understanding response diversity: If one species in a functional group fails, another may survive and "insure the system against the failure of management actions and policies based on incomplete understanding" (Elmqvist et al., 2003, p. 492). Overall, common approaches demonstrate how redundancy in agricultural components with different functions and responses can enhance resilience (Cabell & Oelofse, 2012). These processes exist at multiple scales, including genetic differences at the crop level (intraspecific), different crops planted at the field level (interspecific), and spatial heterogeneity at the landscape level (Mijatovic et al., 2013). Agrobiodiversity can be "planned" in cultivated crops or animals or "associated" in flora and fauna that exist in the ecosystem (Altieri, 1999).

Response and functional biodiversity are understood to advance ecological resilience in agricultural systems in a number of ways (see summary in Table 1). As it relates to response diversification, farmers may plant many crops and varieties to buffer against shocks. At the intraspecific level, farmers can enhance response diversity by planting varieties that are adept at withstanding changing extreme weather and climate conditions, such as those that grow faster and mature during a shorter growing season or those that are flood-tolerant (Mijatovic et al., 2013). Intra-specific response diversity can also bolster resilience to disease, as is the case with rice's vulnerability to blast disease (Han et al., 2016). Response diversity at the interspecific level can enable some crops to survive when a stressor occurs because certain crops respond differently to particular stressors (Yachi & Loreau, 1999). Furthermore, farmers may plant specific ecological functional groups that enhance resilience. Crops like small grains and red clover can increase soil water retention capacity and buffer against the effects of extreme heat and drought (Gaudin et al., 2015). Functional diversity in an ecological landscape generally promotes soil fertility, prevents pests and disease, and enhances productivity (Altieri, 1999). There is a temporal dimension as well. Planting different crops at different times of the year can enhance soil microbial diversity with positive impacts on nitrogen and organic carbon content (Tiemann et al., 2015) and disease suppression (Lin, 2011). At the landscape scale, farmers can integrate different types of production systems—such as crop, orchard, and livestock systems or integrate non-crop vegetation such as hedgerows—into their farms to increase ecological complexity, with potential benefits for pest suppression and climate change buffering (Lin, 2011). Thus, functional and response agrobiodiversity across different scales can contribute to farms' ecological resilience.

Extending these arguments, other literature has taken a more expansive view of diversity in farm systems that includes social dimensions, analyzing how both ecological and social forms of diversity contribute to socio-ecological resilience. For example, diverse livelihood streams can enable the flexibility to shift between them if one is threatened, as demonstrated by research in Huila, Colombia suggesting that farmers earning income from varied livelihood activities were less vulnerable to variable weather patterns compared to those who relied solely on agricultural income from a single crop (Núñez et al., 2023). Alternatively, "diversity" can refer to different forms of knowledge, as is the case of home gardeners in the Iberian peninsula who integrated traditional and modern agricultural knowledge (Reyes-García et al., 2014). Here, diversification exists or is enabled through cross-scalar dynamics in social, economic, and political systems. This is a key contribution from an SES approach, which emphasizes components, interactions and scales that enable resilience.

Diversified Food Systems (DFS) has emerged as a socio-ecological framework to analyze functional diversity across scales in agricultural contexts, where diversity extends beyond on-farm biological diversity to include social aspirations, market channels, knowledge systems, social networks, and governance structures (Petersen-Rockney et al., 2021). Petersen-Rockney et al. (2021) identify *simplifying pathways*—practices that minimize diversity in crops, market channels, and land ownership, centralizing control through the promotion of fewer high-yielding varieties, concentrating markets, and consolidating land ownership; and *diversifying pathways*—activities that manage biodiversity to increase ecosystem services, rather than relying on external inputs, and require multiple forms of place-based knowledge. Diversifying processes not only reduce the need for off-farm inputs by providing ecosystems services, but can also offer a form of “broad and nimble” adaptive capacity by promoting flexibility, cross-scalar interactions, and re-organization of resources and knowledge in the face of change (Petersen-Rockney et al., 2021, pp. 19-20). Calo (2020) builds on DFS by integrating questions of land tenure, arguing that diversification alone, without respect to who has power to make decisions and adapt, is not enough to advance resilience. Hence, social science scholarship has shown how, in addition to on-farm biodiversity, diversity in social systems like governance structures, knowledge types, and social networks can influence the ability of a farm system to adapt to change.

Table 1: Table outlining different forms of response and functional diversity across scales, contributing to both ecological and socio-ecological resilience.

Diversification	Impacts	Diversity type	Resilience type
Intraspecific crop diversity	• Reduce impacts of disease (Han et al., 2016) • Introduces varieties with resistance to specific challenges: heat, drought, disease, shorter growing season, etc. (Mijatovic et al., 2013)	Response diversity	Ecological
Interspecific crop diversity	• Increase response diversity across crops to shocks (Yachi & Loreau, 1999)	Response diversity	Ecological
	• Increase functional diversity with benefits for soil health (Gaudin et al., 2015)	Functional diversity	Ecological
Temporal crop diversity (crop rotations, cover cropping)	• Boost soil microbial diversity, soil carbon and nitrogen (Tiemann et al., 2015) • Suppress disease (Lin, 2011)	Response diversity	Ecological
Mixed crop-livestock systems	• Suppress pests and buffer against climate change (Lin, 2011)	Functional diversity	Ecological
Social network	• Varied social behavioral responses to environmental change can hedge bets across social networks (Leslie & McCabe, 2013)	Response diversity	Socio-ecological
Seed systems and networks	• Formal and informal seed networks complement each other to boost resilience of seed supply (Isbell et al. 2023)	Functional diversity	Socio-ecological

Social science approaches have also broadly defined response and functional diversity to understand socio-ecological resilience at the system level (see Table 1 for examples). For example, Leslie & McCabe (2013) take human behaviors as the unit of analysis instead of different species when analyzing response diversity. They consider the importance of varied behavioral responses to environmental change, arguing that the variety of responses to change may be more important than the most common response. As an example, they offer the case of how individual Turkana herders make different decisions about where they move their herds to in response to drought, allowing them to hedge their bets across members in a social network (Leslie & McCabe, 2013). Here, varied responses to a stressor can be understood as experiments that members of a social group can learn from and choose to repeat or avoid in the future, tying in to SES resilience notions of experimentation and learning (Leslie & McCabe, 2013). The lens of functional diversity for resilience can be applied to the seed system itself, beyond the level of the individual farm. Isbell et al. (2023) argue that farmers in Vermont were able to adapt to the increased seed sourcing challenges posed by the COVID-19 pandemic by relying on both formal and informal seed networks. During the pandemic, farmers faced different kinds of challenges in accessing seed from informal networks (characterized by horizontal exchange of seed between social networks) and formal networks (characterized by vertical exchange of seed from official seed producers to consumers), such that informal and formal networks complemented each other and together enhanced resilience in the seed system (Isbell et al. 2023). Elements of self-organization are evident in this example, as farmers were able to reorient their seed sourcing practices within a system with adequate functional diversity and redundancy. This finding is important in the context of a formal seed system that is increasingly characterized by consolidation, where fewer companies control more seed, reducing the availability of seed varieties and increasing seed prices for farmers (Howard, 2020). From these examples, diversification in food production systems accounts for the ways in which human engagement with ecological features at multiple scales enhances the capacity to learn through experimentation, self-organize, and adapt to change.

However, social scientists caution against applying a framework that emerged from the ecological discipline to social systems (Cote & Nightingale, 2012; Fabinyi et al., 2014; Olsson et al., 2015). In particular, social scientists critique the tendency of resilience frameworks to over-ascribe the role of environmental change in driving decision-making and behavior. Fabinyi et al. (2014) show how resilience scholarship often assumes that norms and formal institutions are primarily motivated by environmental dynamics, when in fact decision-making may be motivated by broader cultural norms and institutions. For example, cultural values around pastoralism and freedom motivate *Fulbe* to remain pastoralists instead of adapting their livelihoods in the face of rainfall variability, indicating that resilience of a group cannot be understood in a vacuum without their socio-cultural context (Nielsen & Reenberg, 2010). Taking these concerns seriously in an agricultural context requires us to understand that climate change may not be the only consideration for farmers when managing agrobiodiversity. For example, market strategies also shape approaches to diversification. Those who sell to large wholesale distributors may be incentivized to grow crops that are uniform in appearance, taste, and harvest time (Carlisle et al., 2022), which is difficult to achieve with high levels of intraspecific diversity and especially open-pollinated varieties. Meanwhile, producers who sell directly to market (more likely to be small and mid-sized producers) find market demand for diverse crops and varieties from their farmers market or CSA customers (Carlisle et al., 2022). Regulatory pressures can also influence diversification strategies—onerous food safety standards can see diversification as a threat to food safety as opposed to a boon for environmental stewardship and rural livelihoods (Carlisle et al., 2022). Thus, crop and seed selection should be understood within a farmer's broader socio-ecological context—and not only as the need to be resilient amidst a changing climate. When seeking to identify processes that promote climate resilience, it is important to investigate the motivators for such behavior—whether or not those motivators explicitly include climate resilience.

This consideration is explored using the case of organic agriculture in the Global North. As opposed to relying heavily on off-farm inputs like pesticides, herbicides, and fertilizers, organic farming systems reduce the need such inputs by integrating and managing the surrounding ecology, and generally exhibit higher levels of agrobiodiversity (Niggli, 2015). As such, organic practices generally exhibit higher levels of planned and associated agrobiodiversity than conventional agriculture (Grandi, 2008). For example, Schaak et al., (2023) found that organic farms in Sweden featured higher levels of functional diversity than conventional farms. Diversified organic agriculture is often positioned as supporting the preservation of crop genetic diversity, to counteract the homogeneity of high-yielding and uniform varieties that cater to "farm specialization" (Grandi, 2008). Benefits of organic production systems expand beyond biodiversity conservation, and include reduced pesticide exposure of farmworkers, reduced fertilizer runoff into waterways, increased water use efficiency, and increased autonomy over food production (Seufert & Ramankutty, 2017). Thus, organic agriculture is commonly known to boast increased on-farm diversity.

Despite diversification's connection with resilience and its occurrence in organic agriculture, little attention has been paid to the relationship between organic agriculture, diversity, and resilience. El Chami et al. (2020) conducted a systematic review of how sustainable agriculture (which included organic agriculture, alongside other alternatives like conservation agriculture and agroecology[1]) contributes to climate resilience. They found that most literature has focused on how a single practice (e.g. soil management) contributes to a single ecosystem service (e.g. water filtration). Thus, crop diversification has mostly been analyzed in relation to single ecosystem services across sustainable agriculture contexts, including but not limited to organic

[1] Because organic typically refers to a set of allowed production practices, it can be considered less transformative than agroecology, which refers to a framework for food sovereignty social movements (Wezel et al., 2009). And while organic agriculture is heavily regulated through certifications geared towards consumers that allow a small list of organic inputs, there is no standardized definition or certifying body for agroecology (Niggli, 2015). This paper focuses on organic precisely because of its widespread meaning and clear (albeit diluted) certification standards that give the label weight to farmers and consumers alike.

(El Chami et al. 2020). Nevertheless, a few studies have offered in-depth and context-specific perspectives on the relationship between diversification and resilience in sustainable agriculture settings. Carlisle (2014) describes resilience from the perspective of a cohort of ecologically-minded farmers in the Great Plains who developed a values-based supply chain and, through constant attention to diversity and flexibility across scales from individual to farm to government, averted a bad harvest during a dry year. French organic farmers view autonomy and consistency as key tenets of resilience, enabled by their lower dependence on external inputs as organic farmers and farm-scale diversification (Perrin et al., 2020). These studies analyze crop diversification alongside other forms of resilience, but a more in-depth analysis of resilience associated with crop diversification in the context of climate change is warranted.

This research contributes to the literature on resilience and diversification in three ways by offering: i) a farmer grounded understanding of the contribution of crop diversification to practices of socio-ecological resilience, ii) a perspective of diversity that is complementary to specialization, and iii) an explanation for how climate interacts with social and economic factors to shape crop diversification that contributes to resilience practices.

First, it contributes research of how crop diversification contributes to practices of socio-ecological resilience—including within contexts of climate stress—in organic agriculture. This extends existing research often focused on how sustainable farming practices contribute to the continued provision of ecosystem services. This research does not conduct an analysis of resilience before and after diversity practices were implemented. Rather, it analyzes how diversity is operationalized to contribute to adaptive management practices associated with socio-ecological resilience. I do this by offering a farmer grounded perspective of the ecological notions of response and functional diversity. These perspectives are narrated by organic farmers sharing lived experiences of everyday livelihood governance in moments of climate and weather-related stress. Not only do different crops and varieties have varying responses to adverse conditions, but also the same crops and varieties planted at different times and places may have varying responses to adverse conditions. Further, farmers understand functional diversity in terms of market functions: they need diversity on the landscape not only to fulfill different ecological roles, but to play different culinary and market roles as well. These forms of diversity enable adaptive management practices of learning through experimentation and a high degree of flexibility. Here, ecological diversity is shaped by and contributes to social processes, showing that crop diversity and its association with resilience cannot be understood outside of its social context. Understanding how diversity matters to the people who are enacting it is important for efforts that aim to increase resilience to climate change on agricultural landscapes.

Second, I offer a more nuanced perspective of diversity that is not at odds with specialization. At the farm-level, farmers' market strategies (to whom, when, and how they sell) along with their own preferences may motivate them to specialize in certain crop strategies to fulfill a market niche, while maintaining high functional and response diversity that contribute to resilience practices. This culminates in a strategy I call "specialized diversification". While specialization is often associated with simplifying pathways that produce "narrow and brittle" adaptive capacity described by Petersen-Rockney et al. (2021, pp. 18-19), these findings suggest that specialization can also exist within and complement diversifying pathways.

Finally, this research contributes to a more nuanced understanding of climate adaptation, contextualizing decision-making that builds resilience within a broader socio-economic context and thus showing how climate change impacts crop selection. Diversified agriculture is well-positioned to handle increased unpredictability brought about by climate change—not necessarily as a result of farmers' explicit drive for climate resilience, but because of their specialized diversification strategies that arose out of a confluence of market, personal, and environmental considerations. As climate change lengthens and warms the growing season, it also opens up opportunities for new crops and planting times. Farmers take advantage of these openings in a way that fits with their specialized diversification market strategy, which can include increased specialization in hardy or culturally relevant crops. This contributes to debates around climate adaptation, helping understand how environmental contexts interact with social and economic factors to motivate behavior that may or may not be adaptive.

Methods

Semi-structured interviews were conducted with twenty-nine participants. Eligible participants were (a) production farmers for whom agriculture was an important contributor to their livelihood; (b) vegetable growers; (c) decision-makers on their farm around crops and seeds (d) self-identifying as using organic practices; and (e) farming in Washington state, west of the Cascade Mountain range. One participant was excluded from the sample because agriculture was not an important part of their livelihood, leaving a sample of twenty-eight participants. While fourteen farmers (half the sample) were officially certified organic, the rest were not certified but self-identified as using organic practices. Farmers who practiced organic agriculture but did not have an organic certification were included in the sample so as to acknowledge those for whom certification is either challenging or unnecessary, including farmers who grow on leased land, speak a first language other than English, have limited capacity for record-keeping, and sell directly to customers.

Farmers were interviewed in eight counties across western Washington (Figure 1), with varying demographic characteristics (Table 2). Generally, the climate in western Washington is characterized by cool, wet winters and warm, dry summers. In many areas of western WA, winter rarely sees temperatures below freezing, making it possible to grow certain crops during the winter months. Seattle and smaller cities like Tacoma, Olympia, and Bellingham are within driving distance of all the interviewed farmers, offering markets of consumers, restaurants, and co-op grocery stores who can afford premium-priced organic produce, as well as market channels like farmers markets.

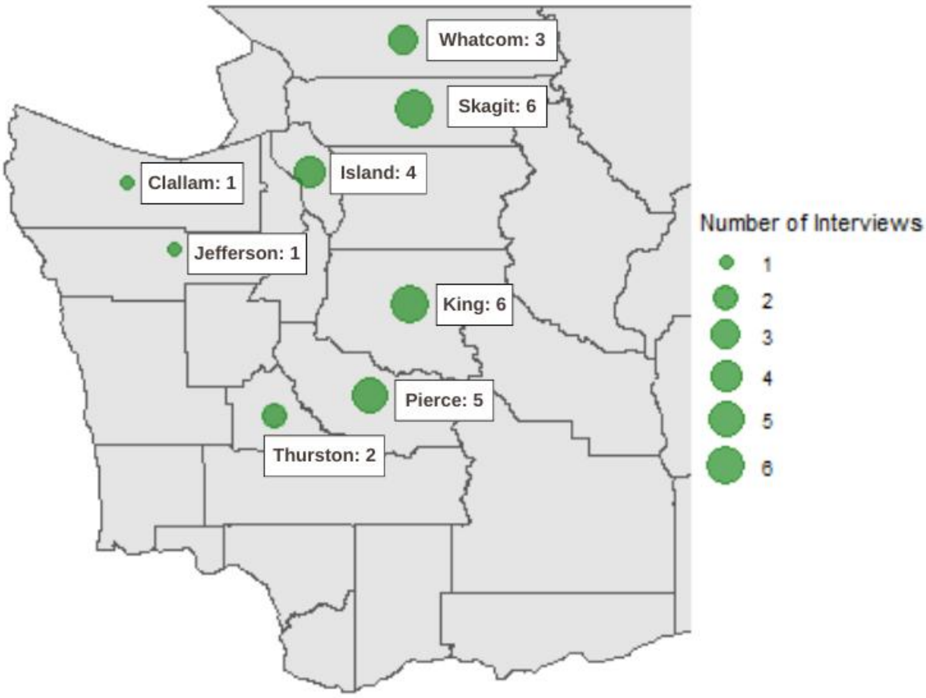

Figure 1: Map displaying county locations of interviewed farmers. Labels include county name and number of interviews.

Farmers were recruited through a combination of convenience and snowball sampling. A number of farmers were recommended and recruited through existing connections and participants. Other farmers were recruited in-person at farmers' markets in the Seattle area. Recruitment messages were also sent through relevant listservs, including local Tilth organizations and the Organic Seed Alliance. Another subset of farmers was recruited through an "incubator" farm, which trains beginning farmers while offering them small parcels of land to lease. Attention was given to interviewing farmers of varying farm sizes and geographically distributed throughout western Washington. Participants were offered free soil testing as compensation for participation.

Participating farmers were interviewed between June and December 2024, with the majority of interviews occurring in the summer months. Respondents were asked questions about their background, their processes for crop planning and seed selection, how they are impacted by and adapt to climate change, and if they view crop selection as an adaptation strategy to climate change. Interviews were auto-transcribed using a combination of NVivo and Trint softwares and subsequently corrected line-by-line for accuracy. They were then thematically analyzed using NVivo software using an inductive, structural coding method (Saldaña, 2009). The resulting codebook is available in Appendix Table 1.

Codes were established describing key groups of questions and responses, such as ‘Climate Impacts’, ‘Crop Strategy’, ‘Practices of Resilience’, and ‘Climate Adaptations’, which were used to inform the results described below. The ‘Climate Impacts’ category arose from questions and informed results around how climate change was impacting the farm. Codes within the ‘Crop Strategy’ category came from questions around how and why farmers conduct crop planning and seed selection. These codes were used to assess motivators driving crop selection and planning, including approaches of diversification and specialization. Codes in this category that presented in at least half of the interviews were used to inform descriptions of motivators for crop diversity. The ‘Practices of Resilience’ group of codes arose from questions around crop planning as well as climate impacts and adaptation. These codes explained how farmers enacted processes of resilience such as learning, flexibility, and proactive planning on their farms. At times, quotes were coded as both ‘diversification’ (as part of the ‘Crop Strategy group’) and ‘Practices of Resilience’. Codes that emerged at this intersection reflected the many ways in which farmers engage with practices of diversification within and outside of the context of climate change, which are reported below. Within the ‘Climate Adaptations’ group, one code titled ‘Seeds and Crop Planning’ was used when farmers discussed how they made intentional adaptations to climate change by adjusting varieties, crops, or planting timings. These quotes described various shifts in crop planning and were used to inform results around the variety of ways farmers shifted their decision-making around crop diversity in the context of climate change.

Table 2: Demographic characteristics of interviewed farmers

Demographic	**Description**		
Gender	11 women, 16 men, 1 person identifying as transgender		
Race/Ethnicity	22 white, 5 Hispanic, 1 Native American, 1 Asian-American, 1 Black farmer*		
Organic Status	14 certified organic, 14 non-certified using organic practices		
Demographic	**Min**	**Median**	**Max**
Farm size	0.25 acres	12.125 acres	820 acres
Gross Income	$1,000	$100,000	$750,000
Age	32 years	42 years	74 years

*Note: People with multiple ethnic or racial identities were counted multiple times in the ‘Race/Ethnicity’ row.

Results

Climate and weather-related challenges

Farmers described a host of climate and weather-related challenges. More frequently than any single event, farmers discussed shifts in the long-term weather patterns, namely increased variability that make seasonal temperature and precipitation patterns harder to predict (86% of interviews) and shifting timing of seasons (32%). The most frequently reported severe weather and climate stressors included extreme heat (71%), wildfire smoke (57%), extreme cold (50%), flooding (50%), shifting pests and disease (25%), and wind (21%). Increased incidence of wildfire smoke was reported by multiple farmers as being the most emotionally challenging weather impact, more so because of concerns around worker safety than crop loss. While farmers associated some of these challenges more clearly with climate change, such as more frequent heat waves and wildfires, other impacts were not always ascribed to climate change, such as wind and flooding. Microclimatic variations mean that farmers in the same region may not experience the same weather patterns and climate impacts. For example, farmers in Skagit

County reported that their weather comes in from the Strait of Juan de Fuca, meaning they experience more mild conditions that are tempered by the ocean. Meanwhile, farmers in Pierce County who are more inland may experience colder winters or warmer summers and thus greater susceptibility to heat waves.

Crop diversity contributes to practices of resilience

This section explains how diversity is understood by organic vegetable farmers in Western Washington and is shaped by their social and ecological growing context in ways reflect adaptive management practices and notions of socio-ecological resilience. I demonstrate farmers' narrations of response and functional diversity in ways that are related but distinct from the conventional ecological concepts and applications. I then explain how such diversity enables adaptive management practices of learning through experimentation and flexibility.

Crop diversity was coded as a narration of resilience for interviewed farmers. This has often manifested through conventional ecological concepts of response and functional diversification. Further, response diversity was narrated in a manner that incorporated a spatio-temporal dimension (when and where crops were planted), while functional diversity was understood to involve a diversity of crops that serve different market functions, beyond ecological roles. Farmers also made connections about how crop diversity promoted both ecological and social resilience.

Response diversity

There was a broad consensus across farm sizes and organic certification status that having a diversity of crop types builds resilience. Farmers often used gambling as a metaphor to describe their motivation for planting different crops and varieties: they *hedge their bets*, such that if one crop or variety fail, others might survive. However, narrations associated with response diversity extended beyond what crops are grown to include *where* and *when* they were. Farmers diversify *where* they plant crops, including multiple areas of their field or across growing contexts, such as greenhouses or in open fields, to mitigate agricultural risks. They also diversify *when* they plant. For instance, farmers can engage in multiple plantings of the same crop to avoid the risks of a single planting failing. They may also diversify when they sell their produce to include winter months. For example, two farmers growing on very different sizes of land with different markets (wholesale and CSA, respectively) both shared their tendency to space out plantings over time to reduce risk:

> *"So if you're berries and you get smoke in the summer and impacts your crop, you only have one month. Whereas we spread our harvesting over 12 months and so it's a different risk factor."*
>
> - *Interview 13, Aug. 2024, total size 300 acres*
>
> *"We like diversity, but also, it's like really nice when you plant broccoli, we try to plant at least two different varieties just so we can have staggered harvests… it kind of hedges against any weird weather anomalies or, some varieties just have very finicky reactions to different weather and pests, and so having two or three kind is a nice buffer against any unsuspected crop failures. But also in an ideal situation, we choose, like cauliflower and broccoli are the best example, we will plant two or three varieties and hopefully have them mature over two to four weeks and then be able to offer them for like three weeks in a row to the CSA."*
>
> - *Interview 2, June 2024, total size 10 acres*

These quotes illustrate that organic farmers can stagger plantings over time to hedge against weather anomalies, expecting different plantings to respond differently to adverse conditions. As such response diversity that contributes to socio-ecological resilience includes not just different crops and varieties, but also when and where they are planted.

Functional diversity

Farmers consider functional diversity when planting crops. However, findings suggest their understanding of it extends beyond the ecological roles that certain crops play in an ecosystem, such as fixing nitrogen, providing shade, or building soil health. One way in which this was evidenced was through how different crops serve particular market functions. This plays out at the crop level when different crops fill different culinary roles in a customer's proverbial grocery basket. For example, one farmer said they make sure that their CSA's always include the following categories: "familiar roots", "a bunched thing", "a sautée green", "a lettuce green" (Interview 15, August 2024, total size 20 acres). This also plays out at the variety level. Different varieties play different roles in terms of what they can offer the customer, but also *when* they can be sold. For example, varieties that are fast-growing go to market earlier in the season and offer earlier income, while long-storing varieties can be sold later in the season and offer later income. Thus, some varieties fulfill the function of being sold earlier, while others are able to be sold later, as evidenced by a farmer specializing in potatoes and onions:

> *"I'm growing yellow potatoes and red potatoes, those are all different varieties. And then within a variety, sometimes it's about storage and sometimes it's about maturity.... So with potatoes, it's like, this is ready, it grows really fast, it's ready three weeks earlier, so I can start selling yellow potatoes three weeks earlier. And then this one will carry me through and store long and I'll have it. You know, so it's about how many weeks of the year can I have that product available.*
>
> - *Interview 20, September 2024, total size 76 acres*

What this quote illustrates is that farmers narrate aspects of functional diversity in terms of the market functions and entry points, including how crops can fulfill their customers' needs and when they can be sold. Here, functional diversity is shaped by market goals and is socially prescribed.

Adaptive Management Practices

Response and functional diversity as narrated by farmers contributed to adaptive management practices of learning through experimentation and flexibility, which are associated with socio-ecological resilience. These adaptive management practices enabled farmers' adaptations to environmental conditions that were changing in both the long and short-term.

Farmers settled on the crops, varieties, and timing that worked for them by learning through experimentation. Eighty-two percent of interviews farmers described a dual approach of growing out "tried and true" varieties that they knew they could rely on, while maintaining a small experimental grow-out of new varieties they wanted to test out. If a trial works well, they grow it in larger quantities the following year. Depending on the crop, they might be looking for productivity, pest and disease resistance, good taste, aesthetic appeal, appropriate days to maturity, cold or heat tolerance, or other traits. Functional diversity is relevant here because farmers may be experimenting with new varieties to fill particular roles in their market strategy. Similar patterns were discussed around experimenting with different timings, where farmers planted crops at reliable times as well as earlier or later in the season to experiment with different planting times, and holding on to what worked in subsequent seasons. One market farmer specializing in hot peppers discusses their adaptive approach to seed selection:

> *"Well, in the beginning of our careers, I was kind of just experimenting because we were market farmers and I pretty much work all the markets, I get really good feedback from what people want or they don't want, what sells, what doesn't sell. And it took a few years, especially with hot peppers, you know, trying different things and seeing what sells the best and what performs the best. And so sometimes I just try new things. And then there's also tried and trues that we grow every year and that's the variety we grow and we're never going to change that variety because it does so good and everyone loves it."*
>
> - *Interview 19, September 2024, total size 10.25 acres*

Thus, crop diversity enables the adaptive management process of learning through experimentation—a key process that is shown to contribute socio-ecological resilience. Of note is that this process occurs at the multi-year time scale: farmers make annual decisions around seed selection based on learnings from previous years.

Similarly, crop diversity was shown to enable flexibility in crop planning—another adaptive management practice that reflects socio-ecological resilience. Farmers by and large accepted that seasons are unpredictable—an inherent feature of farming that is only being exacerbated by climate change. As one respondent remarked, *"So the only thing you can count on is change.*

And Mother Nature will always throw a wrench in whatever best laid plans you have" (Interview 24, September 2024). As such, it was important to be able to adjust strategies depending on changing conditions. Crop diversity in general and response diversity in particular were important to an adjustable crop plan. Farmers increased the response diversity of crops seeded early on, knowing that some crops would fare better than others given a range of possible weather conditions. One farmer growing primarily for CSA described this process:

> *"You're always growing things to see how the weather is going to be. You don't know. So you have spinach at the same time that you have zucchinis and one's going to like it and one's not, you know. So we try to try to take that into account with like having a whole bunch of things. We do a lot of extra seeding, seeding plants that don't get planted just because, you know, especially those transitional seasons, it's like, never mind, it's too hot, we're not going to put the spinach out. Never mind, it's too cold, we're not going to do the first rotation of zucchini, something like that. So we waste some potting soil, we waste some seeds, we waste some time in the seed room, but we don't put it out in the field if the weather is showing that it's not going to be great."*
>
> - *Interview 15, August 2024, total size 20 acres*

Thus, farmers could intentionally increase response diversity among crops planted early in the season to enable flexibility to shift crop plans later on depending on changing conditions. Because flexibility is a key element of adaptive management practices, this quote demonstrates how crop diversity contributes to practices of socio-ecological resilience. This process occurred within the span of a single season—a shorter time range than the inter-annual experimental seed selection described above, and noteworthy because it demonstrates how practices of resilience take place across temporal scales.

Drivers of diversification & specialization

This section describes how crop selection is shaped on the farm through processes of diversification and specialization, culminating in an approach which I term, "specialized diversification."

As demonstrated above, crop diversification contributed to practices of socio-ecological resilience. However, diversification was not necessarily motivated by on-farm resilience, or for that matter, climate resilience alone. Instead, crop decisions are shaped through a number of factors that can increase specialization or diversification. These factors include market strategy (to whom, when, and how produce is sold) and farmer preferences (see Figure 2). Such factors, which contribute to the degree of specialization or diversification, were however limited by constraints and opportunities related to a farmer's land, labor, climate, and resources. Here, diversification is the process of increasing the amount of crop, varietal, or temporal diversity, and specialization is the process of focusing attention on specific crops and varieties. Specialization and diversification are not mutually exclusive and can indeed be complementary.

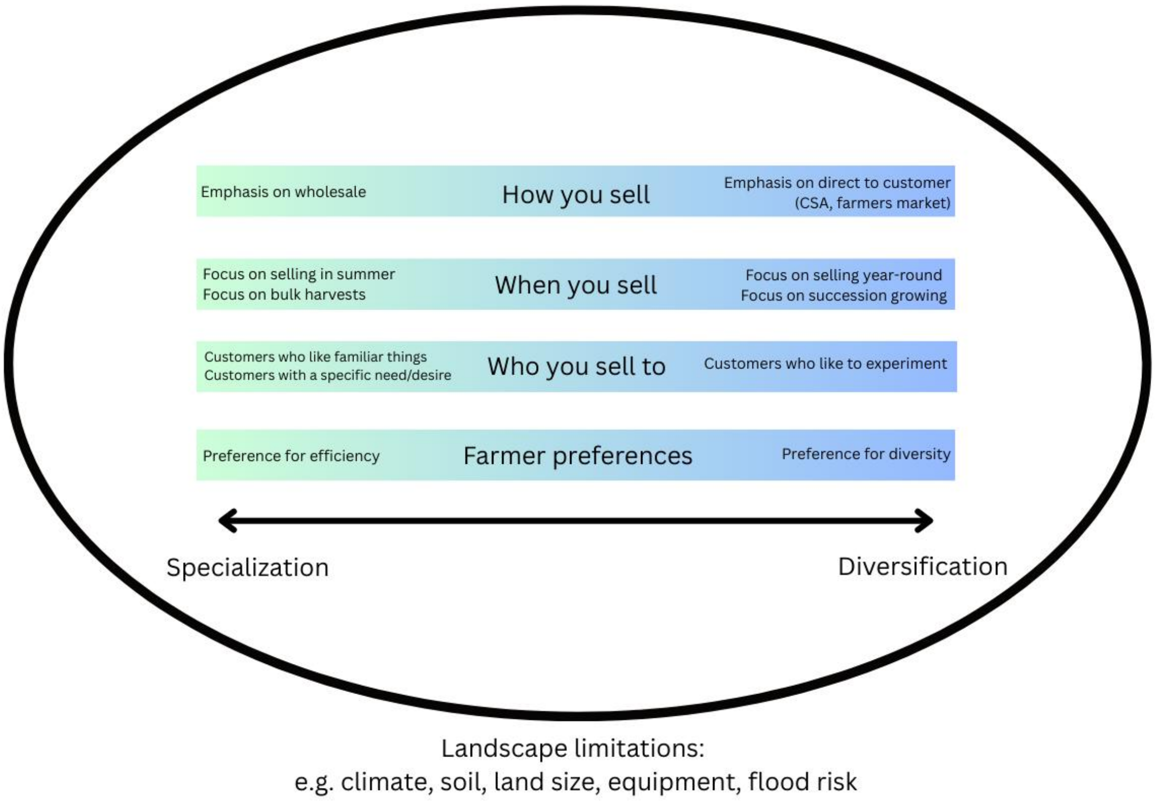

Figure 2: Factors that shape crop selection and driving specialization and diversification of crops, varieties, and plantings

How you sell

Crop decisions were largely motivated by market strategy, including to whom, when, and how the farmers sell their produce. Farmers who sold direct to customers through CSA's and farmers markets were often motivated to provide a 'grocery basket' of produce for their customers, replacing the need for buying produce at grocery stores by offering a wide array of different crops. Meanwhile, those who sold through wholesale methods to grocery stores may have been less motivated to offer a variety of different crops but were nevertheless motivated to have diverse varieties within their major crop groups in order to cover diverse storage and maturation dates. One farmer with decades of experience summarized how different market channels motivate diversity:

> *"Well, at the farmers market, you got to have the variety, you get the wider range of customers. Yeah, it would be easier, just to have it all kale. But then I would be selling to the co-op. I wouldn't be going to the farmer's market."*
>
> - *Interview 21, September 2024, total size 64 acres*

Thus, more direct to customer market strategies motivated diversification, while wholesale market strategies motivated specialization.

Who you sell to

The target customer base was important in determining crop choices, as well. Some farmers catered to immigrant groups and grew culturally relevant crops like sorghum and Asian greens. Others grew for a suburban client base who were more comfortable with "kitchen staples" that are commonly found in American grocery stores. Selling to customers who were interested in out-of-the-ordinary crops was a driver for diversification. Meanwhile, selling to customers with less preference for such crops or with more specific interests or needs (e.g. culturally relevant crops) minimized diversification. One farmer discussed growing crops appreciated by their Mexican customer base:

"[I plant papalo] because it is more for my people. My people talk to me and say, "Do you have papalo? Bring me six bunches, eight bunches." Each family eats a lot, because it's good to eat."

- *Interview 17, August 2024, total size 0.25 acres (translated from Spanish into English)*

Therefore, the target customer base influenced diversity on the farm, such as by driving specialization in particular crops or minimizing diversity to only include foods that are also commonly sold in conventional grocery stores in the U.S.

When you sell

Timing was also a key consideration for farmers. Many farmers wished to maintain income throughout the year, often to ensure employment for workers in the wintertime. In order to prolong the income-generating months, they could grow storage crops in fall to be stored and sold throughout the winter (if they had storage capacity available) or else grow cold-hardy crops to be harvested and sold throughout the winter. Thus, the decision to spread out when crops were sold was a driver of diversification. Timing was also affected by the market channel: while market farmers aimed to harvest a small amount of consistent crops every week, CSA farmers hoped to harvest a large amount of different crops every week. One relatively larger farmer discussed choosing an assembly of crops that enabled selling year-round, and therefore keeping people employed:

"What do we farm? We farm leeks and carrots, and we have some beets and some cabbage and some kale, some collards, some fennel, some parsnips. Sometimes we have some radishes and sometimes we have some spinach. We have some rhubarb and we have some asparagus, and that's about it. Okay. So now why do we have that list? [It] is because the goal is to keep people in year-round jobs as much as possible."

- *Interview 13, August 2024, total size 300 acres*

Therefore, when a farmer aims to sell their produce is a driver of the assembly of crops they choose to plant, such that selling over a longer period of time can drive diversification.

Farmer preferences

Farmers were not only motivated by their market strategies—affect played a role too. About a third of the farmers discussed being motivated by their own and workers' preferences for certain crops. They liked some crops and varieties for how they grew, looked, or tasted and wanted to keep growing them. Some expressed that diversity was desirable in and of itself. One of the farmers (growing on half an acre with more than 100 estimated varieties) discussed how growing so much abundance was how they wanted to farm, and then they found the appropriate customers who wanted to eat the niche fruits and vegetables she already planned to grow. Meanwhile, other farmers wanted a smaller assembly of crops in order to maintain a simpler production system that was easier to keep track of. Thus, farmer preferences were reflected in acts of crop diversification and specialization:

> *"I have just a real love in general for biodiversity, and that keeps me from getting bored… And so for me, the CSA is a nice excuse to get to grow even more with the seasons. I do some season extension for sure, but I don't stress about it and it's just fun, I really enjoy introducing people to new foods and I personally have a very ritualistic approach to life. Like I love, even things that shouldn't be seasonal... And so for me, you know, the first part of the year we have a ritual where we make fennel pizza just having these markers that happen at points through the year that are like vegetable driven is something that I just enjoy on an intrinsic level."*
>
> - *Interview 12, August 2024, total size 0.5 acres*

Landscape limits

The drivers of diversification and specialization described above shape crop selection, within a space of possibility that is influenced by landscape limitations. These landscape limitations include climate, soil type, flooding risk, land size, and equipment availability. They create a space of what is possible to cultivate. The regional climate influences which crops can be grown in the area, while a farmers' microclimates might place further limitations that preclude the possibility of certain crops. Their soil might make certain crops extremely costly or time-intensive to grow well, while seasonal flooding might make annual crops or late-season crops risky to grow in certain areas of their property. Meanwhile, access to equipment might limit their ability to grow crops that require specialized machinery to produce at scale. Land size can also narrow what can be grown: very small farms may have limited ability to plant perennials or do crop rotations necessary to grow certain crops well. Therefore, market strategy and farmer preferences drive diversification and specialization within the window of crops that are even possible to grow given factors like land, climate, and equipment.

Specialized Diversification

Taken together, these factors that drive diversity and specialization in different ways contribute to a strategy of *specialized diversification.* Farmers are incentivized to focus on crops that enable them to occupy a niche in the market (specialization), while engaging in a farming system and market strategies with many points of entry for both response and functional diversity that confer resilience (diversification). Put simply, organic farmers are narrowing their focus while maintaining diversity. Thus, specialization is not necessarily at odds with diversification but can be complementary to it. The following quote from a farmer selling to CSA members and restaurants and specializing in radicchio explains their tendency to reduce the total number of crops without sacrificing diversity:

> *"And then over the years, some crops were, either because of environmental or pest reasons, we found that we weren't succeeding with some things, and so we either stopped growing stuff that just wasn't working for us, some stuff that wasn't profitable and we've narrowed it down to still a pretty wide range of crops."*
>
> - *Interview 10, August 2024, total size 80 acres*

Farmers could develop their niche by growing very specific or culturally relevant crops that were otherwise difficult to access (like radicchio or sorghum), by selling crops that they particularly excelled at and were resilient to temperature swings (like greens), or by getting to market during the shoulder or off-seasons (like early-season cucumbers). One CSA and market farmer discussed how they came to specialize in Asian greens:

"I really enjoy perennial, weird vegetables. I mean, this is my niche for farmer's market and for CSA is growing things that other people aren't, which, you know, might be things that are common in other parts of the world, but hard to grow in this climate, or might be really specific and rare vegetables that different cultures treasure but are hard to find here… I mean just some simple things like amaranth greens. People eat amaranth greens all over the world. But you can't get them in a store."

- *Interview 3, June 2024, total size 19.4 acres*

The process of specialization did not occur in a vacuum, but in the context of the other farmers in the area. Farmers considered what others had available and positioned themselves in relation to other farmers, specializing in produce that others were not.

The tendency to specialize also points to the costs of excess diversity that does not serve a specific function. Because each crop requires its own observation, care, and growing plan, it can be a strain on resources to grow too many crops that do not play specific roles in a farmer's market strategy and that push the limits of what can be easily produced. The process of eliminating crops that take too many resources to produce occurs over time through a process of adaptive management, where farmers continuously change their behavior and incorporate past learnings into future decision-making. The market farmer specializing in hot peppers explained the costs of excess diversity:

"Well, it's funny because I feel like over the years, we were way more diversified at the beginning, like every little thing, and the harvests were super long. And I feel like as we get a little bit more mature in our farm, we actually have diversified a little bit less… So we're a little more streamlined. Like we are pretty diversified compared to a standard row crop farm. But I feel like we have tried to find the sweet spot of a little bit of diversity, but a little more streamlined... We're a small farm. It's me and my partner doing most of the work. Like we have seasonal helpers, this year we have two part time helpers in the summer, and they work two days a week each. And yeah, we want to find a workload that works good for us."

- *Interview 19, September 2024, total size 10.25 acres*

Specialized diversification often relies on alternative seed sources. While farmers order the bulk of their seed from mid-sized seed companies such as Johnny's and Territorial, they often rely on smaller, regional seed companies or on informal seed networks for specialized crops. Mid-sized companies can offer seeds at high quantities and reasonable prices that are reliable, high quality, and consistent. Meanwhile, small companies that produce bioregionally adapted seed can offer more niche varieties that are adapted to the region – albeit at smaller quantities and higher prices. Similarly, farmers often rely on informal, community seed networks to source culturally relevant seed that might not be available in a seed catalogue, though cannot rely on these networks for the bulk of their production. Thus, diversity in *how* and *by whom* seed is produced is important for the specialized diversification strategies that contribute to practices of resilience.

> *"[The Second Generation Seed Cooperative] is a collective based in Northern California. And it's kind of like a collective of various growers around the country, kind of different hubs... But I guess how I participate in it is people growing crops of the Asian diaspora and both selecting for ones that do well in your area and also kind of coming up with like a standardized way to grow things so they kind of look like what people who have purchased these crops expect them to look like. And so some people are selecting for very drought tolerant, some people are selecting for, I guess a lot of crops that are grown in much more like tropical latitudes have a hard time setting seed here. Yeah so how can I get this to flower and set seed in our short season?"*
>
> - *Interview 14, August 2024, total size 12 acres*

Taken together, these quotes show us that farmers' market strategies culminate in a "specialized diversification" approach, where farmers may focus on a small number of crops while maintaining a broad array of crops and varieties planted at different times that enable practices of resilience through both response and functional diversity.

How Climate Change Affects Crop Diversity Approaches

Climate change is understood as a changing context in which crop decisions are made, where weather patterns are more unpredictable and the growing season is generally warmer and longer. Diversified agriculture is well-positioned to handle these changes because of adaptive management strategies and the response and functional diversity built into farmers' crop plans.

These crop plans, which are shaped through farmers' market strategies and preferences, enable resilience practices—even if climate resilience was not the main motivator shaping behavior. Climate change interacts with specialized diversification strategies in two ways. On one hand, diversification enables practices of resilience that help a farm to cope with emerging environmental conditions associated with climate change, as described in the section titled "Crop diversity contributes to practices of resilience". On the other hand, climate change emphasizes the need to focus on crops that can handle fluctuations in weather or on those that can take advantage of a warmer and longer growing season, leading some farmers to increase their degree of specialization.

While climate change offers another reason for farmers to maintain diversity, it also motivates them to specialize in crops that can handle fluctuating and extreme temperatures. One farmer discussed the need to narrow their focus on crops that are more able to handle shifting conditions precisely because of the increasingly variable climate, intending to shift the focus to greens and especially lettuces. These varieties should not only be resilient to fluctuating temperatures but should also work for the farm's market strategy and the other considerations discussed above. For this farmer, growing as a non-profit employee on the largest farm in the sample, increasing the growth of these hardy crops is the most strategic approach:

> *"I definitely am seeing [climate change] and am really just trying as hard as I can to identify things that are considered consistent performers through that variability. So that's really where the idea of shifting our business to mostly greens for the next couple of years has come from. You know, they didn't care that it rained this summer. They didn't care that it was wet a little bit longer in the spring. I mean, it's been pretty darn reliable. But yeah, I definitely am seeing that variability and it's encouragement for me to narrow my focus."*
>
> - *Interview 24, September 2024, total size 820 acres*

Thus, climate change is pushing some farmers to specialize in crops that are able to handle adverse conditions, while still maintaining diversity that allows for practices of resilience.

Climate change can also open opportunities for farmers to specialize in new-to-the-region crops that were less possible to grow before. By lengthening the growing season and increasing summer temperatures, climate change is revising the limitations of what can be grown in the region. As such, it creates new windows of opportunity that are then shaped by the motivators of crop selection and adaptive management approaches described above: they are experimenting with new-to-the-region crops, varieties, and planting timings which fit their market strategy, preferences, and landscape limitations. For example, farmers that specialize in culturally relevant crops noted that climate change is now making growing tropical crops in the Pacific Northwest more possible. Okra, sorghum, persimmons, and pineapple were some of the crops named in this category. These crops may not benefit from the attention of mid-sized seed companies or university breeders, so farmers are taking it upon themselves to save seed from them to adapt to local, changing climates through an iterative process of trial, error, and observation. One farmer who grows as part of a collective specializing in culturally relevant crops for people from African and other diasporas discusses how climate change is helping them continue their specialization in these crops:

> *"I've been a big fan of looking at how the changing climate changes how we grow food. And through that observation has allowed us to really understand that two, five years ago, ten years ago this could not grow here, but now it's growing. For example, sorghum… The timing of when you can put the sorghum down, it's when the temperatures gets to 65. Sometimes that doesn't happen until June. So it's not enough time to produce a grain here in the Pacific Northwest.... So as the climate is changing, we are looking at how early can we plant. So next year, we are dropping sorghum as early as April. So we can see, if the temperature stays stable and get hot in the summer when the sorghum needs to grow because a drought resistant plant or crop, can we push the crop all the way to September and harvest in September before it starts turning and be ready to get a seed. So that would be the project for this year because we've seen it's staying warm until November. So we'll see."*
>
> - *Interview 29, December 2024, total size 4 acres*

The farmer specializing in potatoes (quoted in "Crop diversity contributes to practices of resilience") has a strategy that involves focusing on organic potatoes and incorporating diversity that fits their potato rotation. As such, they are experimenting with onions as a crop that fits into their broader market strategy.

> *"Onions is very much a climate change crop in western Washington. Like people never would have, people maybe grew onions just around a little bit, but it's not like a commercial crop west of the mountains because there's not enough heat. And then if it starts raining in August or it rains at the beginning of September, that's just not enough time to field cure an onion. So but now it seems like you can almost reliably get into the middle of September. And then there's suddenly enough time, which kind of opens that crop up as an option. So I'm answering the opposite question, of actually climate change is good, in some ways is good for my business here."*
>
> - *Interview 20, September 2024, total size 76 acres*

All of these 'new' crops (or later plantings of existing crops) are incorporated into a farmer's production plan over time through trial and error. Thus, adaptive management is integral to finding crops that fit both the changing climate context and a farmer's specialized diversification strategy. One farmer explains how one year's experiment can be a future year's standard practice, indicating the importance of adaptive management in taking advantage of new windows of opportunity offered by climate change:

> *So much like those market factors, those climate factors are incremental in terms of how you're adapting to them in your year-to-year planning. And some of it, you know, you roll the dice. Like I was talking about with sweet corn. Can we get one more planting in on the 1st of July that makes in early October? But you know, I can imagine a situation where all of a sudden that what was this roll of the dice planting 5 or 10 years, down the line is now just standard. And the roll of the dice is July 15th.*
>
> - *Interview 6, July 2024, total size 400 acres*

Taken together, these quotes indicate that climate change opens windows of opportunity for new crops or later plantings that fit a farmer's specialized diversification strategy. This can motivate specialization in crops that can handle fluctuating temperatures or that benefit from longer seasons, determined over time through an adaptive management process. Therefore, farmers maintain diversity enable adaptation to changing conditions, while climate change also motivates specialization in particular crops.

Diversity at the seed system level is critical for farmers to take advantage of new openings that are created by climate change. In order to adapt new crops to this region, some farmers stress the importance of buying seed grown in this bioregion or at least at the same latitude. The assumption is that seed grown in the same region will be adapted to local conditions and shifting climates, which is especially important for crops that are sensitive to the climate or that are newer to the region. However, most seed companies do not share where the seed was grown, and instead farmers need to either save seed themselves, buy from a small regional seed company, or otherwise receive seed through informal networks. While these sources generally cannot provide enough consistent seed at affordable prices to make up the bulk of a farmer's production, they are important in helping farmers experiment with new crops in openings created by climate change that fit with their specialized diversification strategy.

> *"I think the base level is like I prefer to support smaller companies that are doing active work and trying to have other seeds for us on this side of the coast. And I feel like with climate change, especially like lettuces and stuff like that that can bolt. What are crops that are going to do better. Like I don't want to put a crop that is bred in Georgia here in the Pacific Northwest because I feel like I'm setting it up for a little bit of failure. So a lot of it has mostly been like finance based. And so I kind of have to pick the crops that I really wanted from the region. But as I become a little bit, well and some of these companies are getting a little bit bigger and they're providing a little more of an affordable cost for farmers, so I would say I would probably, just as I progressed in my farming career, I would try to buy bioregionally as I can. But yeah, a lot of it is definitely because of the climate change, because I know these seeds are going to do a lot better in my area than other seeds."*
>
> - *Interview 27, November 2024, total size 13 acres*

Discussion

This research accepts the general premise that functional and response diversity can contribute socio-ecological resilience to climate change on farms. Findings complicate the understanding of diversity in agriculture by grounding and explicating the concepts from farmers' lived experiences. Response and functional diversity enhance resilience, but what both entail from the semi-structured interviews with farmers appear broader than an "ecological" conception.

My findings indicate response diversity becomes important through planting crops and varieties at different times and different places, in addition to diversity at the crop and variety level. Functional diversity refers to the roles that different crops and varieties play within the context of markets that they sell to. Such response and functional diversity enable adaptive management practices that are key to socio-ecological resilience, namely learning through experimentation as well as flexibility.

While crop diversity is associated with resilience practices, it is not primarily motivated by a desire for resilience. Rather, crop selection is shaped by a host of factors including market strategy, farmer preferences, and landscape limitations (including climate). Thus, a strategy of 'specialized diversification' emerges, wherein farmers specialize in particular crops, varieties, or seasonal availability while still maintaining the functional and response diversity that confers resilience. Here, specialization is not at odds with diversity, but complementary to it.

Thus, climate change can be understood as altering the climatic context in which a farmers' specialized diversification strategy emerges over time. The diversity shaped by these strategies positions diversified organic farms to better handle the variability and increased extremes that climate change is bringing. On the other hand, climate change can incentivize specialization in particular crops that can handle or take advantage of climate change that work with a farmer's strategy, such as those that can handle fluctuating weather conditions and culturally relevant crops that originate in warmer climates.

Organic agriculture & resilience

These findings speak to our understanding of the intersection between organic agriculture and resilience: diversified, organic agriculture contributes to adaptive management practices that reflect socio-ecological resilience.

My findings centrally point to the context and conditions that enable organic vegetable farms to diversify in western Washington. Diversification emerges based on when, how, and to whom farmers sell their produce. While some farmers in this sample did sell to food banks and lower income communities, they also relied on income from selling to customers who could pay premiums for local, organic produce at prices that are inaccessible to most. They sold through market channels that can support organic agriculture, allowing for a higher degree of flexibility than large-scale wholesale distributors (Carlisle et al., 2022) and (in the case of direct to customer outlets) require a high level of diversity: CSA's, farmers' markets, organic produce co-ops, organic wholesale distributors, and high-end restaurants. While these market outlets may exist in western Washington, the same is not true everywhere in the country or the world. Thus, diversification may not be an option for those farmers who may want to spread their risks, but do not immediately have the necessary market channels. Future research could focus on identifying conditions that allow organic markets and practices to flourish in a particular area. Understanding why organic agriculture thrives in one area can pave the way to creating conditions for it to proliferate further.

Diversity at the seed system level is also an important condition that enables crop and variety diversification. Farmers purchase the bulk of their seed from mid-sized seed companies that can offer high quantities of trustworthy seed at affordable prices. But they often purchase more specialized or new-to-the-region seed from small, regional seed companies or informal seed networks, which offer more niche varieties that mid-sized seed companies do not, alongside bioregionally adapted seed that the farmers know was bred and grown in their region. Many authors have pointed to the threat of increased consolidation in the seed system and the prominence of high yielding hybrid varieties displacing heirloom or open-pollinated varieties. But my research shows that hybrid varieties from well-established formal seed networks can be important in diversification for resilience, especially when they exist alongside open-pollinated, regionally adapted, and heirloom varieties from informal seed networks. Thus, heterogeneity in *where* farmers source their seed an important condition for resilience conferred through diversification.

This study was limited by a lack of farmworkers in the sample. Because the sample focused on people making crop planning decisions, interviewed farmers were often either farm owners or managers. Sometimes, the interviewed farmer was the sole worker on the farm, and in other cases the participant employed farmworkers to do the bulk of the labor. Farmworkers may have different relationships with crops and experiences with climate change impacts. As those on the frontline of climate impacts, farmworkers' perspectives on agricultural resilience merit further investigation.

Limits of diversification

My findings also speak to the limits of diversification. While crop and variety diversity across spatial and temporal scales can enable practices of resilience, there are limits to that resilience. In addition to crop planning, farmers also discussed other areas where they adapt to climate change. Although a detailed accounting is outside the scope of this thesis, these behaviors include season extension through greenhouses and row covers; shifting irrigation infrastructure and implementing water conservation practices; seeking varied sources of information from institutions, sensory equipment, and other farmers; implementing worker protections; harvesting in anticipation of an extreme event; and diversifying market outlets. However, not all farmers were able to implement these practices. They discussed access to capital and land as constraints to climate adaptation. Without capital, farmers could not purchase infrastructure to help them cope with climate impacts. For smaller, newer farmers, these desired adaptations were often basic equipment necessary for farm functioning that made climate change easier to deal with as well, such as water pumps, shade structures, or storage space. For more established, mid-size or larger farmers who already had basic needs met, desired adaptations included extra greenhouses, heating for greenhouses, or relocated infrastructure out of floodplains. Land tenure also emerged as an adaptation constraint: farmers on leased land were unwilling to make investments in immobile infrastructure that may help cope with climate impacts in the short-term, but would be lost investments in the long-term (e.g. a new well, a pack shed, or a catchment pond). Farmers of color, first generation farmers, low-income farmers, and immigrant farmers were especially likely to lack access to capital and land, which are mediated by broader structural forces.

Thus, diversification alone is not enough and should not be hailed as a silver bullet when it comes to climate resilience. Indeed, the capital and land constraints that are barriers to marginalized farmers also limit their ability to adapt to climate. This adds to the growing argument that climate change should not be understood in isolation from broader socio-economic inequalities.

Precisely because many other adaptations are inaccessible to all farmers, crops and seed selection as an adaptation strategy is valuable because it was discussed by farmers across scales, land tenure status, age, racial background, experience, and other identities. This indicates that seed and crop decisions are climate adaptations that are broadly accessible to farmers of various socio-economic backgrounds—as long as the seed they are looking for is available.

While there are limits to the resilience conferred from diversity, there are also benefits to specialization. Occupying a particular market niche can also shelter farmers from climate-related disturbance –as long as there is demand for those specialty crops, a farmer will maintain their market. Oftentimes, organic agriculture is positioned in opposition to highly specialized industrial agriculture (Grandi, 2008) and specialization is positioned as part of simplifying, not diversifying processes (Petersen-Rockney et al., 2021). And even though organic agriculture *is* often more diversified, that does not negate the incidence and indeed *benefits* of specialization on these farms.

Climate adaptation

Finally, my findings speak to broader debates about how climate change motivates adaptive behavior. Climate, alongside other landscape factors like soil type and equipment availability, limit what crops are possible to grow and when. Thus, my research suggests that climate change alters the *context* in which crop decisions are made. Given this changing context, other factors like market strategy and farmer preferences shape a farmer's specialized diversification strategy. Regardless of whether farmers are consciously adapting to climate change, they constantly fine-tune crops that fit their strategy given the changing climatic context through a constant process of adaptive management. Thus, my findings offer evidence for the idea of 'autonomous adaptation,' where adaptation is not only a conscious decision but a response to climate impacts on the social and ecological contexts in which decisions are made.

Conclusion

Diversified agriculture that organic farms in this study exhibit helped farmers cope with the increased variability and extremes associated with climate change. However, this diversification was not the unique result of farmers' desires for resilience or otherwise; rather it was shaped by a number of structural factors that enable this diversification. This points to the importance of addressing structural barriers and increasing incentives for diversification (see Carlisle et al. (2022) for specific policy recommendations), both in areas with organic markets and those with predominantly conventional, industrial agriculture.

These findings also speak to how climate change interacts with other ecological, cultural, social, and economic variables that shape behavior. If climate is a context in which decisions are made, climate change can be understood as changing that climatic context. Farmers autonomously adapt to this changing context through adaptive management in a way that emphasizes their existing specialized diversification strategy shaped by market strategies, farmer preferences, and other landscape limitations. Whether the changing climatic context plays a larger or smaller role in shaping behavior, it should not be understood outside of the broader social, ecological, cultural, and economic context in which decisions are made. This means that initiatives to promote climate adaptation and resilience should understand how climate interacts with the full array of factors that motivate behavior before attempting to change them in a way that motivates climate adaptation. Climate adaptation initiatives should identify the existing practices that offer resilience (whether or not those practices are motivated by climate change) and identify the structural and cultural factors that enable those practices, as well as their limitations.

Chapter 3: Exploring the relationship between land access and perceived adaptive capacity to climate change among organic farmers in the United States: A Bayesian modeling approach

Abstract

As seasons become less predictable and extreme weather events become more frequent and intense, farmers learn to adapt. This challenge is no less for organic farmers, who make important contributions to social well-being and ecological regeneration through their food production practices. Thus, it is vital to understand the constraints that affect the extent to which organic farmers can engage in climate adaptive practices. This Chapter uses Bayesian structural equation modeling to assess the relationship between land access and perceived adaptive capacity to climate change among certified organic farmers in the United States. Survey data collected by the Organic Farming Research Foundation are integrated with meteorological data measuring drought, temperature extremes, and climatic variability. Perceived ability to adapt to climate change is used as the outcome variable to reflect the cognitive dimensions of adaptation decision-making. This Chapter more broadly signals how Bayesian approaches offer a promising way to integrate qualitative findings into quantitative analyses, while accounting for uncertainty inherent in complex socio-ecological systems. This Chapter employs a mixed-methods approach, where qualitative data informs variable selection and model priors. A latent variable is created that represents both current land access and future land needs. The model results suggest that at the population level, increased land access and land needs have a moderately negative, albeit uncertain, association with challenges adapting to climate change. Precipitation variability, relative heat extremes, challenges accessing financial capital, and increasing number of sales channels are positively associated with challenges adapting to climate change with more certainty, while increased sales through wholesale channels has a more certain, negative association.

Introduction

Globally, climate-related hazards are becoming more frequent while weather variability is increasing, both of which are associated with crop losses and yield variability (Bezner Kerr et al., 2022). In the United States, climate change is disrupting agriculture through more frequent and extreme heat and precipitation events, drought, and less predictable seasonality (Bolster et al., 2023). While in 2021, organic agriculture made up less than 1% of total agricultural acreage in the United States, it is a rapidly growing sector that accounted for 3% of U.S. farm receipts in that year and has more than doubled in acreage since the turn of the century (Raszap Skorbiansky et al., 2023). Further, organic agriculture provides numerous environmental and social benefits, including biodiversity conservation, increased soil quality, and healthy and resilient livelihoods (Seufert & Ramankutty, 2017). Therefore, it is important to understand organic agriculture's vulnerability in a changing climate.

Vulnerability to climate change is not merely caused by exposure to weather stresses—instead, it is a function of exposure to stress combined with sensitivity to that stress and capacity to adapt to it (Engle, 2011). Accordingly, adaptive capacity can moderate sensitivity and exposure and reduce vulnerability (Engle, 2011). While there is academic debate around the relative contributions of environmental stressors or social contexts to vulnerability, there is consensus that adaptive capacity is an important component that mediates vulnerability (O'Brien et al., 2007). Adaptive capacity includes minimizing exposure to stress, recovering from losses associated with that stress, and taking advantage of new opportunities (Adger & Vincent, 2005). Thus, understanding the factors that shape adaptive capacity can support agricultural management in the context of climate change. However, how to adequately measure adaptive capacity is a subject of academic debate and is laden with uncertainty (Adger & Vincent, 2005; Engle, 2011; Mortreux & Barnett, 2017; Siders, 2019; Vincent, 2007). Because adaptive capacity is formed through a complex set of interactions between social, economic, and environmental contexts and across geographic and time scales, there is uncertainty in attempts to measure it (Adger & Vincent, 2005; Vincent, 2007). Bayesian approaches can help reconcile this inherent uncertainty because they offer probabilistic, non-definite frameworks to understand relationships between variables.

This Chapter contributes to the literature on adaptive capacity to climate change by i) offering an example of how Bayesian approaches can support mixed-methods analyses while working with the inherent uncertainties in measuring adaptive capacity, ii) assessing *perceived* adaptive capacity and its relationship with land access, and iii) exploring these questions at a population-level using a nationally representative survey dataset of U.S. organic farmers.

This Chapter uses a Bayesian structural equation modeling approach to investigate the role of land access in perceived adaptive capacity to climate change among organic farmers in the United States. Bayesian approaches offer a promising way to integrate qualitative findings into quantitative analyses, while accounting for uncertainty inherent in complex socio-ecological systems. This Chapter integrates climate exposure data with a nationally representative survey of certified organic farmers in the U.S. that includes examination of perceived adaptive capacity. This paper employs "perceived adaptive capacity" as a novel outcome variable—the first study to do so using a sample of certified organic farmers in the United States to the author's best knowledge. Measuring perceived adaptive capacity allows farmers to self-assess the challenges they face with climate adaptation, as opposed to super-imposing an adaptive capacity variable or index that may lack relevance. Explanatory variables representing land access, capital access, market outlets, and climate exposure and prior beliefs around how farmers interact with perceived adaptive capacity are selected based on the qualitative study discussed in the previous Chapter. Using Bayesian approaches in a nationally-representative dataset can help assess whether and to what extent relationships identified through qualitative studies at the local level between land access, market outlets, and perceived adaptive capacity can be identified at larger scales—and provide a basis for exploring such a relationship further.

Theoretical Approaches

This Chapter employs the Sustainable Livelihoods Approach (SLA) and the contextual vulnerability frame to set up the argument that self-perceptions contribute to one's capacity to adapt to climate change and are important to consider in efforts to investigate and measure adaptive capacity.

The SLA is a widely used framework to assess the sustainability of a means of living, for which adaptive capacity contributes to. A sustainable livelihood is one that can cope with both gradual and sudden changing conditions, maintain capabilities and assets, and provide opportunities for future generations (Chambers & Conway, 1992, p. 6). Central to the SLA is the concept of capabilities, which refers to being able to perform basic functions, like eating, socializing, having shelter, and living in dignity (Sen, 1986). What is considered basic functioning can be defined relatively based on the person or the place (Chambers & Conway, 1992). Capabilities are combined with assets that are tangible (e.g., resources and stocks) and intangible (e.g., claims and access) to build a livelihood (Chambers & Conway, 1992). In other words, assets are the physical and non-physical resources that a person or household has access to, while capabilities reflect the abilities to act and mobilize those assets to build a means of living.

Scoones (1998) builds on the SLA by elaborating different types of capital that contribute to both resources and capabilities: natural capital such as land and water, social capital including networks and relationships, human capital reflecting skills and knowledge, and financial capital such as loans and savings. Researchers have included physical capital like roads and infrastructure in subsequent analyses (Pandey et al., 2017; Knutsson & Ostwald, 2023; Colting-Pulambarit et al., 2018). Capitals vary in the degree to which they are vulnerable to different shocks. For example, financial capital can be volatile and vulnerable to external markets

(Morse, 2025). Having access to a broader array of capitals can increase the resilience of livelihoods, as individuals and households are able to switch between them if one becomes less important or untenable (Morse, 2025).

A group or individual may be deemed vulnerable when they are unable to mobilize these capitals to adapt to changing conditions (Knutsson & Ostwald, 2023). Vulnerability is often framed as the extent to which an individual or group is able to cope with stresses on livelihoods and well-being (Knutsson & Ostwald, 2023). It is operationalized, historically, as a combined function of exposure to stress, sensitivity, and adaptive capacity—emphasizing the importance of an individual or household's context that contribute to vulnerabilities (Engle, 2011). The contextual (or social) framing of vulnerability reflects a dynamic interaction between environmental change and the social, economic, and political contexts with/through which it occurs (O'Brien et al., 2007). In contrast, the outcome (or biophysical) framing understands vulnerabilities as an outcome of a linear process whereby climate shocks impact a particular "exposure unit," offset by their ability to adapt (O'Brien et al., 2007). While the outcome framing of vulnerability focuses attention on naming and measuring climate exposure, impacts, and responses, the contextual framing of vulnerability invites consideration of contextual factors that influence the capacity to prepare for and respond to changing conditions. In other words, the contextual framing emphasizes research into *why* people are differentially vulnerable (*ibid*). This Chapter employs the contextual framing of vulnerability because it allows for the exploration of contextual factors like cognition and perceptions that may influence adaptive capacity and therefore vulnerability. The Chapter is guided both by a contextual vulnerability approach and the SLA in so far as adaptation means mobilizing assets to reduce vulnerability, and assessing adaptive capacity involves understanding what kinds of capitals a particular group or individual is able to mobilize (Knutsson & Ostwald, 2023).

Traditional approaches to examining adaptive capacity commonly measure it as a composite of the five capitals (or a subset of them) and their interactions with each other—often with little attention to how the assets are used. The different capitals are often combined into an index to assign scores to different actors, reflecting their access to resources and by proxy their capacity to adapt (Colting-Pulumbarit et al., 2018; Defiesta & Rapera, 2014; Kamsi et al., 2025; Li et al., 2017; Pandey et al., 2017). For example, in their research in the Philippines, Colting-Pulambarit et al. (2018) calculated a Household Adaptive Capacity Index using indicators collected through interviews and secondary datasets that were identified and categorized according to the five capitals, finding that organic farmers had higher scores than conventional farmers in all of the capitals, with the exception of physical capital. In Uttarakhand, India, Pandey et al (2017) created indices for adaptive capacity and vulnerability based on indicators aggregated at the village level, which were selected according to the five capitals and the three dimensions of vulnerability (exposure, sensitivity, and adaptive capacity), finding that rural households had higher levels of vulnerability than those closer to district headquarters.

While traditional approaches measure adaptive capacity as a set or index of capitals that reflect one's socio-economic circumstances, other research challenges the assumption that having access to more resources necessarily translates into adaptive action (Mortreux & Barnett, 2017; Nielsen & Reenberg, 2010). Cognitive factors like perceptions of risk and adaptive capacity are also important, where perceived adaptive capacity refers to people's self-assessments of their ability to act in response to threats (Elrick-Barr et al., 2017; Grothmann & Patt, 2005; Mortreux & Barnett, 2017). How one perceives their adaptive capacity may impact their capability to act: while the resources that someone has available to them can certainly constrain action, the cognitive factors around perception can influence adaptation decisions and how they use those resources (Grothmann & Patt, 2005). Perceived adaptive capacity is shaped not only by the resources available and accessible (known as 'objective' or 'generic' adaptive capacity), but also by cognitive biases and heuristics as well as social discourse on risks and adaptation (Grothmann & Patt, 2005). Perceived adaptive capacity consists of one's perceptions of how effective an adaptation action is, their ability to carry out that action ('perceived self-efficacy'), and the cost of implementing it (Grothmann & Patt, 2005). For example, when local resource managers self-assess their own ability to adapt to change, they draw on their own perceptions and experiences as opposed to assessing a standard set of capitals that may or may not be relevant to their particular context (Lockwood et al., 2015). Lockwood et al. (2015) tested constructs related to SLF's five capitals in relation to perceived adaptive capacity among farmers in Australia, finding that the most crucial construct in determining perceived adaptive capacity was not an external characteristic, but the farmer's orientation to change. Similarly, Elrick-Barr et al. (2017) find that among households in two Australian coastal communities, there were discrepancies between a household's perceived ability to act (capability) and the resources that provide the means to act (capacity): households with low socio-economic resources could nevertheless considered themselves well-equipped to handle climate impacts. In fact, one U.S. study found only a weak correlation between objective attributes of adaptive capacity and farmers' perceived adaptive capacity, indicating that perceived and adaptive capacity may be distinct measurement constructs (Gardezi & Arbuckle, 2019). Research underscoring perceived adaptive capacity is also in line with research investigating risk perceptions, independent of objective risk exposure, such as farmer's perceptions of climate change (Ricart et al., 2022; Takahashi et al., 2016). In sum, perceived adaptive capacity is an important consideration for adaptation action, and because it may be only partially affected by the resources available to an actor, merits study in its own right.

In past research, qualitative approaches have been particularly adept at assessing perceived adaptive capacity and the types of capital that most relate to them. Researchers have used qualitative approaches to apply SLA to questions around the capacity of livelihoods to adapt to changing conditions, including but not limited to environmental change. For example, through a series of focus group discussions across villages in Bangladesh, Azad & Pritchard (2022) asked participants to assess the five capitals and their interactions in contributing to adaptive capacity to flooding, finding that financial capital was most discussed. Because such qualitative studies ask participants about their adaptation strategies, they are able to directly assess perceived adaptive capacity; however, they are often unable to measure these trends at population scales. Investigating trends at population scales can help identify when phenomena are localized or generalized, such that solutions can be targeted at the appropriate scale. Investigating phenomena at population-level scales can also identify discrepancies with local-level findings, provoking lines of questioning for future studies. Thus, incorporating perceived adaptive capacity into quantitative, population-level approaches has promise. Perceived adaptive capacity can be used as a standalone response variable or integrated into an index that also measures generic adaptive capacity (see Gardezi & Arbuckle, 2019). These approaches have the benefit of directly assessing perceived adaptive capacity, while being able to look at trends over large scales that are often inaccessible in qualitative approaches.

Natural Capital, Financial Capital & Adaptive Capacity

This Chapter moves beyond index-based approaches that risk superimposing index-based definitions of adaptive capacity to more specific explorations of types of capital and their associations with perceived adaptive capacity. Namely, it explores land access as natural capital, and market channels as well as perceived access to financial capital. By exploring the quantitative relationships between these variables, this study allows for a deeper analysis of how they associate with perceived adaptive capacity in a way that grouping them together in an index may obscure.

The SLA understands land as a natural capital (Scoones, 1998) that contributes to a households' portfolio of resources (Chambers & Conway, 1992). These resources, along with other tangible and intangible assets, can then be mobilized with the support of capabilities to form a household's livelihood strategy (Chambers & Conway, 1992). As such, land is often included in quantitative analyses using SLA. Studies employing SLA often assume that having access to land increases natural capital, and therefore objective adaptive capacity (Pandey et al., 2017; Colting-Pulambarit et al., 2018). However, Bryan et al. (2015) found that at the regional scale, total cropped land was among a number of indicators defying theory-driven expectations, where regions cropping less land had greater adaptive capacity. This suggests that at the regional scale, more land does not always mean more objective adaptive capacity, and the authors suggest more research is needed to test individual indicators and their relation to vulnerability and adaptive capacity. Eakin et al. (2016) also complicate the relationship between land access and perceived adaptive capacity. They describe a farmer population in Arizona with high objective adaptive capacity, including flexible and opportunistic land access alongside other factors like irrigation infrastructure, but nevertheless feel uncertain about an increasingly volatile future, partially because of fluctuating land prices. Thus, it should not be assumed that because SLA associates more land with higher objective adaptive capacity, that that relationship always holds for perceived adaptive capacity. The relationship is worthy of further investigation.

In addition, qualitative research suggests that land size may have a non-linear relationship with adaptive capacity at the farm scale. A qualitative study in central California found that during the COVID-19 pandemic, mid-sized farmers had both the resources to quickly adapt to changing conditions and the flexibility to access new markets (Ory et al., 2024). On the other hand, small-scale farmers were often resource-constrained and encountered challenges in recouping lost sales in farmers markets and balancing new childcare responsibilities, with particularly difficult impacts for Spanish-speaking farmers. Meanwhile, large wholesale growers had resources available, but less flexibility given rigid market outlet demands and limited ability to diversify crop portfolio (Ory et al., 2024). These findings suggest a more complicated relationship between land size and adaptive capacity, which may be difficult to capture in an index-based study that doesn't isolate effects of individual variables, and warrants closer inspection.

Beyond the amount of land that farmers have access to, their security of access to that land can influence practices associated with adaptive capacity and resilience. Calo (2020) infuses the discourse around diversified food systems and adaptive capacity with questions of land tenure, asking 'who has the power to adapt?' The author argues that diversification and resilience alone, without respect to who has power to make decisions and who benefits from them, may entrench unequal power relations by placing the responsibility of responsible land management on those who may not benefit from it. Carlisle et al. (2022) found that high land rents and short-term leases restricted farmers' investment in practices that build soil health and diversified farming systems in the United States. Deaton et al. (2018) investigated the role of land tenure on the adoption of conservation practices on farms in Ontario, Canada. Generally, farmers were less likely to use cover crops on rented land compared to owned land, but similarly likely to use conservation tillage. When farmers rent land from other farmers (as opposed to non-farmers) and when they expect to rent the land for more than five years, they are more likely to employ conservation practices like cover crops, which may have high upfront costs, but longer-term benefits that support climate resilience (Deaton et al., 2018). In Malawi, farmers who owned their land were more likely than renters to use organic fertilizer, trees, intercropping, and soil water conservation – practices that yield long-term benefits by steadily building soil health (Asfaw et al., 2016) and contributing to natural capital. Therefore, literature suggests that more secure land tenure can influence production practices that build natural capital in a way that is assumed to contribute to adaptive capacity. However, the association between land tenure and *perceived* adaptive capacity requires more investigation, given literature that shows that access to resources does not necessarily translate to using those resources for adaptive action (Mortreux & Barnett, 2017).

While some might assume that farmland access within the United States is more stable than in places with weaker government institutions, this neglects the disparate and racialized distribution of land within the United States, wherein some have more secure land access than other. Land size and tenure are connected with broader systems of power and discrimination that make land access particularly challenging for new and beginning farmers, especially immigrant farmers and farmer of color (Horst & Marion, 2019; Minkoff-Zern, 2025).

Access to market outlets can also shape agricultural practices that can influence climate resilience and adaptive capacity, where market access is often understood as social or financial capital, and is related to growing scale and farm size. In California, larger growers selling to wholesale markets likely need to follow strict production schedules, which dissuade cover cropping and incentivize working land even when it's too wet, damaging soil health with negative impacts on climate resilience (Carlisle et al., 2022). Wholesale buyers place a premium on crops that are uniform in appearance, taste, and harvest time (Carlisle et al., 2022), which is difficult to achieve with high levels of intra-specific diversity. Meanwhile, producers who sell directly to market (who are more likely to be small- and mid-sized producers) find the market demand for diverse crops and varieties from their farmers market or CSA customers (Carlisle et al., 2022). Planting diverse mixes of crops can increase adaptive capacity by creating a 'portfolio effect', such that if one crop fails because of a stressor, another may survive (Yachi & Loreau, 1999). Petersen-Rockney et al. (2021) describe diversifying process that increase socio-ecological complexity and enable 'broad and nimble' capacity to adapt to the triple threat of climate change, biodiversity loss, and food insecurity. Thus, it is reasonable to assume that selling to mostly wholesale outlets and selling to fewer kinds of outlets is associated with less flexibility, resilience and adaptive capacity.

Bayesian Statistics & Mixed Methods Research

Bayesian models are adept at representing the uncertainty laden in attempts to quantify dynamics in complex socio-ecological systems. There is inherent uncertainty in measuring adaptive capacity, especially when applying similar indexes across different scales (Vincent, 2007). Vincent (2007) describes sources of uncertainty in adaptive capacity measurements, including theoretical decisions about which variables to include, how to measure them, which direction they influence adaptive capacity, and how those variables change over time. Adaptive capacity relies on a range of socio-economic as well as cognitive variables, including governance, market forces, demographic change, and technological diffusion—each with their own specific uncertainties in how they are measured and in their interactions with each other (Adger & Vincent, 2005). Thus, the range of uncertainty can be non-trivial when attempting to assess adaptive capacity (Adger & Vincent, 2005). This uncertainty compounds across geographic and time scales, as vulnerability operates differently at particular scales (Adger & Vincent, 2005). Accordingly, it has been suggested that adaptive capacity should be understood as a space of possible options within which adaptation decisions can be made, as opposed to a singular defined path (Adger & Vincent, 2005).

Bayesian models reflect uncertainty inherent in modeling complex phenomena because they suggest probabilistic, non-definite relationships between variables (Kelly (Letcher) et al., 2013). As explained by Kruschke (2015, p. 20), "The essence of Bayesian inference is reallocation of credibility across possibilities," or in other words, the assignment of probability distribution to parameters ("posterior") based on both previous information ("prior") and observed data. In the model presented in this Chapter, parameter estimates reflect the relationships between explanatory and latent or outcome variables. Thus, instead of providing single, definite values for parameters, Bayesian statistics offer a *set of possible values* for parameters that show how explanatory variables (e.g. land access) are associated with the outcome variable (e.g. perceived adaptive capacity). Just as Adger & Vincent (2005) understand adaptive capacity as a range of possible actions as opposed to a single, defined pathway, Bayesian statistics offer a range of possible associations between explanatory and outcome variables, as opposed to single, fixed values. Embracing uncertainty in this way is especially useful in this study, as there is considerable uncertainty in applying findings at the local level to a model at the population scale.

The use of "credible intervals" exemplifies the probabilistic nature of Bayesian modeling approaches. In the Bayesian world, a 95% credible interval refers to a 95% probability that the parameter estimate lies between A and B (Hespanhol et al., 2019). On the other hand, frequentist statistics offer confidence intervals, wherein a 95% confidence interval means that if the experiment were repeated 100 times with different samples, we expect that 95 of those confidence intervals would contain the true, fixed value, and therefore can be 95% confident that the interval contains that value (Hespanhol et al., 2019). By offering *probability distributions* of parameter estimates (instead of "fixed" values from frequentist approaches), Bayesian approaches can directly quantify uncertainty in the association between two variables. For example, if the upper and lower 95% credible intervals for a parameter are both positive, then there is 95% credibility that the associated variable has a positive relationship with the outcome variable. Meanwhile, if the lower 95% credible interval of a parameter estimate is negative and the upper interval is positive, this indicates increased uncertainty around the directionality of the relationship between the predictor and outcome variables. While frequentist confidence intervals may be interpreted similarly, they are often read as fixed values, compared to the distributions offered by Bayesian credible intervals. Probabilistic parameter estimates can address some of Vincent (2007)'s points around uncertainty in measuring adaptive capacity. Namely, they can encompass uncertainty in the directionality and ongoing shifts of predictor variables' interactions with each other and the outcome variable – however, they cannot address the larger uncertainty involved in selecting variables and how to measure them.

Bayesian statistical approaches are also particularly useful in mixed-methods studies as they are adept at incorporating qualitative findings into quantitative models. Hypotheses based on qualitative studies can be incorporated into Bayesian models through "priors" – initial beliefs about the distribution of possible values for model parameters – which are then combined with the observed data to determine "posterior distributions" – reallocated distributions of possible values for model parameters. Thus, Bayesian approaches can support the investigation of complex socio-ecological phenomena like vulnerability and adaptive capacity, which have been investigated across scales and with a variety of methodologies. In particular, through priors, Bayesian approaches enable the integration of qualitative and quantitative approaches, reflecting a view of knowledge that is partial and iterative.

In this Chapter, Bayesian structural equation modeling is used to assess the relationship between perceived adaptive capacity and variables that represent access to land and natural capital, like farm size and land tenure. Qualitative studies discussed above suggest relationships between these variables and adaptive capacity: insecure land tenure, very small and very large farm sizes, as well as market channels associated with inflexible production may reduce adaptive capacity. However, these relationships have yet to be explored at population level scales and with respect to perceived adaptive capacity. Bayesian approaches allow for the incorporation of prior information from qualitative findings into quantitative models, and therefore lend themselves well to testing hypothesized relationships between variables suggested by qualitative studies (Kelly (Letcher) et al., 2013). Models with different priors can be compared against each other to assess which priors best enable the prediction of observed data. For example, Bayesian approaches allow for incorporating priors reflected in statements such as 'land access increases perceived challenges adapting to climate change' (by setting a prior distribution that is mostly positive) or 'land access decreases perceived challenges adapting to climate change' (by setting a prior distribution that is mostly negative), and comparing the fitness of two models with the same structure but different priors. The inclusion of strong priors can be understood as an admission of the partiality of knowledge—we have prior beliefs about how we think the world works, and we choose to be explicit about those beliefs. Priors can also be iteratively revised as new information is gained through either qualitative or quantitative methods, reflecting the iterative process of knowledge production. Findings from Bayesian models can then be used to guide future qualitative studies to assess if and how relationships at the population scale present at local scales.

Some studies have begun using Bayesian approaches to assess sustainable livelihoods strategies and resilience, vulnerability, or adaptive capacity. For example, Merritt et al. (2016) use Bayesian networks to create a model for natural capital that can assess the impact of watershed development programs on household resilience to drought in India. However, it is a budding methodological approach in the human dimensions of environmental change literature, used by only a handful of studies.

Methods

Survey data source

This model uses secondary survey data collected by the Organic Farming Research Foundation as part of the National Organic Research Agenda (NORA) (Snyder et al., 2022). One thousand fifty-nine (N = 1,059) certified organic farmers in the United States conducted the online survey in 2019 and 2020. Figure 1 shows a map displaying locations of survey participants whose responses were used in the model. Eligible participants were invited to complete the survey using a mix of convenience and random sampling, and the sample reflects demographic and geographic population distributions among organic farmers in the U.S. (see survey documentation in Snyder et al. (2022) for more information). The survey asked about farm descriptors, production practices, production and non-production challenges, market channels, and information sources. The NORA survey was distributed in tandem with the State of Organic Seed Survey (Hubbard et al., 2022).

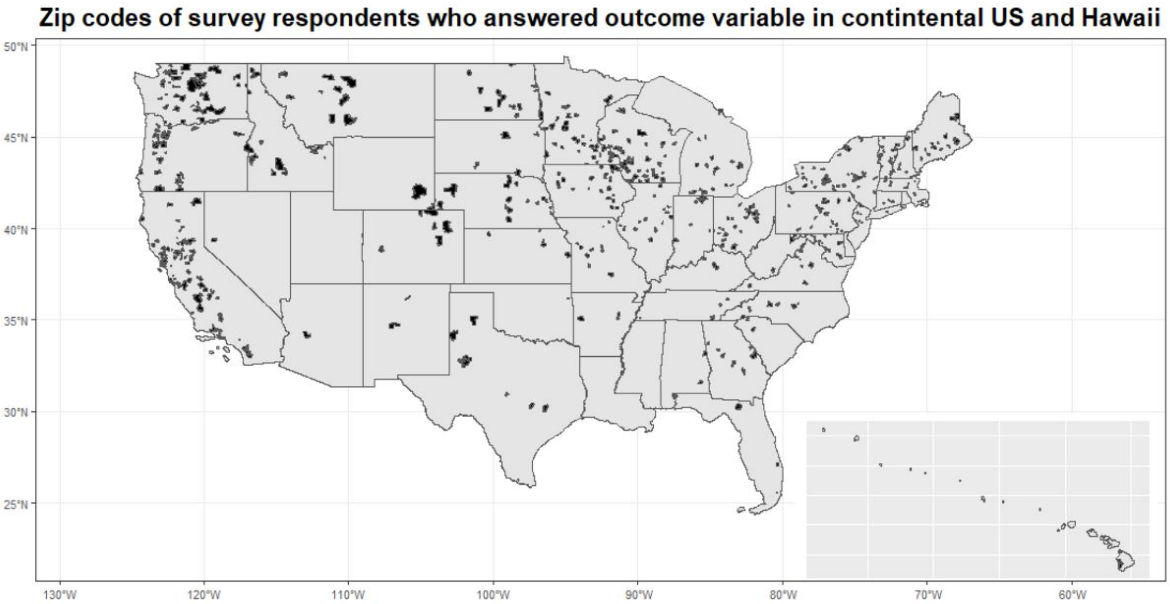

Figure 1: Map displaying zip codes of survey respondents whose answered the outcome variable and whose responses were used in the model.

Model description

Among other questions, survey respondents were presented a list of twenty-one production challenges and asked, "How much has each of these been a challenge to you in your certified organic farm operation?" One of the listed challenges was "Adapting to climate change" (others included "managing production costs", "controlling weeds", and other common production issues). Participants responded on a Likert scale ranging from "not a challenge" to "strong challenge" or could mark not applicable. The response to this question is understood as a proxy for perceived adaptive capacity to climate change and serves as the outcome variable for this model. The 718 eligible survey respondents who answered this question constituted the sample used in the model.

Two versions of a Bayesian ordinal structural equation model were developed to estimate the associations between land access, market outlets, perceived access to capital, and climate exposure with perceived adaptive capacity to climate change (model structure is displayed in Figure 2). All modeling was conducted using the R package "brms" (Bürkner, 2017). A Bayesian approach was selected to allow for the integration of prior beliefs collected through qualitative data and as it is compatible with this Chapter's understanding of uncertainty as inherent in measurements of adaptive capacity. A structural equation model was created to estimate direct effects of variables representing natural capital, financial capital and climate exposure on perceived adaptive capacity, as well as indirect effects through the construction of a latent variable representing land access and future land needs. Model 1 included only direct effects, while Models 2 and 3 included both direct effects and indirect effects modeled through the latent variable. While concurrently modeling both direct and indirect effects may surface concerns around multi-collinearity in frequentist approaches, such a model structure is standard practice in Bayesian SEM, where priors can be used to regularize parameter estimates if issues with identification arise (Bollen & Noble, 2011; Gelman et al., 2013). Partial least-squares SEM was selected over covariance-based SEM to enable model complexity given the sample size.

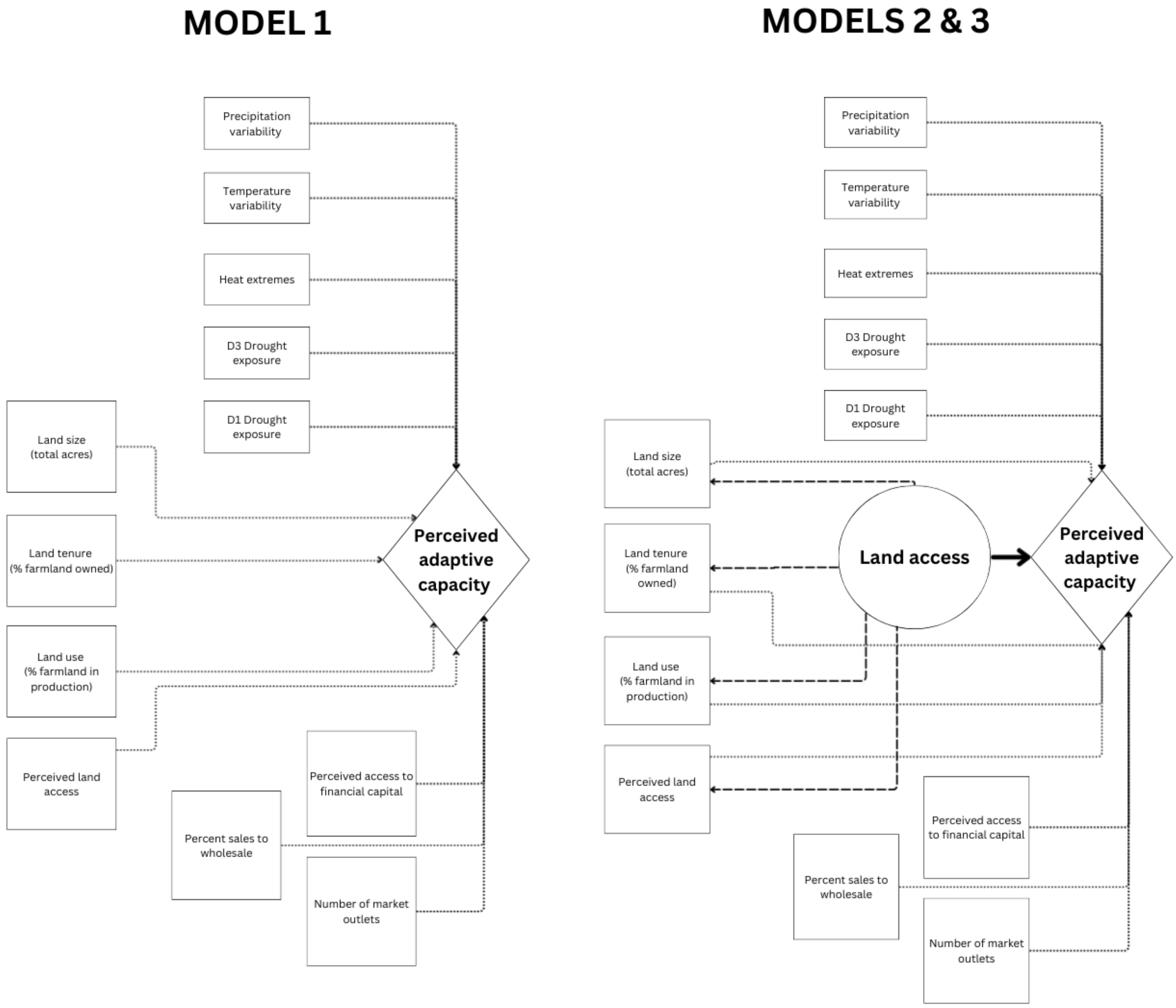

Figure 2: Conceptual diagram of the Bayesian structural equation model. Squares represent explanatory variables that are observed; circle represents latent explanatory variable; diamond represents outcome variable.

Survey variable selection

The primary variable of interest for this model is a latent variable representing land access. Qualitative interviews with farmers in western Washington State in summer of 2024 indicated that lack of secure access to land can constrain the ability to adapt to climate change. Table 1 gives examples of the challenges around land and capital access that were discussed in relation to climate adaptation, and how frequently they were mentioned over 28 interviews.

Table 1: Table displaying examples of adaptation constraints related to land and financial capital from the author's qualitative research.

Adaptation Constraint	No. of Interviews	Illustration
Land	11	
Land size	4	*"But I will tell you, the biggest challenge for us is resources. So most people can deal with climate change because there's things you can do to protect your crop. And because we are small scale, we are not farming a hundred to a thousand acres of land. If you have the resources, you can cope with the climate change. One of the things that we've faced the first year we tried to grow sorghum was water. We did not have any money to install irrigation, so we bought a small pump that was hooking up to the back of the tractor, and my husband would drive. And then we had horses, and then we bought two tanks that we put on both sides of the farm to feed at the water and then pump the water from there to the sorghum. That was really hard."*
Land tenure	6	*"The well that we have is not big enough really, doesn't have enough capacity for what we need. But then good luck getting a new one. Because permits. And then the cost of digging a well on property we don't own."*
Land location	2	*"All my infrastructure is hardcore in the floodplain. We were actively trying to do this: We want to build a wash station, pack shed, cooler out like closer to where we farm, like out in the high ground away from the floodplain so we can actually have a space that never gets flooded. That infrastructure, that's my main stress and my main thing right now. We got this place with all infrastructure in a floodplain. We're trying to totally redesign it so that it's far away from any flood waters, closer to where we actually grow the food anyway."*
Financial capital	14	*"If money really weren't a consideration, if I had lots of capital, which I don't, I probably start to consider about doing more heating in some of my high tunnels. Just so that I could stretch the season that extra three-four weeks."*

A latent variable was constructed using four observed variables representing land access: total acreage, percent of land owned, percent of land not in production, and the Likert scale response to “accessing land” as part of the question: “How much has each of these been a challenge to you in your certified organic farm operation?” Here, total acreage was used to indicate land size, percent of land owned indicates land tenure, percent of land not in production shows how much extra land farmers have to use for crop rotations, and their Likert scale response indicates perceived challenges accessing land. Using the SLA, total acreage and percent of farmland owned approximate resources, percent of farmland own represents capability to use those resources, and perceived challenges accessing land represents perceived access to resources. These variables were both used as individual predictors for the outcome variable and also combined into a single latent variable that then was an input for the outcome variable.

Sales channels and perceived access to capital were also included as explanatory variables in the model. As per Ory et al. (2024) sales channels and access to capital are related to farm size and influence adaptive capacity: larger growers selling to wholesale outlets may have less flexible production schedules, rendering adaptation difficult, but more access to capital. Of the market channels collected in the survey, only wholesale was included in the model because descriptive statistics showed that it negatively correlated with other market strategies. Number of sales channels was also included by summing the total number of sales channels used, with the assumption that selling through more market outlets can increase flexibility if a farmer needs to pivot how they sell their produce due to a challenging weather condition. Access to financial capital was approximated using the Likert scale response to “accessing capital” as part of the question: “How much has each of these been a challenge to you in your certified organic farm operation?”. While there were no direct measures for economic status, this approximates perceived ability to access capital necessary for desired projects.

Climate variables

Climate variables included in the survey are precipitation variability, temperature variability, extreme heat exposure, and moderate and severe drought exposure. Precipitation variability, temperature variability, and extreme heat data were collected at the zip code level for 2015-2019, encompassing the five growing seasons preceding survey collection (which occurred in between fall 2019 and summer 2020). This five-year time span reflects the length of time farmers referenced in interviews about climate change impacts. Drought data were collected over a slightly longer time span, for the six preceding growing seasons from 2014-2019, to reflect its cumulative and multi-year nature and ability to persist over several seasons.

Precipitation & temperature variability: In qualitative interviews, twenty-five out of twenty-eight farmers discussed increasingly unpredictable weather as an impact of climate change. Climate science has also shown that climate change causes increased variability in precipitation across most of the global land area (Pendergrass et al., 2017) and in variability in summertime temperatures in mid-latitude regions (Vargas Zeppetello & Battisti, 2020). One farmer in a qualitative study conducted by the author investigating climate adaptation among organic farmers in western Washington remarked:

> *"Some years it's freezing cold and rains every single day until July 4th or whatever. And other years we're scrambling to get the irrigation running in early April.* ***It's like, not reliable****."*

Thus, precipitation and temperature variability were included as predictor variables as two indicators of exposure to climate change (alongside drought and extreme heat). Data for these metrics came from ERA 5 – Land, which has a 9 km spatial resolution (smaller than 99.7% of zip codes in the dataset) (Muñoz-Sabater et al., 2021). Variability was measured as the sum of squares over a five-year period of the difference between each zip code's daily mean temperatures and long-term average mean temperature. For each day between 2015 and 2019, daily mean temperatures were subtracted from smoothed long-term average temperature for that day and its four nearest neighbors for all the years leading up to the focal year, starting from 1998 (when the median farmer in the dataset started farming). For example, the mean temperature of July 10th in 2015 was subtracted from the average mean temperature of July 8th-12th from 1998-2014. This value was calculated for each day for each year from 2015-2019 (the five years leading up the survey). The five-year time span was selected because in qualitative interviews, farmers discussed climate events that had occurred in the past five years. These difference values were filtered to each zip code's respective growing season (first and last frost dates for each zip code were scraped from *The Old Farmer's Almanac*, n.d.). For each year, for each zip code, these difference values were squared and summed together. All years' precipitation and temperature variability metrics had roughly equivalent loadings onto precipitation and temperature variability latent variables, respectively, indicating that summing all years together (instead of getting sums for each one and using them as separate variable in the dataset) would yield similar results. Thus, the sum of squares was calculated for each growing season day from 2015-2019, for each zip code.

Heat extremes: Heat extremes were also selected as a variable to calculate given the increasing incidence of heatwaves associated with climate change, particularly in the western US (Su et al., 2023). Relative heat extremes were calculated as opposed to absolute heat extremes, given the adaptability of humans and human systems to average heat temperatures for their area (Sheridan & Dixon, 2017) and because average temperatures in a given area are often used instead of absolute thresholds (Sheridan & Allen, 2015). Thus, the daily long-term average temperatures were used to calculate the temperature at the 98th percentile for each zip code, after filtering for the growing season. This 98th percentile temperature was used as a threshold for each zip code to determine a location-specific 'extreme heat'. Then, the number of days with a mean temperature exceeding that threshold was calculated for each year from 2015-2019. These yearly extreme heat days all had similar loadings onto a latent extreme heat variable, indicating that they could all be combined. Thus, the yearly extreme heat days were summed into a single variable. This number represents the number of days between 2015 and 2019 exceeding a location-specific extreme heat threshold.

Drought: Drought was selected as a variable given the changing nature of drought associated with climate change (Su et al., 2023). Drought is a complex phenomenon that can be measured in different ways and using different metrics (Zargar et al., 2011). Given the complexity of drought measurements, an existing and well-established metric was used: the United States Drought Monitor (USDM). USDM is a composite drought index that takes into account agricultural, hydrological, and meteorological drought indicators, alongside information from local experts (Svoboda et al., 2002). It offers a weekly classification of droughts on a scale of D0 (abnormally dry), D1 (moderate drought), D2 (severe drought), D3 (severe drought) to D4 (extreme drought). Oftentimes, consecutive weeks above a certain drought threshold is used to assess the length of time and severity of drought exposure (Leeper et al., 2022). This paper integrates two drought metrics: the total number of consecutive weeks in D1 drought or higher between 2014 and 2019, and the total number of consecutive weeks in D3 drought or higher between 2014 and 2019. These two metrics capture length of time exposed to droughts that were at least moderate, and those that were at least extreme, respectively. These drought data were available to download from the USDM website at the county level, and spatially weighted averages were created using ArcGIS to find the drought data at the zip code level.

Multiple imputation

Multiple imputation was used to fill in missing data for explanatory variables, using the mice R package (v3.13.0; van Buuren & Groothuis-Oudshoorn, 2011). See Table 2 for number of missing values per variable. Seven datasets were imputed across forty iterations. All numeric or ordinal variables for all observations in the OFRF dataset were used during the imputation process. Then, the dataset was filtered to only include the 718 observations with original data for the outcome variable and only include variables that would be used in the model. Climate data was joined by zip code. For observations with missing climate data (i.e. respondents who did not share a zip code or who shared a non-existent zip code), the mean of the respective climate variable was used.

Diagnostics of multiple imputation were conducted to ensure that missing information was filled in accurately. Diagnostic plots in the mice package show that the chains were well-mixed. Distribution plots for each of the imputed variables were also created (see Appendix Figures 1-6). Distributions were relatively similar, except for the variable indicating percent of sales to wholesale. This problem is currently being addressed, though it has yet to be resolved.

Table 2: Number of missing and subsequently imputed observations for each variable used in model.

Variable	Number of imputed observations	Percent of observations used in model that were imputed
Survey variables (imputed with mice R package)		
Perceived challenges accessing land	128	17.83%
Perceived challenges accessing capital	100	13.93%
Number of sales channels	71	9.89%
Percent of sales to wholesale	71	9.89%
Total acreage	18	2.51%
Percent of acres owned	18	2.51%
Percent of acres not in production	18	2.51%
Climate variables (imputed with mean values)		
Temperature variability	27	3.76%
Precipitation variability	27	3.76%
Moderate drought	23	3.20%
Severe drought	23	3.20%
Extreme heat	27	3.76%

Scaling

Select variables were scaled in order to minimize skewing model results. Original distributions of model variables were compared against multiple scaling techniques. The scaling technique that preserved the original distribution of the focal variable was selected. Total acreage was logged, while all the climate variables were scaled to obtain a mean of 0 and a standard deviation of 1. The variable representing sales to wholesale was converted from a 0-100 scale to a 0-1 scale.

Prior Selection

Weakly regularizing priors were used for all explanatory variable effects on the outcome variable in Models 1 and 2, suggesting that the model should explore parameter estimates within a distribution that is equally negative and positive. Weakly regularizing priors reflect a lack of strong beliefs about the direction of the effect of an explanatory variable on the outcome and are thus appropriate to use as baseline models to compare against others with stronger priors. Distributions for the weakly regularizing priors were established as normal distributions with a mean of 0 and a standard deviation of 1, creating a prior distribution centered on 0 and with 95% credible intervals from -1.96 to 1.96. A mean of 0 was selected to reflect the prior belief that positive and negative parameter estimates were equally likely. A standard deviation of 1 was selected to constrain the model's exploration within a range wide enough to allow for the possibility of larger effects, but not so wide as for the model to spend an excessive amount of time exploring the distribution and therefore risk not converging.

In Model 3, a stronger prior was used for the land access latent variable, while weakly regularizing priors were used for all other explanatory variables' effect on the outcome. A stronger prior was used exclusively for the land access latent variable to isolate the effect of the prior belief for the variable of interest on model fitness, given this Chapter's focus in the effect of land access on perceived adaptive capacity. This prior reflected the belief that increased land access is associated with decreased reported challenges adapting to climate change (or in other words, greater perceived adaptive capacity). The prior was specified using a normal distribution with a mean of -1 and a standard deviation of 2, establishing a distribution centered on -1 and where the 95% credible interval is -4.92 to 2.92. This created a distribution that is mostly negative while also being slightly positive, in order to reflect the belief that the latent variable most likely has a negative relationship with the outcome variable, but a positive relationship is also possible. Because the prior distribution was not fully negative, it reflected uncertainty in the author's belief that increased land access is associated with increased perceived adaptive capacity: the belief is based on quotes from several farmers in a qualitative study, which is not enough to imply certainty in the association. A standard deviation of 2 was selected to widen the prior distribution, allowing for the possibility of a stronger negative association than was suggested by the weakly regularizing prior.

Results

Three models were estimated using Bayesian structural equation modeling. Model 1, or "Individual model" estimates only the direct effects of variable representing natural capital, financial capital, and exposure to climate change. Model 2, or "Full Model", estimates both direct effects and indirect effects through the addition of a latent variable representing the shared variance of the natural capital variables. Model 3, or "Full Model with Priors," similarly estimates both direct and indirect effects and has the same structure as Model 2, while also including a stronger prior for the belief that decreased land access is associated with increased challenges adapting to climate change. For each model, seven versions were estimated—one for each of the seven imputed datasets. All versions converged successfully. The results were then combined using the combine_models function in the R package "brms" (Bürkner, 2017), which merges the posterior samples from each version into a single summary model that reflects uncertainty across the imputed datasets. Model results are discussed in detail below.

Model 1: Individual model

Table 3 displays results from the model which only included direct effects of individual variables predicting the outcome variable (i.e. without the latent variable).

Table 3: Results from model with only direct effects on outcome variable. Variables are grouped by financial capital, natural capital, or climate change exposure.

	Variable	Estimate	Est.Error	Lower 95% CI	Upper 95% CI
Financial Capital					
	Number of sales channels	0.183	0.080	0.024	0.339
	Percent sales to wholesale	-0.525	0.188	-0.890	-0.154
	Challenge accessing capital	0.232	0.055	0.125	0.341
Natural Capital					
	Total acres (logged)	0.030	0.040	-0.049	0.108
	Percent of land owned	0.047	0.195	-0.335	0.429
	Percent of land not in production	0.425	0.270	-0.105	0.955
	Challenge accessing land	-0.013	0.055	-0.121	0.095
Climate Change Exposure					
	Precipitation variability	0.176	0.105	-0.012	0.399
	Temperature variability	-0.094	0.086	-0.264	0.076
	Extreme heat	0.131	0.096	-0.056	0.319
	Moderate drought	0.010	0.140	-0.264	0.285
	Extreme drought	-0.064	0.133	-0.324	0.198

Two elements of uncertainty can be interpreted from these results. Estimated error values represent the standard deviation of the posterior distributions. In other words, estimated error values represent uncertainty in the *magnitude* of the effect of the explanatory variable on the outcome. Meanwhile, the locations of the 95% credible interval (CrI) values represent uncertainty in the *direction* of the effect. If both the upper and lower bounds are above or below zero (e.g. number of sales channels), this represents greater certainty that the explanatory variable has a positive or negative association with the outcome. If one of the bounds is positive and the other is negative, but one of them is near zero (e.g. temperature variability), this represents a suggested association, albeit slightly less certain. If zero is near the center of the lower bound to upper bound range (e.g. moderate drought), this represents greater uncertainty in the direction of the association between the explanatory and outcome variables. All intervals reported are 95% credible intervals.

The variables that had more certain positive or negative associations with perceived adaptive capacity were all associated with financial capital, representing perceived access to financial capital and sales strategy. Perceived challenges accessing capital had a more certain and moderately positive association with perceived challenges adapting to climate change (0.23, CrI [0.13, 0.34]), as both 95% CrI values were positive. Increases in number of sales channels also had a more certain, though slightly weaker relationship with the outcome variable, (0.18, CrI [0.02, 0.34]). Increasing the produce sold through wholesale channels was negatively associated with perceived challenges adapting to climate change, with a degree of certainty because both 95% CrI estimates were negative (-0.53, CrI [-0.89, -0.15]). However, it is important to note that the imputation for the variable representing percent of produce sold through wholesale did not accurately reflect the distribution of that variable in the original data (see Appendix Figure 3).

Land variables associated with natural capital had more uncertain effects on the outcome variable. Farm size (0.03, CrI [-0.05, 0.11]), percent of farmland owned (0.05, CrI [-0.34, 0.43]), and perceived challenge accessing land (-0.01, CrI [-0.12, 0.10]) all had estimates near zero and 95% credible intervals that spanned zero. This indicates that there is a greater degree of uncertainty in the direction of their effect on perceived challenges adapting to climate change, compared to the financial capital variables. Percent of land not used in production had a positive and slightly more certain relationship with the outcome variable, with an estimate of 0.42 (CrI [-0.11, 0.96]), suggesting that it is much more likely to be a positive than a negative effect. In other words, the land variable with the more certain association with perceived adaptive capacity is having a higher percent of land not used for production: more 'spare' land is associated with more reported challenges adapting to climate change.

Interestingly, only two climate variables had a very likely positive relationship with perceived challenges adapting to climate change: precipitation variability (0.18, CrI

[-0.01, 0.40]) and extreme heat (0.13, CrI [-0.06, 0.32]). As precipitation becomes increasingly uncertain and as the number of extreme heat days (measured relative to the local averages) increases, so does perceived challenges adapting to climate change. Exposure to moderate drought (0.01, CrI [-0.26, 0.20]), extreme drought (-0.06, CrI [-0.32, 0.20]), and temperature variability (-0.09, CrI [-0.26, 0.08]) had weak and uncertain relationships with the outcome variable.

Model 2: Full model

Table 4 displays model results from a model that includes both direct effects of climate, land, sales, and capital variables, as well as the indirect effects of land variables. The model is estimating the indirect effects of the land variables through their shared variance, represented through the latent variable, as well the direct effect of each individual variable's leftover variance. Table 4 displays combined model results from the seven imputed datasets, which all converged.

Table 4: Model with both direct and indirect effects. Variables are grouped first by whether they predict the outcome variable or the latent variable, then by whether they represent financial capital, natural capital, or exposure to climate change.

		Variable	Estimate	Est.Error	Lower 95% CI	Upper 95% CI
Predicting Perceived Adaptive Capacity						
	Climate Change Exposure					
		Extreme drought	-0.071	0.134	-0.333	0.192
		Extreme heat	0.130	0.096	-0.058	0.318
		Moderate drought	0.012	0.140	-0.262	0.288
		Precipitation variability	0.176	0.105	-0.014	0.398
		Temperature variability	-0.092	0.087	-0.262	0.077
	Financial Capital					
		Challenge accessing capital	0.235	0.055	0.128	0.344
		Number of sales channels	0.186	0.080	0.028	0.342
		Percent sales to wholesale	-0.523	0.188	-0.891	-0.153
	Natural Capital					
		Land access (latent variable)	-0.353	0.298	-0.938	0.230
		Challenge accessing land	-0.015	0.056	-0.124	0.094
		Percent of land not in production	0.466	0.274	-0.070	1.004
		Percent of land owned	0.081	0.198	-0.304	0.471
		Total acres (logged)	0.127	0.090	-0.049	0.303
Predicting Land Access						
	Natural Capital					
		Challenge accessing land (indirect)	0.347	0.137	0.082	0.619
		Owning all land (indirect)	1.024	0.091	0.850	1.207
		Percent of land not in production (indirect)	-0.463	0.043	-0.545	-0.379
		Percent of land owned (indirect)	0.200	0.043	0.115	0.285
		Total acres (logged, indirect)	1.000	0.000	1.000	1.000

The observed variables comprising the latent variable (labeled "Land access (latent variable)" in Table 4) included perceived challenge accessing land (0.35, CrI [0.08, 0.62]), percent of land owned (0.20, CrI [0.12, 0.29]), the condition of owning all land (1.02, CrI [0.85, 1.21]), percent of land not in production (−0.46, CrI [−0.55, −0.37]), and total acres (logged; 1.00, CrI [1.00, 1.00]). The latent variable had reasonably high certainty in estimating the shared variance of these land variables. This is because each of the variables have 95% credible intervals that were either fully above or below 0, indicating high certainty in the direction that each of the land variables load onto the latent variable. Most of the variables predicted by the land access latent variable had high certainty because they had small estimated errors relative to the estimated values, except for challenge accessing land which had slightly higher uncertainty. The latent variable was constructed with respect to total acreage, which was set to a constant of 1.

Expectedly, owning all of one's land (1.02, CrI [0.85, 1.21]) or a larger share of their land (0.20, CrI [0.12, 0.29]) and having a larger farm size (1.00, CrI [1.00, 1.00]) implies "increased access to land" (i.e. has a positive loading onto the latent variable representing land access with high certainty). However, reporting increased challenges accessing land (0.35, CrI [0.08, 0.62]) also loads in the same direction and with similar certainty as having larger total land size and owning more of that land. This is surprising, because the assumption was that those who already had large farms or owned most of their farms would not report challenges accessing land. This may be explained, however, if people who already have access to large amounts of land need more to make a marginal difference in their production practices. Similarly, having a larger percent of land not in production (−0.46, CrI [−0.55, −0.37]) loaded negatively onto the latent variable, indicating that people who had a higher percentage of their land in production had higher land access. This was also surprising, because the hypothesis was that those who had more 'spare' land would have more land for crop rotations and therefore more land access. However, it is possible that these who used most of their land are the ones that need more land for future production. In sum, I interpret the land access variable as indicating a respondent's current land access (high total acreage and high land tenure) *and* their need and challenge in accessing additional land (high reported challenges accessing land and low percentage of 'spare' nonproductive land).

Overall, the latent variable, which represents high current land access *and* the need for and challenges accessing additional land, has a non-definite negative relationship with the outcome variable (-0.35, CrI [-0.94, 0.23]). This means that it is more likely that as current land access and future land needs decrease, farmers perceive greater challenges adapting to climate change. However, there is relatively high uncertainty. While this negative relationship is more likely, it is also possible that there is a positive relationship between land access and perceived challenges accessing climate change.

While most of the direct effects of the land variables remained relatively stable, some of the individual land variables do change in their relationship with the outcome when they are modeled both directly and indirectly through the latent variable. The direct effects represent the ‘leftover’ variance in the explanatory land variables that are not accounted for through their shared variance modeled by the latent variable. The relationship between total farm size and perceived challenges adapting to climate change increases and becomes more likely to be positive (0.13, CrI [-0.05, 0.30] in Model 2, as compared to 0.030, CrI [-0.05, 0.11] in Model 1). This implies that when land access is accounted for, as total acreage increases, perceived challenges adapting to climate change also likely increases. The other land variable did not see a significant change following the inclusion of the latent variable.

Notably, the latent variable (-0.35, CrI [-0.94, 0.23]) has a stronger relationship than three out of the four individual land variables in either the full or the individual model. This indicates that the latent variable of land access/land needs predicts the individual variables, and when that latent variable is accounted for, it explains more variation in the outcome variable than explained by the individual variables of total size, percent of farmland owned, or perceived challenges accessing land. Thus, it is an important variable to include in the model in order to understand the relationship between land and the outcome variable. The same is not true for percent of land not in production, which has a similarly moderate effect on the outcome variable both with and without the inclusion of the latent variable.

Model 3: Full model with stronger prior

Table 5: Model with both direct and indirect effects, where a stronger prior for the latent variable suggests a more likely negative relationship between the latent variable and the outcome variable. Variables are grouped first by whether they predict the outcome variable (perceived adaptive capacity) or the latent variable, then by whether they represent financial capital, natural capital, or exposure to climate change.

		Variable	Estimate	Est.Error	Lower 95% CI	Upper 95% CI
Predicting Perceived Adaptive Capacity						
	Climate Change Exposure					
		Extreme drought	-0.071	0.134	-0.335	0.193
		Extreme heat	0.130	0.096	-0.058	0.318
		Moderate drought	0.012	0.140	-0.264	0.288
		Precipitation variability	0.176	0.105	-0.013	0.397
		Temperature variability	-0.092	0.086	-0.262	0.077
	Financial Capital					
		Challenge accessing capital	0.235	0.055	0.128	0.344
		Number of sales channels	0.186	0.080	0.028	0.341
		Percent sales to wholesale	-0.522	0.188	-0.889	-0.155
	Natural Capital					
		Land access (latent variable)	-0.390	0.310	-1.004	0.211
		Challenge accessing land	-0.015	0.055	-0.124	0.093
		Percent of land not in production	0.472	0.275	-0.066	1.009
		Percent of land owned	0.084	0.198	-0.303	0.472
		Total acres (logged)	0.137	0.093	-0.044	0.320
Predicting Land Access						
	Natural Capital					
		Challenge accessing land (indirect)	0.347	0.137	0.083	0.620
		Owning all land (indirect)	1.024	0.091	0.851	1.207
		Percent of land not in production (indirect)	-0.463	0.043	-0.546	-0.378
		Percent of land owned (indirect)	0.200	0.043	0.114	0.284
		Total acres (logged, indirect)	1.000	0.000	1.000	1.000

Table 5 shows the full model, with a stronger prior to incorporate prior beliefs about the influence of natural capital on adaptive capacity. Specifically, a prior was included to suggest a negative relationship between increased land access and fewer perceived challenges adapting to climate change (displayed in Figure 3, alongside the prior and posterior distributions for land access in Model 2). In other words, this prior reflects the belief that as land access and future land needs increases, so does perceived adaptive capacity, while allowing for uncertainty. This prior was specified with a normal distribution of a mean of -1 and a standard deviation of 2. This means that most of the prior is negative, while allowing for the possibility of a positive estimate. Because more of the prior distribution is negative, it more strongly suggests a negative relationship between land access and the outcome variable, especially compared to the prior of land access in model 2, where half of the prior distribution is positive and the other half is negative.

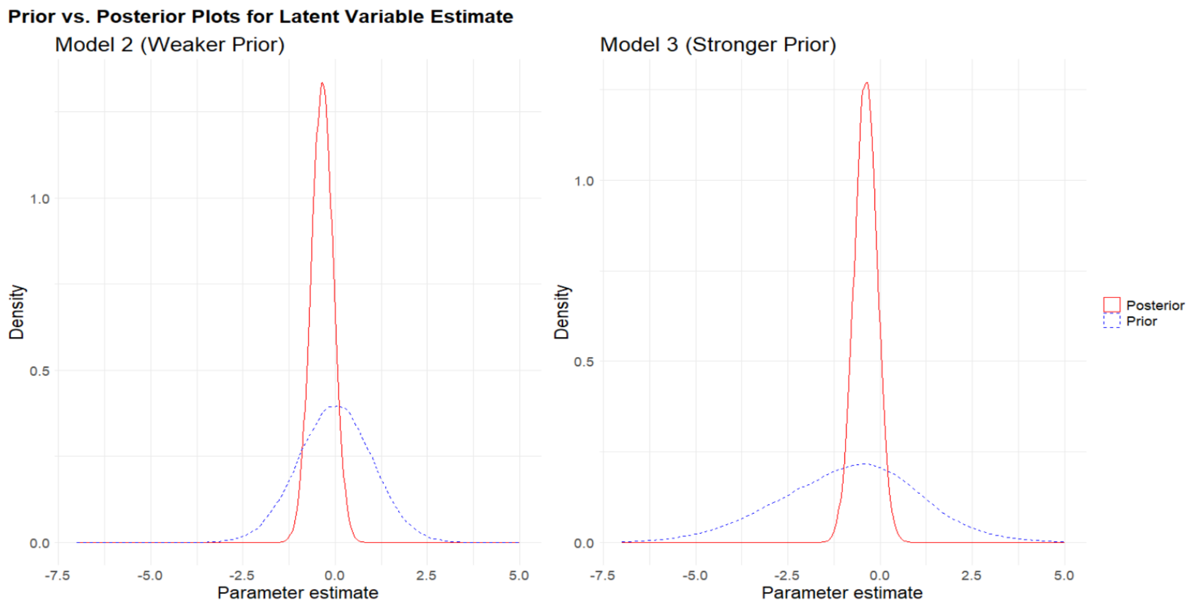

Figure 3: Plots comparing the prior and posterior distirbutions for the latent variable parameter's effect on challenges adapting to climate change in Model 2 and Model 3.

Including the prior did not have a meaningful effect on the posterior distribution of the effect of the land access/land needs latent variable on perceived adaptive capacity to climate change (-0.39, CrI [-1.00, 0.21] in Model 3, compared to -0.35, CrI [-0.94, 0.23] in Model 2). The estimated error shifted to 0.310 in Model 3, compared to 0.298 in Model 2. This suggests that the prior belief that increased land access increases perceived adaptive capacity does not significantly help the model explain the data, but it does not significantly harm the model's explanatory power, either. Thus, the prior belief is compatible with the data, but not extremely important in explaining it.

Model diagnostics

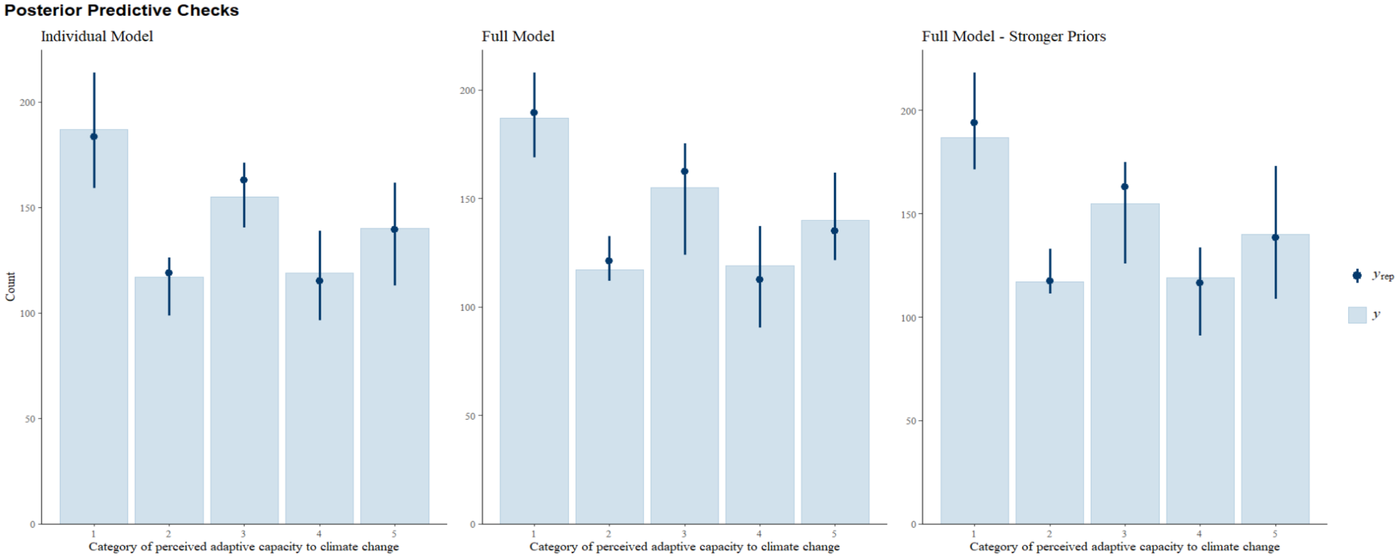

Figure 4: Posterior predictive checks for model predictions of outcome variable. Bars represent observed number of respondents in each category of perceived adaptive capacity to climate change, points represent the model's predicted number of responses per category, and lines represent error bars.

Figure 4 shows the posterior predictive checks for each of the three models. All three models perform reasonably well using posterior predictive checks, as the number of observed responses for each category of the outcome variable are estimates that are within the realm of possible values predicted by the model. For all three models, error bars for values predicted by the model overlapped with observed values for each of the five response categories. And for all three models, the error bars were reasonably small relative to the observed counts – no error bar spans a significant portion of the observed counts.

Model comparisons

Table 6: Leave one out cross validation for model comparison for all three models.

	Difference in predictive performance, relative to best model	Standard Error in Difference in Predictive Performance
Model 1: Individual Model	0	0
Model 2: Full Model	-2.4	1.5
Model 3: Full model with stronger land access prior	-2.8	1.7

The three models were compared using leave-one-out (LOO-CV) cross validation, with results displayed in Table 6. Leave-one-out cross-validation estimates model error by iteratively training the model on all but one observation, testing the model error on the excluded point, repeating this process for each observation and combining the resulting errors. These results indicate that by a small margin, the best performing model is 'individual model', which only estimated direct effects of variables on the outcome (i.e. the one that did not include a latent variable). However, the full model which included the latent variable and the full model with a stronger prior for the latent variable were not significantly worse. While the prior did not help the model explain the data, it did not significantly worsen the model's explanatory power, suggesting that it is a reasonable belief that fits with the data.

Table 7: R^2 values for the three models: the individual model, full model including the latent variable, and full model with the latent variable and priors.

Model	Estimated Variation Explained	Est. Error	Lower 95% CI	Upper 95% CI
Model 1: Individual model	10.71%	2.34	6.54%	15.70%
Model 2: Full model	9.99%	2.01	6.32%	14.21%
Model 3: Full model with stronger land access prior	10.39%	1.84	6.91%	14.09%

The three models were also compared using R^2 analysis. Table 7 displays the amount of variation in the outcome variable each model explains, with a 95% credible interval. The R^2 analysis shows that the three models all explain a similar amount of variation in the outcome variable, around 10-11%. They have similar credible intervals as well. Thus, modeling indirect effects through the latent variable (in "Full model") and adding a prior for that latent variable (in "Full model with stronger prior") have similar explanatory power compared to the model with only direct effects and weakly regularizing priors.

Counterfactuals

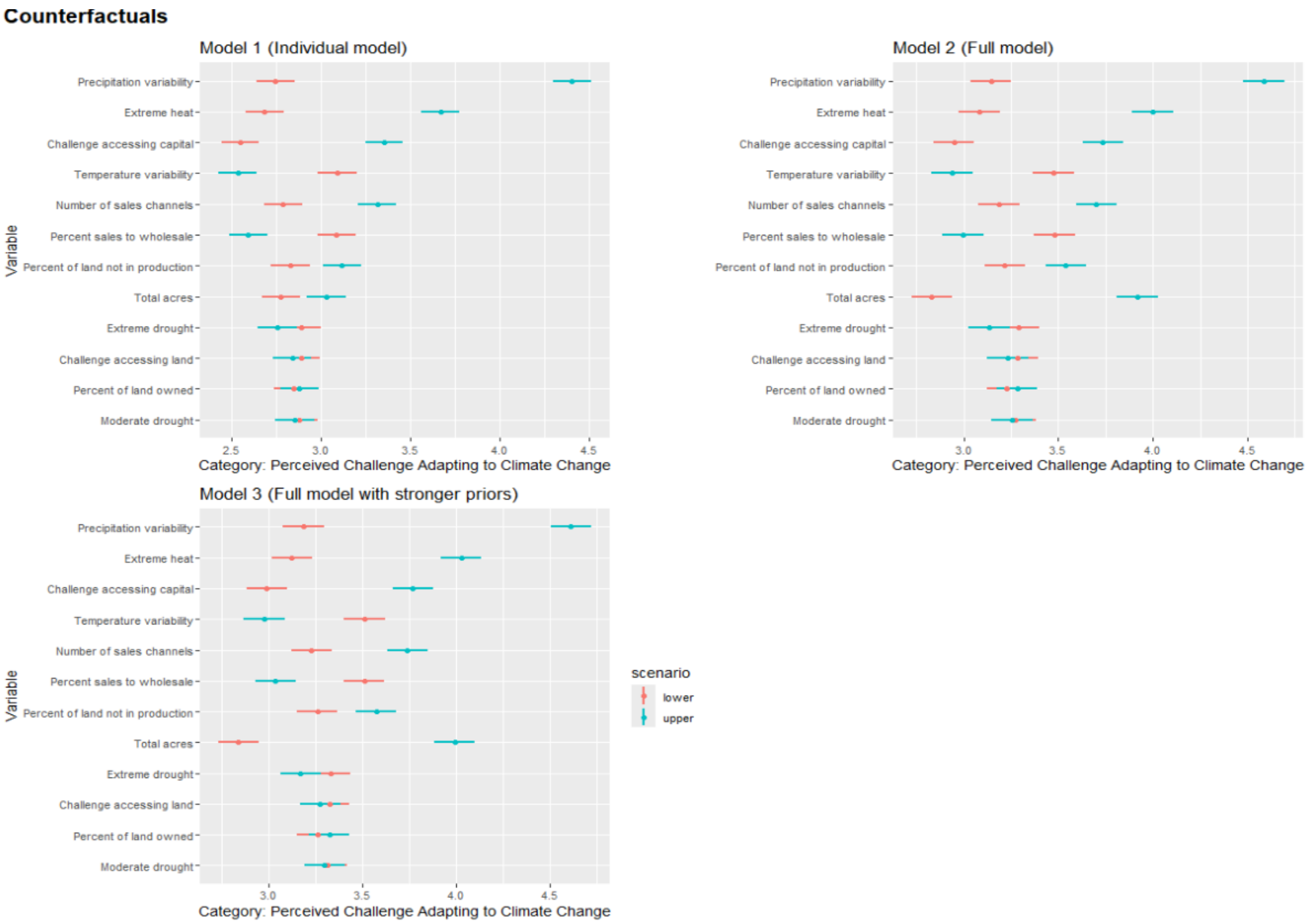

Figure 5: Counterfactuals showing the individual and full models' predicted mean categorizations, given minimum and maximum values for each variable.

Counterfactuals were run for all three models (Figure 5). These counterfactuals represent predicted mean categories in the outcome variable, given changes between minimum and maximum values for a specific variable while all of the other variables remain at their regular values. For example, the first row represents the mean categorization if all the observations had the smallest precipitation variability and the largest precipitation variability, while all the other variables remain as they were for each individual.

All counterfactuals show that a shift from minimum to maximum precipitation variability is most likely to increase the predicted category of perceived challenges adapting to climate change, following closely by exposure to heat extremes and challenges accessing capital.

Interestingly, all models show that increased temperature variability is linked with decreased perceived challenges adapting to climate change, though to a lesser magnitude – opposite from what would be expected. They also both show that increasing number of sales channels makes the model predict higher values in the outcome category, while increasing wholesale percentage makes the model predicted lower values – contrary to literature discussed in the introduction that suggests that more wholesale and fewer sales channels are linked with less flexibility and adaptive capacity. In both models, changes in challenges accessing land, exposure to moderate drought, exposure to extreme drought, and the percent of land owned are not likely to shift the predicted outcome category.

The biggest difference between the counterfactuals in Model 1 compared with Models 2 and 3 is the shift in predicted categories given changes in total acreage. The individual model, which does not include a latent variable representing land access and land needs, suggests that total acreage does not have a large impact on predicted outcome category. However, the full model, which does include the latent variable, suggests that a shift from the minimum to the maximum total acreage can increase perceived challenges adapting to climate change by at least one category. Contrary to the assumption that more land means more natural capital and therefore objective higher adaptive capacity, this model suggests that more land can lead to lower perceived adaptive capacity. Once the model accounts for the portion of variation of total acreage that is attributable to land access, the connection between leftover total acreage and perceived adaptive capacity to climate change is stronger.

Discussion

Land Access & Perceived Adaptive Capacity

Overall, the latent variable represents a combination of existing land access and future land needs. A high score on the variable may indicate existing access to land (with large land sizes and secure land tenure), but a need to access more land and having challenges doing so (reporting high challenges accessing land and having a majority of land in production). The model displayed reasonable certainty in this grouping of land variables: all of the land variables predicted by the latent variable had 95% credible intervals that were either above or below zero. These results indicate that natural capital is more complicated than merely the size of someone's land base. A farmer who has a large and secure land base may not necessarily believe that they have *enough* land and indeed may perceive challenges accessing more. Insufficient access to land, despite already having a larger than average amount, could in turn impact the ability to do necessary crop rotations or have flexibility with land use that might be necessary for climate adaptation. Thus, these findings suggest that indicators representing natural capital do not necessarily impact perceived adaptive capacity in the same direction, and call for a nuanced approach to understanding the relationship between natural capital and perceived adaptive capacity to climate change.

However, the model demonstrated less certainty in how land access and land needs relate to perceived adaptive capacity. While the latent variable has a moderately negative relationship with perceived challenges adapting to climate change, there was high uncertainty in the magnitude and direction of the latent variable's effect. The standard error was large relative to the estimate for the latent variable's impact on the outcome variable, and the 95% credible interval was wide, spanning zero. This suggests that while it is more likely that someone with higher land access and land needs also reports fewer challenges adapting to climate change, the opposite relationship is still within the realm of possibility. Including a prior for the belief that land access is associated with perceived adaptive capacity neither increased nor decreased the model's ability to explain variation in the outcome it. This indicates that the prior belief can fit with the data but is not extremely important in helping explain it.

Although the latent variable has an uncertain relationship with the outcome variable, it is a useful construct for interrogating the complex relationships between natural capital and perceived adaptive capacity. Accounting for shared variation across the land variables by including the latent variable in the model did not necessarily help explain more variation in perceived adaptive capacity. All three models had similar R^2 values and leave-one-out cross validation did not demonstrate a significant difference in model fitness. However, including the latent variable did help apportion variation across the land variables in order to gain insight into how they interact with each other to affect the outcome variable. Notably, including the latent variable altered the model's estimate for land size on the outcome variable. Unlike counterfactuals from Model 1, counterfactuals from Model 2 shows that an increase in total acreage increases the probability that someone will report higher challenges adapting to climate change. This aligns with findings from Eakin et al. (2016), which show that having access to resources does not necessarily align with perceived ability to avoid risk. Thus, model results call for caution around assuming that increased land size relates to increased natural capital and therefore perceived adaptive capacity.

The moderate and uncertain impact of land access on perceived adaptive capacity does not negate the important findings through qualitative research that suggest that limited land access and insecure land tenure can negatively affect adaptive capacity. These results merely suggest that it is not the most significant factor at the national level for this population of certified organic farmers. Notably, the group of organic farmers who are certified may already have secure land access, because precarious land access can dissuade farmers from certifying their farms in the first place. Rather than disproving qualitative findings, this quantitative research shows the importance of looking at smaller samples, precisely because population-level studies can miss important contextual vulnerability that may only present at smaller populations. A future direction of this or related studies may investigate the relationship between land access and perceived adaptive capacity at sub-populations. It is possible that land access is more of an adaptation constraint in areas with higher land prices or with less developed market infrastructure. Thus, it may be fruitful to look at how the relationships change across geographies and demographic groups.

Financial Capital, Climate Exposure & Perceived Adaptive Capacity

The results show a positive and more certain relationship between reported challenges accessing financial capital and perceived challenges adapting to climate change. Across the three models, the estimate for perceived challenges accessing financial capital was positive and had a small error relative to the estimate, with both 95% credible intervals above zero. Additionally, the counterfactuals showed a notable increase in perceived challenges adapting to climate change when challenges accessing capital increased. This aligns with assumptions in the SLA that financial capital increases adaptive capacity (Scoones, 1998), underscoring the importance of contextual vulnerability. People's access to resources may influence one's perceived ability to adapt to climate change beyond the exposure itself. For example, a farmer may need capital to install new irrigation equipment or greenhouses for season extension in order to adapt to climate change.

Financial capital variables around market strategy also had more certain impacts on perceived adaptive capacity – but in the opposite direction as was expected. Qualitative findings from previous studies suggest that wholesale accounts often carry strict timelines and can reduce the flexibility necessary for adaptive capacity, while a higher number of sales channels can offer flexibility to pivot if one of the sales channels becomes untenable (Ory et al., 2024). However, the model demonstrated that selling more through wholesale channels and selling to fewer market channels reduced reported challenges with adaptive capacity. The models indicated reasonable certainty with low relative estimated errors and credible intervals that were both either above zero (for number of sales channels) or below zero (for percent of sales through wholesale). This Chapter's quantitative findings do not necessarily contradict previous qualitative ones, but suggest that they may not hold at the population scale while being true for smaller sub-groups.

Of the climate variables, variability in precipitation had the largest influence on the outcome variable, followed by exposure to heat extremes. An increase in precipitation variability was associated with an increase in perceived challenges adapting to climate change, with reasonable certainty. The majority of the posterior distribution was positive, with the lower 95% credible interval slightly below zero and the upper 95% credible interval mostly above it. Based on the counterfactual scenarios, a jump from the smallest to the highest precipitation variability caused the largest increase in perceived challenges with adaptive capacity. Precipitation variability was included following qualitative interviews with farmers in western Washington, where it was repeatedly discussed as a concern particularly in early season months – underscoring the importance of qualitative findings to guide quantitative approaches. Exposure to heat extremes was also significant in shaping perceived adaptive capacity. With a similar posterior distribution to that of precipitation variability, increased exposure to heat extremes are most likely associated with increased challenges adapting to climate change. Interestingly, exposure to drought and temperature variability had less certain relationships with the outcome variable. This may be because drought is location-specific, such that its associations may not reveal themselves at the national scale. Meanwhile, relative temperature extremes and precipitation variability can happen anywhere and therefore have stronger relationships at the national scale.

Bayesian statistics for mixed methods research

Bayesian methods offer a promising approach to mixed-methods research. Both frequentist and Bayesian modeling techniques allow for the investigation of specific variables of interest based on qualitative findings. If discussions with informants suggest that a certain condition influences their decision-making, that is an important variable to include in a quantitative model. For example, this paper investigates land because of discussions with interviewees about climate adaptation on their farms, where land tenure was mentioned as a factor that limits investment in long-term infrastructure needed for climate adaptation. Climate variables were also included that captured variability in temperature and precipitation due to discussions with farmers who said that increased variability in springtime precipitation made crop planning especially difficult. This would also have been possible using a frequentist approach:

While non-Bayesian approaches can integrate qualitative understandings through variable selection, they do not have the capacities to integrate that qualitative expectation quantitatively into a model. Here, Bayesian statistics offer an additional advantage to integrating qualitative findings into quantitative models through the addition of priors, which allow the researcher to explicitly integrate previous beliefs from qualitative studies in the model. A researcher can tell the model what they expect to be the probability distribution of the estimate of the parameter's impact on the outcome variable. These priors can be stronger or weaker, depending on the researcher's qualitatively-informed understandings of said relationships. Incorporating prior beliefs into models can allow for more accurate models and for the comparison of fitness between models with different priors.

Data collected for Chapter 2 suggested that having more available and secure land was associated with adaptive capacity. Thus, a prior was integrated into Model 3, suggesting that decreased land access was associated with increased challenges adapting to climate change. A normal distribution with a mean of -1 and a standard deviation of 2 was used as the prior for the land access latent variable, which creates a distribution that is mostly negative, but also offers a small probability of being positive. This prior told the model that the distribution of the estimate of the land access latent variable parameter would most likely be negative, but might also be positive. Ultimately, the model with the stronger priors did not increase the explanatory power or the fitness of the model, but also did not decrease it: the prior belief did not help the model explain the data better, but also did not hurt the model's ability to explain variation in the outcome variable. This suggests that decreased land access may be associated with increased challenges adapting to climate change; however, this belief is not important in helping explain perceived adaptive capacity at the population scale.

Bayesian statistics also offer a strong advantage by allowing researchers to interpret model results while considering varying degrees of uncertainty. Because there is inherent uncertainty in measuring adaptive capacity (Adger & Vincent, 2005; Vincent, 2007), a modeling approach that reflects that uncertainty is warranted. Because Bayesian models offer *distributions* for parameter estimates, they suggest a range of possible values for how an explanatory variable can affect the outcome. This uncertainty can be reflected both in the researcher's prior beliefs, as well as in the model's estimate via the posterior distribution. Model results from this Chapter suggest that the latent variable representing land access and land needs has a moderate negative effect on perceived challenges to adaptive capacity, with high uncertainty. On the other hand, perceived challenges accessing financial capital has a more certain positive impact on the outcome variable, suggesting the relationship between perceived financial capital access and perceived adaptive capacity is more certain. Being able to speak about the effects of explanatory variables with an eye for uncertainty is critical to accurately reflecting the complexity in estimating the complex phenomenon of adaptive capacity.

Another advantage of Bayesian statistics is that it does not encounter the same kinds of limitations as Ordinary Least Squares (OLS) approaches regarding the number of model parameters compared to observations. OLS relies on transposing matrices, such that it generally requires 10-20 observations per parameter included in the model. Bayesian approaches do not require this matrix, and therefore can often fit models with more complexity than an OLS model with the same number of observations. This can be advantageous when applying qualitative findings to quantitative modelling approaches, because it is not as rigid in the restrictions around how many parameters can be included in the model.

Limitations

One limitation of this study resides in the sampled population. All farmers sampled were certified organic farmers. Because certification requires a certain level of financial and labor resources to track production practices and pay for certification, it is possible that more vulnerable farmers were not included in the sample. And because land is certified instead of the farm, farmers with precarious land tenure may not be inclined to certify their land. Thus, it is possible that people for whom land access was a major challenge were excluded from the sample.

From a modeling perspective, there were issues with the multiple imputation for the variable representing percent of sales sold through wholesale channels. This variable's imputed distribution did not reflect its original distribution of the variable in the raw dataset. Attention should be paid to fixing this variable to ensure more accurate imputation for further analysis. Furthermore, the model did not estimate mediating or moderating effects of how the natural capital, financial capital, and climate exposure variables interact with each other to affect the outcome variable.

Future Directions

Future research can expand on this Chapter by comparing more models with different priors. For example, a model can be included with a prior for the belief that land access is associated with decreased perceived adaptive capacity, which can then be compared against Models 2 and 3. Additionally, priors suggesting either a positive or negative relationship between the latent variable and the outcome variable can be tightened to be either fully positive or negative. Even though such priors are less reflective of the author's beliefs (which do include a degree of uncertainty), such exaggerations can be useful if they significantly reduce model fitness and thus demonstrate a belief that is clearly incompatible with the data. Comparison can also be conducted between models with different priors for farm size and its effect on the outcome variable. Such analysis would be pertinent because total acreage is often used as an indicator for natural capital when measuring adaptive capacity. Comparing different beliefs about how land size impacts perceived adaptive capacity can more directly inform such debates.

Conclusion

This study offers a compelling case study of using a Bayesian approach to mixed methods research. The Bayesian framework offered a means of testing prior beliefs from qualitative findings while reflecting varying degrees of uncertainty. Qualitative findings suggested that land access and tenure can constraint perceived adaptive capacity. These prior beliefs were incorporated into the model, and neither improved nor degraded model fitness or explanatory power – suggesting that the prior belief may be true but is not important in helping predict perceived adaptive capacity. Model results also suggested that land access and land needs have a moderate, though uncertain, negative relationship on perceived challenges adapting to climate change. While land access may not constrain perceived adaptive capacity with certainty at the population level, this does not discount the possibility that land is still a constraint for *some* farmers. Bayesian approaches mirror this uncertainty and leave space for different possible relationships between variables. Thus, future research can further investigate the demographic, climatic, or spatial conditions in which land access does constrain perceived adaptive capacity.

The model results call for a nuanced approach to understanding the relationship between natural capital and perceived adaptive capacity to climate change. A latent variable was constructed representing both existing access to land and needs for future land. This latent variable in turn had a moderately negative, albeit uncertain, relationship with the outcome variable. Thus, these findings suggest that indicators representing natural capital do not necessarily impact perceived adaptive capacity in the same direction. For example, while traditional studies with SLA assume that more land means more adaptive capacity, these findings suggest that larger farm sizes can be associated with decreased perceived adaptive capacity – which is in turn an important determinant of adaptive action. This may be because larger farms require larger shifts in practices to adapt, and may have less flexibility to do so quickly. Alternatively, it may be more difficult to manage large farms in a resilient way. These results also confirm other findings that access to resources does not always correlate with increased perceived ability to avoid risk (Eakin et al., 2016; Mortreux & Barnett, 2017): being able to access resources does not always translate into the capability to use them. On the other hand, these results do align with data from Chapter 2 and findings elsewhere in the world that suggest that challenges accessing capital can decrease perceived adaptive capacity, and therefore potentially the propensity to take adaptive action (Azad & Pritchard, 2022). This suggests that capital can constrain adaptation in similar ways across different contexts.

Conclusion

Climate resilience & adaptation

As climate change accelerates, the question of how to adequately prepare and adapt our food and farm systems has become paramount. However, climate change does not occur in a vacuum. It interacts with complex and dynamic socio-ecological systems, and any initiative to build on-farm resilience must first understand how climate change interacts with social, economic, and ecological contexts within which these farms operate. This thesis focuses on two factors that influence climate resilience and adaptation: crop diversification and land access. This thesis takes a mixed-methods approach to investigate i) the association between crop diversification and resilience and ii) the relationship between land access and perceived adaptive capacity, using qualitative methods at the sub-regional scale and quantitative methods at the national scale, respectively.

Through interviews with twenty-eight organic vegetable farmers in western Washington, Chapter 2 focuses on how climate change interacts with a farmer's socio-economic context to influence crop diversification which confers resilience. The Chapter draws on ecological notions of response and functional diversity, offering a farmer grounded perspective of how these phenomena play out on farms: response diversity includes a temporal dimension and functional diversity refers not only to ecological functions but also to market ones. Both contribute to adaptive management practices that are known to contribute to socio-ecological resilience. The Chapter finds that social, economic, and ecological factors shape crop diversification decisions, culminating in an approach termed 'specialized diversification.' In this approach, farmers specialize in crops to fill market niches while maintaining enough diversity on their farms to enable resilience practices. Thus, the Chapter offers a view of diversification that is complementary and not at odds with specialization. Here, climate change can be understood as the shifting climatic context within which crop decisions are made, narrowing the possibility for certain crops while opening opportunities for others. Farmers autonomously adapt to climate change through a continual process of fine-tuning crops to fit within their both specialized and diversified market strategy. Although not the focus of Chapter 2, data collected during interviews suggested that inadequate land access can constrain adaptive capacity to climate change. This spurred further investigation to test this hypothesis through a modeling approach implemented in Chapter 3.

Chapter 3 investigates the role of land access, alongside financial capital and climate exposure, in influencing perceived adaptive capacity to climate change. The Chapter used a Bayesian structural equation model to estimate perceived adaptive capacity among organic farmers across the U.S. To the author's knowledge, it is the first study to use a nationally-representative survey with an explicit question about perceived adaptive capacity to investigate it at the national scale among organic farmers. Model results suggest that land access correlates with future land needs: farmers who have already have large farms and secure land tenure are also more likely to need more land and encounter challenges accessing it. The Chapter finds that land access and future land needs have a moderately negative, uncertain relationship with challenges adapting to climate change. In other words, someone who has access to a large and secure land base, but also needs more land, *may* also be less likely to report challenges with climate adaptation—though the strength of this relationship is uncertain, and the effect could plausibly be in the opposite direction. While many studies assume that higher natural capital leads to higher adaptive capacity, these findings suggest the relationship between specific natural capital indicators may be more uncertain and do not always go in the same direction. Contextual factors related to financial capital had more certain associations with perceived adaptive capacity: those who had more secure access to financial capital, a higher percentage of sales sold through wholesale channels, and fewer numbers of sales channels also reported better perceived adaptive capacity. Some climate exposure factors also influenced perceived adaptive capacity with more certainty: higher precipitation variability and more exposure to relative heat extremes were associated with fewer perceived climate adaptation challenges, while drought and temperature variability had weaker and uncertain effects.

Bayesian statistics for mixed-methods approaches

Because mixed-methods research can capture both trends at the population scale and in-depth dynamics at the local scale, they are particularly useful in explaining complex phenomena that occur across scales. As such, this thesis took a mixed-methods approach to analyzing climate resilience and adaptation, whereby findings from Chapter 2 were used to inform the modeling framework used in Chapter 3. A Bayesian statistical approach was particularly valuable in integrating qualitative and quantitative data because of its ability to a) explicitly incorporate prior beliefs into the modeling framework, and b) quantitatively reflect uncertainty in parameter priors and estimates.

Qualitative findings from Chapter 2 were used to inform model structure, variable selection, and prior distributions in the modeling framework used in the second chapter. Land access was investigated because a number of interviewed farmers discussed land size and tenure as an adaptation constraint, and a prior belief was incorporated to suggest that decreased land access was associated with increased challenges adapting to climate change. Precipitation and temperature variability were included because most farmers in the dataset discussed them as major climate impacts. Number of sales channels was included because it was discussed as an adaptation by some farmers, while access to capital was discussed as an adaptation constraint. While frequentist approaches also allow qualitative findings to drive variable selection, Bayesian models are unique in their ability to incorporate prior beliefs into how variables affect each other and the outcome variable. In Chapter 3, a prior was added for the effect of the land access latent variable on the outcome variable, suggesting that it was more likely negative but could still be positive. This prior did not affect the model's fitness, indicating that the belief may be consistent with the data but was not very important in helping explain it.

Bayesian methods are adept at reflecting uncertainty in model results, which is particularly important in mixed-methods research as conditions and uncertainty fluctuate across scales. Importantly, the two chapters examined different scales: while Chapter 2 interrogated climate resilience at the sub-regional scale, Chapter 3 investigated perceived adaptive capacity at the national scale. Some of the findings from the sub-regional scale held true at the population scale with high certainty, while others were more uncertain or went in the opposite direction. Based on Chapter 2's findings and previous literature, precipitation variability, exposure to heat extremes, and access to financial capital were more certain predictors in the expected direction: higher precipitation variability and extreme heat exposure, and lower perceived access to financial capital were related to higher perceived challenges with adaptation. Meanwhile, number of sales channels and percent of sales sold through wholesale were also more certain predictors, but in the opposite direction of what was expected. Land access and land needs as expected had a negative relationship with the outcome variable, although there was high uncertainty in this estimate. These uncertainties can help reflect incongruencies across scales. For example, the uncertainty in the land access variable estimate at the population scale does not negate farmers' experiences collected in Chapter 2 – rather, it shows that there is a wide range of possible effects that vary across farmers and conditions. Thus, land access may exist as a stronger adaptation constraint at local levels under specific conditions that do not uniformly occur at the national scale. Thus, Bayesian methods are congruent with an epistemic view of knowledge as non-definite and dependent on shifting conditions that may not be measured in this specific framework, or indeed measurable at all.

Future Directions

Incongruencies across scales uncovered through Bayesian modeling can point to directions for future research. The negative, though uncertain variable estimate for the land access latent variable points to the need for further investigation into the specific sub-populations experiencing social and economic conditions that mean land access constrains perceived adaptive capacity with higher certainty. And while qualitative data from Chapter 2 and other studies demonstrated that diversity in market channels can support adaptive capacity, this did not hold at the population scale. Such incongruencies beg the question: for which subpopulations may the qualitative findings hold? What were the conditions that made the findings true for a number of farmers in the qualitative dataset, even if it was not a clear trend across farmers in the survey dataset? By helping identify these discrepancies, mixed-methods studies can offer these tensions across scales precisely as areas of future investigation.

One limitation of this thesis is that the populations in the dataset were slightly different, also representing an area for future investigation. While the first chapter interviewed farmers who used organic practices, including a mix of certified and non-certified organic farmers, the second chapter used survey results from a population limited to farmers who had organic certification. Because organic certification applies to the land and not the farm business, farmers on rented land may be disincentivized from seeking organic certification. Thus, land access challenges may have been more represented in Chapter 2's sample than in Chapter 3's. Future research could further investigate if land access is a stronger adaptation constraint among non-certified farmers using organic or sustainable practices.

Farmers are no stranger to change: farming is an occupation that requires a certain intimacy with and understanding of environmental variability. As climate change accelerates, their farming contexts are increasingly characterized by climatic instability. But the idea of continuing in the face of uncertainty is not new, and accepting change is a first step in adapting to it. As one farmer interviewed for Chapter 2 eloquently shared: *"The only thing you can count on is change. And Mother Nature will always throw a wrench in whatever best laid plans you have."*

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Appendix

List of Codes

Table 1: List of codes that emerged through data collected for Chapter 2. Note: Codes not pertinent to the analysis were excluded.

General • Background • Benefits • Challenges • Irrigation • Land size, tenure, type • Market Outlets • Organic certification • Organic motivation • Organic practices • Magic wand	**Climate Impacts** • Benefits from climate change • Cold • Distrust • Flooding • Heat and drought • Mental health • Microclimate • Pests & Disease • Seasonal Shifts • Spring wetness • Unpredictability • Wildfire • Wind
Crop Strategy • Appropriate for farm location • Crop list • Culturally relevant • Diversifying • Efficiency and use of time • Farmer preference • Learned • Market demand • Planning • Profitability • Simplifying • Soil health • Source from other farmers • Specialize • Timing • Tried and true vs. experimental • Winter strategy • Workers	**Practices of Resilience** • Acceptance • Already resilient • Diversification • Flexibility • Learning & Observing • Proactive planning • Relationships
Specific Adaptations • Beyond the farm • Greenhouses & tunnels • Information • Irrigation • Market shifts	**Adaptation Constraints** • Capital • Cooperation and community • Few constraints • Land ○ Land access

• New crops • Other crop plan changes • Other infrastructure • Row covers & tarps • Seed selection • Shifting timing • Soil health • Storage • Water conservation • Worker protections	○ Land Size ○ Land tenure ○ Land type • Language & Knowledge • Rules • Time
Seed sourcing • Challenges with seed sourcing • Community sourcing • Corporate seed • Mid-sized seed companies • OP vs. Hybrid • Organic seed • Regionally adapted seed • Relationships with seed reps • Save own seed • Transparency	**Desired Seed Traits** • Appropriateness for farm • Cold tolerance • Consistency • Continuous vs. discrete harvest • Days to maturity • Dry farm • Farmer preference • Harvestability • Heat-bolt tolerance • Market outlet • Nutrition • Pest and disease resistance • Productivity • Rain tolerance • Seed quality • Storability • Taste • Visual

Multiple Imputation Density Plots

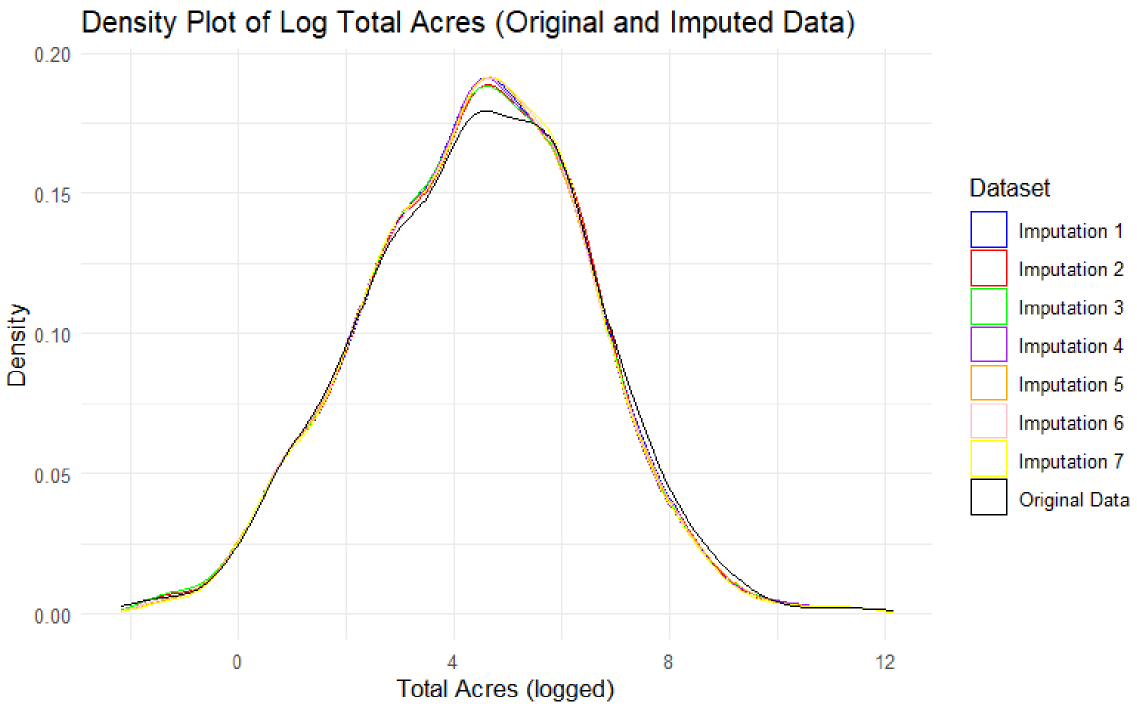

Figure 1: Density plots comparing imputed and original data for log of total acres (farm size)

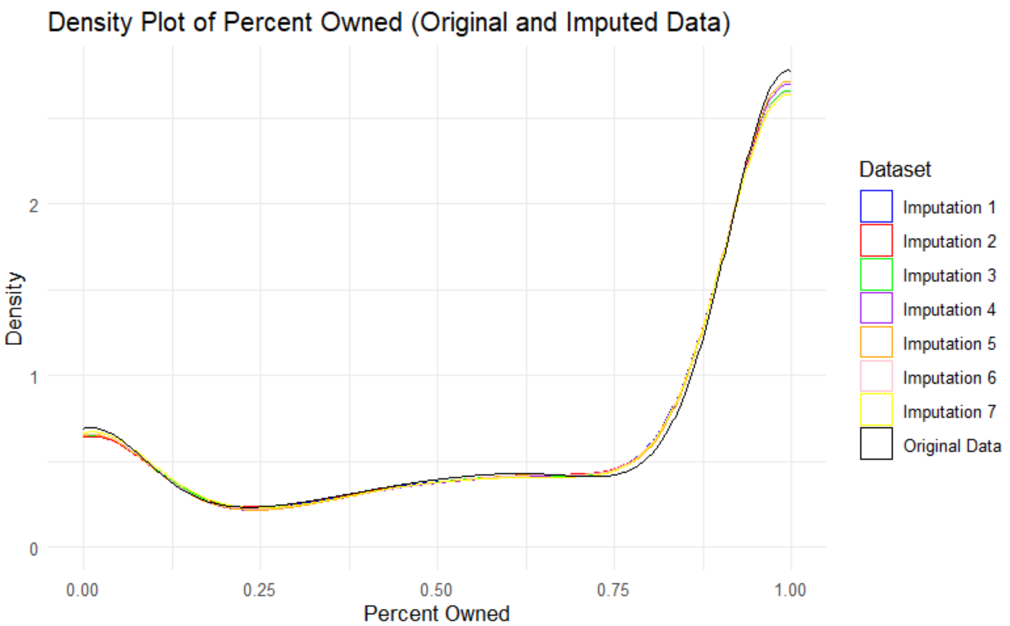

Figure 2: Density plots comparing imputed and original data for percent of land owned

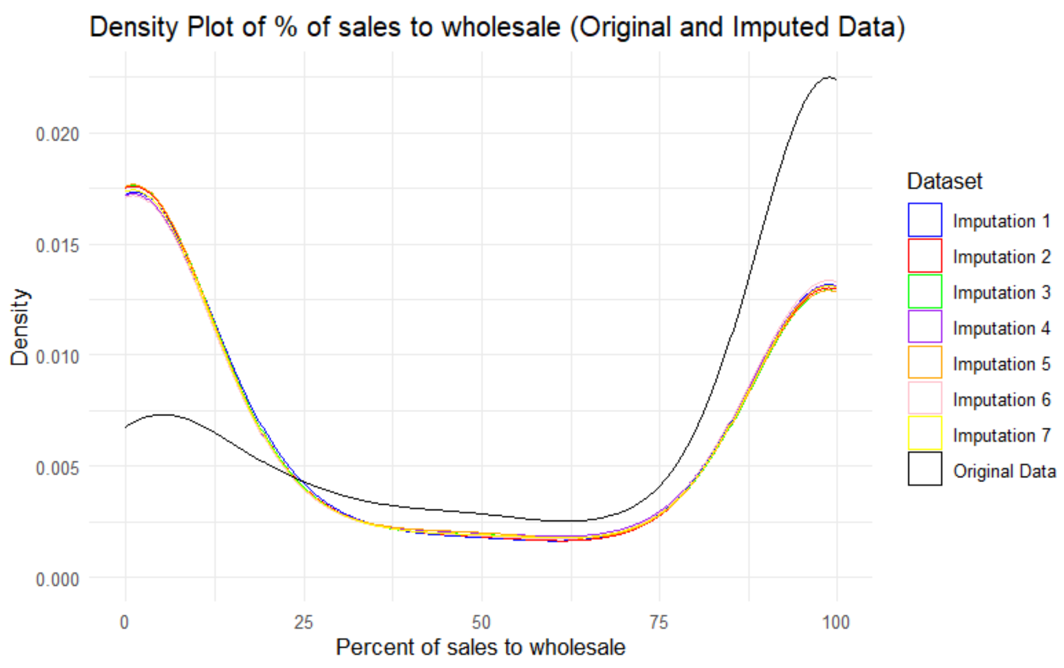

Figure 3: Density plots comparing imputed and original data for percent of sales sold through wholesale

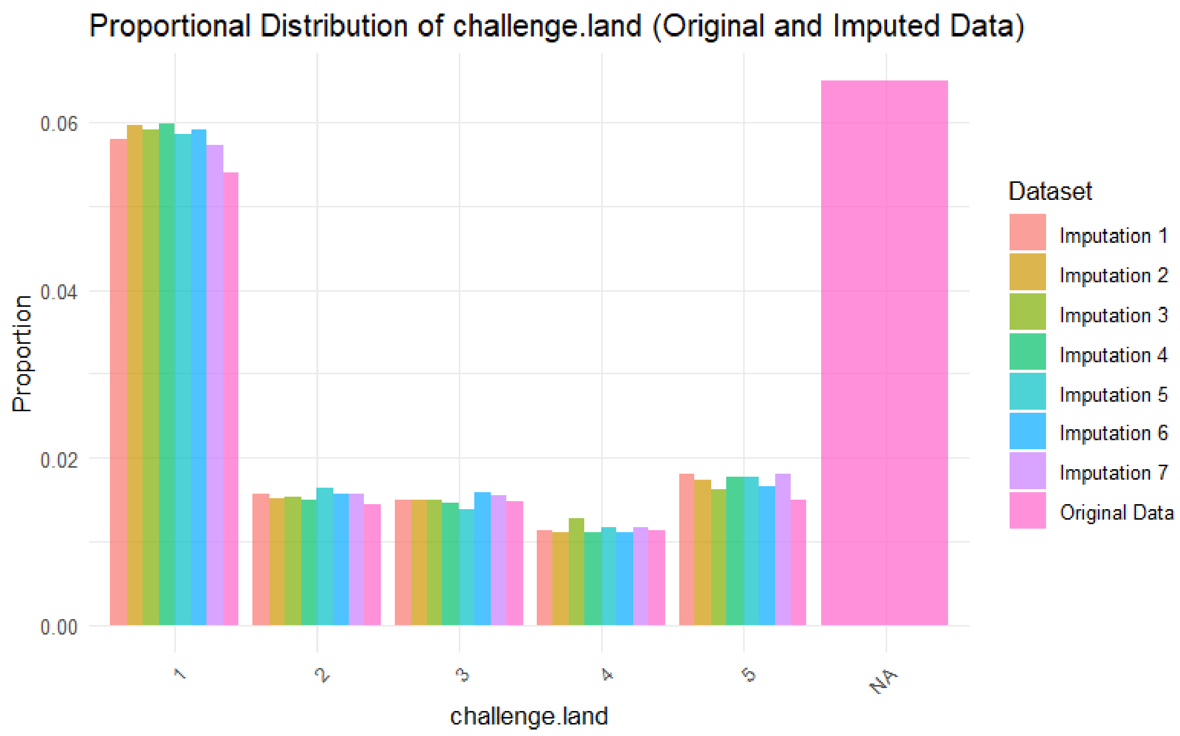

Figure 4: Proportional bar chart comparing imputed and original data for perceived challenges accessing land

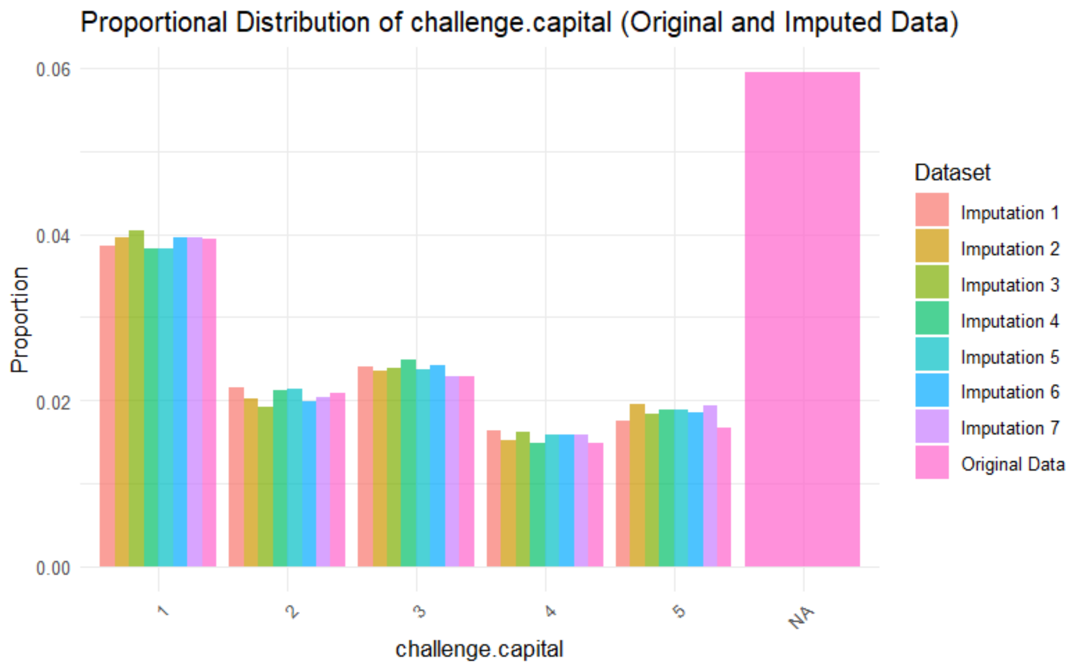

Figure 5: Proportional bar chart comparing imputed and original data for perceived challenges accessing capital

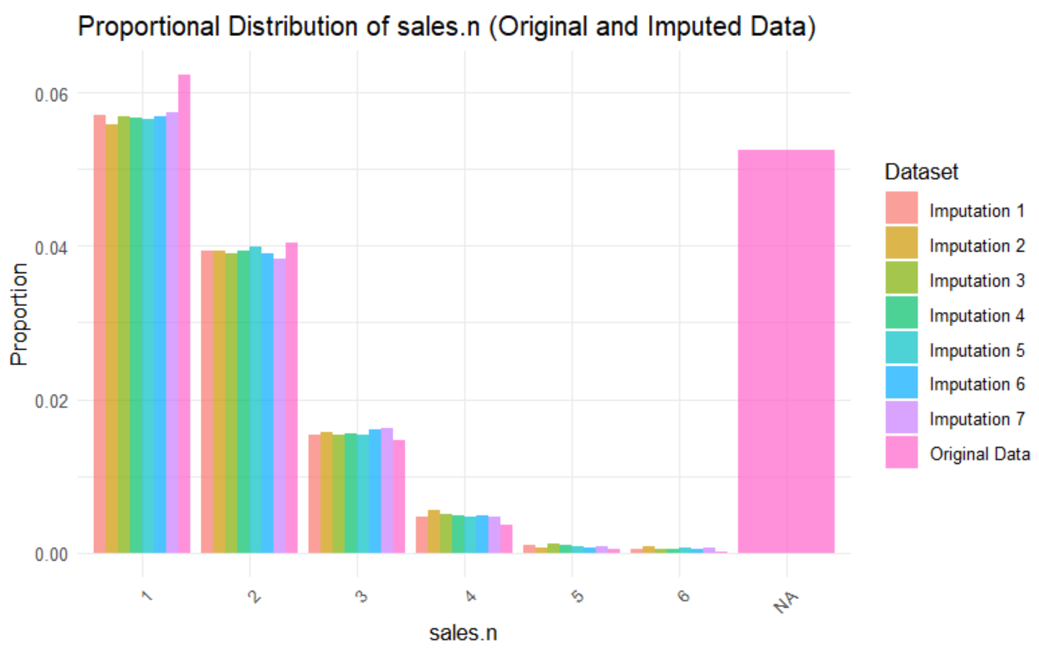

Figure 6: Proportional bar chart comparing imputed and original data for number of sales channels