“Hunkering Down” under Climate-Driven Risks in Subsistence Farming Communities

Abstract

Increasing climate risks introduce new sources of uncertainty to smallholder farmers’ livelihood decisions. In response, several governments have invested in climate information services for farmers, but current evidence is mixed on how farmers actually integrate such information in their livelihood decision-making. In this study, we conduct a survey of 500 farming households in Nepal’s Chitwan Valley and employ a suite of cross-sectional and time series econometric techniques to analyze how farmers’ information sources, social capital, and previous exposure to climate hazards shape climate risk perceptions and livelihood decisions. We find that climate-driven risks are highly salient to household perceptions of farming risks; however, they also drive higher perceived risks of common livelihood diversification strategies, including rural-urban migration and off-farm employment. Further, access to greater informational and social capital may actually decrease the perceived risk of specific climate-driven hazards, including droughts and groundwater scarcity. Finally, we find that while farming households generally maintain diversified income portfolios, exposure to droughts and/or floods leads to persistent increases in the reliance on farming income, which we term a “hunkering down” response. Our results indicate that efforts to build farmers’ resilience to climate risks should especially account for perceived risks of livelihood alternatives, financial constraints, and loss-averse behavior in response to income shocks.

1 Introduction

Increasing climate risks over the coming decades are likely to threaten the livelihoods of many of the world’s 500 million smallholder farming households (i.e., those who farm on less than 2 ha of land) [Lowder et al., 2016, Intergovernmental Panel on Climate Change, 2012, Intergovernmental Panel on Climate Change, 2022]. Here, we define climate risks as weather-related events that impact the economic success of farming activities, and whose frequency and/or severity will likely shift over the long term due to global climate change. Such risks include the amount and timing of precipitation with respect to typical cropping cycles, the severity and frequency of droughts and floods, accelerating snowcap melting, and changes to mean and extreme temperatures.

While subsistence farmers have contended with high income volatility and natural hazards for decades [Dercon, 2002, Ellis, 1998], climate-driven risks introduce new sources of uncertainty to livelihood decisions. Farmers face uncertainty regarding the timing and scale of changes to natural hazard risks [Arbuckle Jr. et al., 2015, Dang et al., 2012], which may affect decisions regarding whether to invest in coping strategies to manage short-term shocks or longer-term adaptive strategies [Singh et al., 2016]. A second source of uncertainty is how climate-driven risks may affect farmers’ financial and natural capital. Over short time horizons, climate-driven risks may actually increase farmers’ capital, e.g. through longer growing seasons or a particularly wet season that increases yields of staple crops [Manandhar et al., 2011]. However, over the longer term, climate impacts are likely to erode farmers’ assets, further constraining the capacity to respond to livelihood shocks. As most smallholder farmers rely primarily on agriculture for subsistence, climate shocks may further entrench poverty traps [Dasgupta, 1998] and lead to maladaptive strategies that can cascade to societal-wide shocks, e.g. involuntary displacement, deforestation, and food insecurity.

Over the past two decades, research conducted in different parts of the world has elucidated a few stylized facts regarding farmer perceptions of climate risks. First, despite high inter-annual variability in weather conditions, there is evidence that farmers accurately perceive long-term climatic trends, even if they do not directly attribute this to anthropogenic climate change [Manandhar et al., 2011, Truelove et al., 2015, Bro, 2020]. However, given the constraints faced by smallholder farmers, perceived climate risks do not necessarily lead them to take adaptive actions [Bro, 2020, Mulwa et al., 2017]. Further, government interventions seeking to provide farmers with climate information appear to have had success in spurring shifts in farmer behavior in a limited number of cases [Mulwa et al., 2017], while in other cases, farmers have discounted negative climate forecasts [Grothmann and Patt, 2005, Ziervogel, 2004] or trusted that public adaptation measures would be sufficient to manage climate risks [Dang et al., 2014]. In other cases, access to agricultural extension services increased the likelihood of farmers adopting a technical strategy e.g. increased fertilizer use, but did not affect the uptake of other climate resilience strategies, e.g. changing crop types or planting/harvesting times [Tessema et al., 2018]. Despite this rich body of evidence, there are still several puzzles regarding the processes by which climate risks affect smallholder farmer decision-making. These include how climate hazards shape risk perceptions not only of farming but also livelihood alternatives such as migration and off-farm employment, and the salience of such perceptions to livelihood diversification decisions.

To help address these puzzles, in this study we analyze how farmers' information sources, social networks, and previous experience with climate hazards shape perceptions of climate risks and livelihood diversification strategies. Specifically, through a survey of 500 farming households in the Chitwan Valley of south-central Nepal, this study investigates three main research questions:

- How does access to diverse sources of informational and social capital influence perceptions of climate risks to farming?
- How salient are climate-driven risks to farmers' general perceptions of both farm and non-farm livelihood risks?
- How do perceptions of climate risk and experience with climate-driven hazards affect observed changes in farmers' livelihood diversification strategies, as measured by how they derive income?

By addressing these questions, we seek to make two main contributions to literature on climate resilience decision-making and rural-urban migration. First, we assess how different information sources and social networks – including conventional radio/TV/print media, digital media, government offices, farmer social networks, and migrant networks – shape perceptions of climate risks to various livelihood strategies. Second, we investigate how risk perceptions factor into livelihood diversification responses to climate hazards, including rural-urban migration. In so doing, we hope that our analysis may help inform the design of more effective climate information services for this context.

2 Methods

2.1 Study Area and Survey Design

To investigate these questions, we administered a cross-sectional, face-to-face survey of 500 farming households in Nepal's Chitwan District from May – July 2022. The agricultural sector in Nepal represents an important case study to better understand how climate risks affect farming livelihoods and how smallholder farming communities may adapt to such risks.

While the country is undergoing a rapid urbanization process, as of 2021 agriculture still accounts for 21.3 percent of Nepal's GDP, higher than the regional average for South Asia (16.7 percent) and far higher than the global average (4.3 percent) [World Bank Group, 2021]. More strikingly, 64 percent of the population is employed in the agricultural sector, the highest among any country outside of sub-Saharan Africa, and higher than both regional (42 percent) and global (27 percent) averages [International Labour Organization, 2022]. Furthermore, Nepal faces several substantial climate risks, ranging from changing monsoonal patterns that affect the timing and volume of precipitation [Aryal et al., 2020], temperature rise at higher-than-global averages that affects soil fertility [Karki and Gurung, 2012], and increased potential for catastrophic events that can wipe out harvests and homes, e.g. glacial lake outburst floods [Ministry of Forests and Environment, 2019]. Most of the country's farmers operate small-scale farms (average size of 0.7 hectares) that rely on rainfed agriculture [Ministry of Agriculture, Land Management, and Cooperatives, 2018], limiting the resources and capital that they can deploy to adjust to changing environmental conditions. Gaining a better understanding of the factors that influence Nepali farmer risk perceptions and livelihood decisions can provide useful insights for other Global South agricultural contexts that may face similar threats in the coming decades.

The Chitwan District is one of the country's main agricultural regions, cultivating a variety of subsistence and cash crops, including rice, wheat, maize, and a variety of fruits and vegetables. Most households also supplement crop harvests with livestock ranging from capital-intensive buffalo and cows to less-expensive goats and chickens. In Nepal's 2010 National Adaptation Plan of Action, the Chitwan District ranked "High" (fourth out of five categories) on an index of overall vulnerability to climate change, reflective of its high exposure to increasing droughts, floods, and pests, among other hazards [Ministry of Environment, 2010]. Demographically, the region is home to a diverse mix of ethnic and caste groups, including Brahmin, Chetri, Dalit, Gurung, and Indigenous Tharu and Janjati populations. Additionally, over the last 20 years, the Chitwan District has seen a marked increase in outmigration to several countries, including India, Saudi Arabia, Qatar, and East Asian countries [Massey et al., 2010, Ghimire et al., 2019, Ghimire et al., 2021]. Geographically, the 15 km by 30 km region is located in the Terai plains and is transected by two main rivers, the Narayani and East Rapti, with different propensities to flood during the monsoonal rains. This study site therefore provides a high degree of heterogeneity in livelihood strategies, exposure to climate risks, ethnic/caste identity, and connection to migrant and other social networks that allow us to investigate a variety of factors hypothesized to underlie risk perceptions and climate adaptation strategies.

Participants for our survey were recruited from two rural wards of Chitwan's main metropolitan city, Bharatpur, with one bordering the larger, more flood-prone Narayani and the other bordering the smaller, less flood-prone East Rapti (Fig. 1a). In each ward, we stratified the sample by randomly selecting 200 households within 1 km of the riverbank and 50 households at least 3 km from the river. This sampling strategy allows us to exploit localized variation in exposure to climate hazards while controlling for similar economic and political conditions, strengthening the inferential power of our research design with respect to the effects of hazard exposure, social capital, and climate risk perceptions on livelihood diversification strategies.

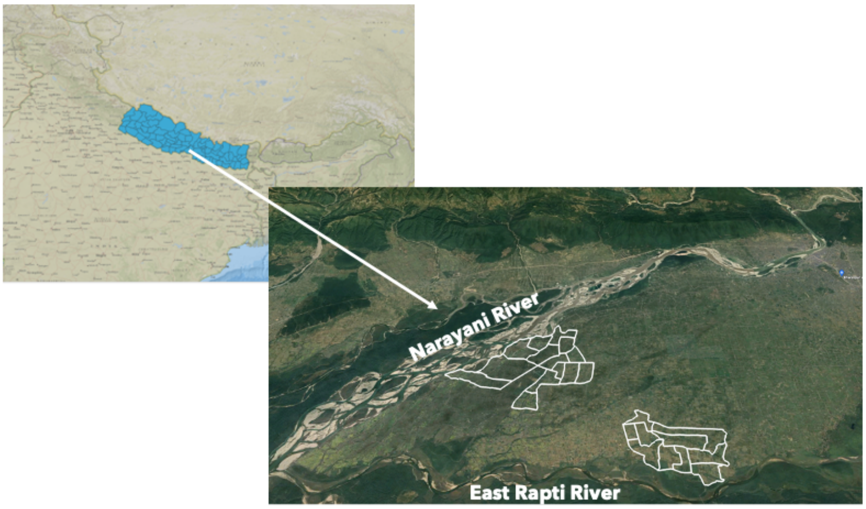
Survey questions were designed to measure several categories of independent, intervening, and dependent variables, and were refined after pre-testing questions through 12 semi-structured interviews with farmers across the Western Chitwan Valley. While many variables were assessed through a cross-sectional design, we also asked respondents to recall their exposure to various natural hazards (including droughts, floods, excess heat, pests, etc.), livelihood activities they engaged in (including farming cereal crops, farming fruit/vegetable crops, raising livestock, engaging in non-farm jobs, engaging in rural-urban migration, etc.), and income earned from these activities for each year from 2015-2021. These variables were assessed using a life history calendar method, in which respondents are presented with a physical calendar that contains Nepali years and memory cues of locally-relevant events. This design was developed in in previous demographic surveys and extensively used in various studies in the Chitwan Valley Family Study, a 28-year panel study of this area, which have demonstrated its efficacy in improving respondent recall of various life history events, including migration trips, farming choices, marital events, and experience with mental disorders [Axinn et al., 1999, Axinn et al., 2020, Brauner-Otto et al., 2020, Ghimire et al., 2021, Brauner-Otto et al., 2022]. In particular, this version of the life history calendar contained significant natural hazard events (the 2015 Nepali earthquake), political events (a local election in 2017), and societal events (the onset of COVID-19 in 2020) as cues to help respondents situate their personal life history and household events in an accurate chronological order.

2.2 Theoretical Framework and Analytical Strategy

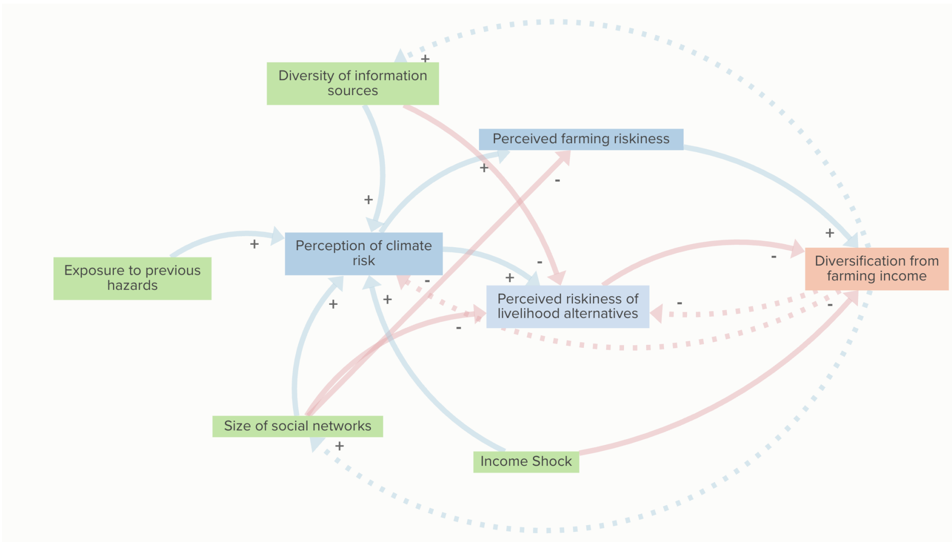
In addressing our research questions, we form hypotheses based on three theoretical frameworks that are especially relevant to questions of how subsistence farming households perceive and act on climate risk: Protection Motivation Theory (PMT), the New Economics of Labor Migration (NELM), and Security Potential/Aspiration (SP/A). Briefly, PMT states that decision-makers mitigate the risk of perceived threats [Rogers and Prentice-Dunn, 1997, Dang et al., 2012, Arbuckle Jr. et al., 2015] based on two main variables: the perceived severity of a threat and the perceived capacity to mitigate this risk. NELM postulates that households engaged in rural livelihoods seek to minimize income risks and overcome credit constraints by engaging in multiple livelihood strategies, including rural-urban migration [Lucas and Stark, 1985, Stark and Bloom, 1985], and aim to minimize perceived gaps between their well-being and that of others in their social network [Massey et al., 1993]. Finally, (SP/A) [Lopes and Olden, 1999] demonstrates that individuals set a basic security aspiration in choosing among risky options; they are risk-seeking in attempting to meet the aspiration, but exhibit more risk-averse behavior once they are reasonably assured of achieving the aspiration.

Informed by these principles, Figure 1b summarizes our hypothesized relationships between independent (green), intervening (blue), and dependent (red) variables. More formally, our hypotheses are:

- H1a: *In general, farming households that (i) have experienced more natural hazards and (ii) have greater access to informational capital will be more likely to perceive climate risks as a salient threat to their livelihoods.*
- H1b: *Among information sources, farming households that rely on professionalized information sources e.g. scientists and agricultural extension officers should exhibit a higher overall perceived climate risk than those relying on less professionalized sources.*
- H2a: *In general, farmers' likelihood of diversifying livelihoods (e.g. engaging in off-farm employment or sending a household member as a migrant) will be positively correlated with (a) their perceived climate risk, (b) the diversity of information sources to which they have access, and (c) the size of their social networks.*
- H2b: *Among social groups, households who are active in farming-based networks e.g. farmer group cooperatives are less likely to exhibit livelihood diversification compared to households that are less active in such networks.*
- H3: *In years with a natural hazard-induced income shock, farming households will exhibit less livelihood diversification in order to meet a basic harvest aspiration.*



(a) **Study Site**



(b) **Theoretical Model**

Figure 1: **Study Site and Conceptual Framework for Analytical Strategy. a)** Map illustrates location of Chitwan District in south-central Nepal, and of the wards within Chitwan District sampled in this survey (white boundaries). **b)** Arrows indicate hypothesized relationships between independent variables (green), intervening variables (blue), and dependent variables (red). Where applicable, a + or − sign indicates the hypothesized directional effect of a relationship. Dashed lines represent potential feedback relationships.

SI 1 includes a fuller description of how we derive each set of hypotheses from PMT, NELM, and SP/A frameworks. Below, we employ a three-stage analytical design to test these hypotheses. First, we use a linear probability model to estimate the effects of independent variables - social networks, access to information sources, and exposure to previous natural hazards - on farmers' perceptions of climate risks to their livelihoods, controlling for demographic factors e.g. gender, age, education, and caste identity. Next, we estimate the degree to which farmer climate risk perceptions are salient for their general risk perceptions of livelihood options, including farming cereal crops, investing in livestock, engaging in migration, and seeking off-farm employment. Third, we estimate the effects of risk perceptions, exposure to droughts and floods, information sources, and social networks on households' income sources via a time-series model. Section 3 provides more detail on the operationalization of key variables and the econometric models used to estimate their effects. We test for robustness in various alternative ways to measure risk perceptions and informational and social capital, along with potential sources of endogeneity, in SI 4.

3 Key Variables and Descriptive Statistics

3.1 Demographic Variables

To assess representativeness of our survey sample, we compare key demographic variables for the survey sample, with 2021 Nepali Census data for the Chitwan District and for Nepal nationally [National Statistics Office,]. There are several important demographic differences between the survey sample and both populations (Table 1). First, there were markedly more female respondents in the survey (62.8 percent) compared to the sex composition of the Census. Survey respondents also skewed older, with only 22 percent of respondents between 18-34 (whereas this age group comprises 45 percent of Chitwan adults). Respondents had less formal educational attainment than either Chitwan or the overall Nepali population, with roughly half the survey sample not having received secondary education. With respect to caste identity, Dalit and Tharu/Darai/Kumal respondents were more highly represented in the sample than the broader Nepali population. These castes have historically had lower socio-economic status compared to other caste identities. These differences likely reflect highly-selective migration patterns from rural areas, in which working-age men are more likely than other demographic groups to be living outside of the survey area. Demographic differences may also be due in part to our selection criteria of only including farming households in the sample, and tailoring our sample on regions that were likely to have experienced at least one climate-related hazard in recent years. While we cannot claim large-scale representativeness, our sample consists of demographic groups - smallholder farmers with generally lower than average socio-economic status - that are most likely to be at the frontlines of managing climate-linked risks.

3.2 Independent Variables: Previous Hazard Exposure and Social Capital

To measure the key independent variables in our study, we construct standardized indices for exposure to past climate-driven hazards ($\tilde{H}_i$), membership in various social groups ($\tilde{G}_i$), and access to multiple information sources ($\tilde{I}_i$), and based on a series of event frequency questions. To measure exposure, we asked respondents to identify how many times over the past seven years they have experienced each of seven climate-driven hazards (drought, flood or heavy rain, excess heat, pests, frost, hail, and lack of groundwater). Pests and frost were the most commonly-reported hazards, with 81 and 57 of the survey population, respectively, reporting exposure in 2021 (SI 3.1). A sizable trend in the past three years has been a five-fold increase in flood exposure: 11 percent of households reported experiencing a flood in Nepali Year 2075 (April 2018 - March 2019), whereas 57 percent experienced a flood in Nepali Year 78 (April 2021 - March 2022). Finally, a smaller but relatively stable proportion of households, roughly 27 percent, reported experiencing drought conditions through the past seven years.

To measure social capital, we asked respondents to indicate how many times per year someone from their household has participated in each of eight different types of social groups present in the Western Chitwan Valley, e.g. a women's group, youth group, farming cooperative, and other options. A substantial proportion of respondents belong to women's groups, which meet on average once per month (Fig. 3a). Other influential groups appear to be farmer cooperatives, lending groups, and community forest user groups, each meeting a few times per year. However, assessing social capital through participation in formal social groups may miss informal social networks that are also important in shaping risk

Variable	2022 Survey Population	2021 Census Chitwan District	2021 Census Nepal Population
Total Individuals	2,389	719,859	29,164,578
Households	500	179,345	6,666,937
Average Household Size	4.78	4.01	4.37
Gender			
Female	62.8	51.1	51.1
Male	37.2	48.9	48.9
Age (Pct of Adult Population)	45.0 (median)		
18-34	22.0	44.6	42.5
35-44	30.6	19.6	20.8
45-54	22.2	14.8	15.7
55-64	16.4	10.5	10.7
65+	7.4	10.5	10.4
Annual Income (NRs)	29,800 (average)	N/A	N/A
0- 100,000	17.4		
100,000 - 250,000	32.2		
250,000 - 500,000	31.8		
500,000 - 1,000,000	15.4		
1,000,000+	3.2		
Educational Attainment (Grade)	5.48 (avg grade)		
0-5	48.2	28.8	33.1
6-10	43.8	33.0	35.4
SLC-Intermediate	6.2	27.8	22.5
Bachelor's or above	1.8	7.8	6.7
Caste			
Brahmin-Chetri	35.8	39.8	28.5
Newar	1.8	4.9	4.6
Gurung-Magar-Tamang	12.4	10.6	14.4
Dalit	15.0	N/A	N/A
Tharu-Darai-Kumal	31.4	6.7	6.7
Other	3.6	38.1	45.8

Table 1: Demographic Summary Statistics

perceptions. We partially capture this mechanism through our final independent variable, in which we ask respondents to identify how often they consult each of 12 types of information sources, including radio, television, agricultural offices, social media, relatives and friends, and other options. Here, two broad categories of information sources emerge: a set of informal sources (e.g. friends in Chitwan or abroad, social media) that are consulted frequently by the majority of the population, and a set of professional sources (e.g. agricultural extension services, veterinarians, migrant recruitment agencies) that are consulted less frequently, and by fewer farmers (Fig. 3b).

Summary statistics for the raw numbers of each of these variables are reported in Table 2 and Figure 3; the full list of hazards, information sources, and social groups, as well as their transformation into indices, is included in SI 2.1. In the analyses presented in the main text, we create indices based on a cumulative count of the types of hazards to which a household reports exposure, and cumulative counts of the information sources and social groups to which a respondent reports consulting. However, some hazards may exert greater influence on overall risk perceptions than others, and some information sources/groups may present more relevant information than others on local climate risks and livelihood opportunities. In SI 4, we present alternative specifications of these indices and reference key findings in the main text.

Factor	Range	Mean	Std. Dev.	IQR
Hazards Experienced at least Once from 2015-2022	[0,7]	3.09	1.32	[2.00, 4.00]
Sources Consulted at least Once per Year	[0,12]	3.93	2.17	[2.00, 5.00]
Groups Participated in at least Once per Year	[0,5]	1.36	1.06	[1.00, 2.00]

Table 2: Independent Variable - Summary Statistics

3.3 Intervening Variables: Climate Risk Perceptions

The main intervening variable in our research design is farmers' perceptions of climate risk to their livelihoods. To operationalize this variable, we draw from existing climate risk perception indices in the literature [Dang et al., 2012, Waldman et al., 2019, Zander and Garnett, 2020], and we measure two dimensions of perceived climate risk: (i) the degree to which respondents perceive that climate-driven hazards are likely to improve or worsen in impact over the near term, and (ii) the salience of climatic factors to respondents' economic and adaptation decision-making. Similar to Waldman et al., [Waldman et al., 2019] we measure the first indicator by focusing on respondents' perceived risk of future climate-driven hazards for their crop harvests through the question: *"Over the next five years, how do you think the impact of [X hazard] will change, compared to today?"* Following Dang et al.'s [Dang et al., 2012] approach in summing perceptions along several dimensions of climate risk, we construct a directional risk perception index, D_i, by assigning a score of +1 to each hazard that household i identified as becoming more severe in the future, and -1 for each hazard the household identified as becoming less severe. We standardize this measure such that $\tilde{D}_i$ can take on values in the interval $[-1, 1]$, with negative values indicating a general perception that climate risks are likely to alleviate in the near future and positive values indicating a general perception that risks are likely to worsen in the near future (SI 2.2).

To measure the salience of climate-related risks, we follow [Zander and Garnett, 2020] in asking respondents to assess the relative salience of a variety of factors (e.g. health, access to labor, weather conditions, etc.) to their livelihood decision-making through the question: *"How significant would you say [X factor] has been in determining your level of economic success from growing crops?"* However, whereas Zander and Garnett measure this numerically on a 100-point scale, we simply ask respondents to rate the salience of each hazard on a Likert scale ranging from 1 (no influence) to 3 (a lot of influence). We then calculate the salience of climate-related risks ($\tilde{S}_i$) by comparing respondents' assessment of "long-term weather conditions" (defined for respondents as conditions lasting more than two weeks) with how they assessed each of the other 14 factors. To avoid potential biases due to the availability heuristic (i.e. respondents may over-weigh factors that first come to mind), we asked respondents this set of questions before engaging in any climate- and weather-specific questions. We standardize respondents' answers to these questions such that $\tilde{S}_i$ takes values between 0 (climate factors are not at all salient) and 1 (climate factors are highly salient).

Finally, we are interested in combining information on the salience of climate factors and the perception of future climate risks through a composite climate risk perception indicator, $\tilde{R}_i$:

$$\tilde{R}_i = \tilde{D}_i * \tilde{S}_i \quad (1)$$

This composite index is different from previous indices reported in the climate risk literature, but captures several characteristics that facilitate analysis of our research questions. First, it takes on values in the interval [-1, 1], and the direction indicates whether the respondent believes climate risks will alleviate ($\tilde{R}_i < 0$) or worsen ($\tilde{R}_i > 0$) in the near future. Second, the magnitude is an indicator of how much of an effect a respondent believes future climatic conditions are likely to have on their farming success. A value $\tilde{R}_i \approx 1$ indicates that the respondent believes most climate-driven hazards will worsen in the coming years, and that this is highly salient to their farming success. However, if a respondent believes that only a few hazards may worsen, and/or that long-term weather conditions are not particularly salient to their farming success, then $\tilde{R}_i$ will take on some fraction between 0 and 1.

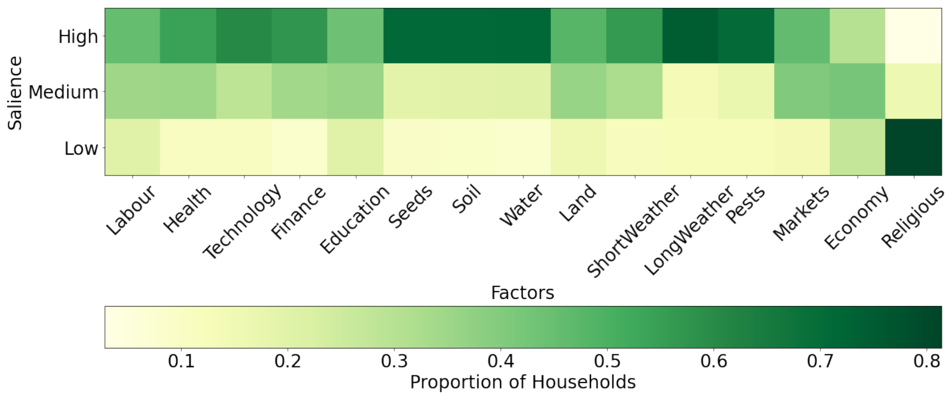
Summary statistics for the measures $\tilde{R}$, $\tilde{S}$, and $\tilde{D}$ are summarized in Table 3 and Figure 2. Generally, "long-term weather" rated the highest of all 14 factors regarding its impact on farmers' economic success, with 74 percent of respondents assigning it a high importance (Fig. 2a). Furthermore, for most hazards, the majority of respondents assessed that the impact of climate hazards on their economic success was likely to worsen over the coming 5 years (Fig. 2b). This was especially true for pests, which 87 percent of farmers expect to worsen in the coming years. Farmers also largely expected floods (68 percent of respondents), frost (63 percent), and droughts (59 percent) to worsen. One notable exception to this trend was hail, which more respondents expected to lessen in impact in the coming years. Although we did not follow up on reasons for these answers, there may be a general perception that warming temperatures will lead to fewer hailstorms.

Variable	**Range**	**Mean**	**Std. Dev.**	**IQR**
Risk Direction Index $\tilde{D}$	[-1,1]	0.407	0.395	[0.167, 0.667]
Salience Index $\tilde{S}$	[0.169,1]	0.655	0.138	[0.610, 0.746]
Composite Risk $\tilde{R}$	[-0.797,0.915]	0.268	0.270	[0.105, 0.455]

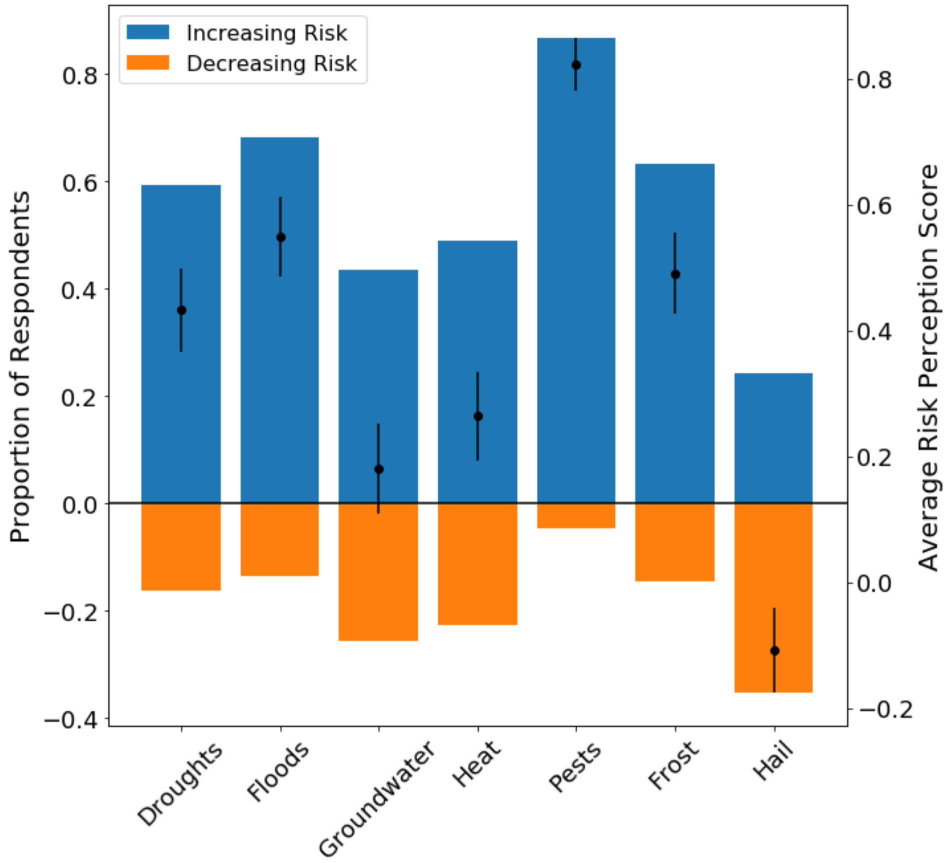
Table 3: Intervening Variables - Summary Statistics

3.4 Dependent Variable: Observed Livelihood Diversification

To assess our main dependent variable, livelihood diversification, we used the calendar format to ask respondents whether they had deployed each of 14 types of livelihoods over the Nepali years 2072-2078 (roughly, 2015-2021), and if so, approximately how much income their household had earned from each livelihood for that year. This generated a quasi-panel dataset of livelihood choices and incomes for 500 farming households that respondents recalled over seven years, which allows us to estimate the composition of household incomes as a function of the independent and intervening variables. For the purposes of analysis, we aggregated the 14 livelihoods into five general categories: farming, raising livestock, engaging in off-farm jobs within the Chitwan District, migration, and other (e.g. government pensions, see SI 2.3 for full list of livelihoods and their generalized categories). In aggregate, households generally maintained highly diversified income portfolios throughout the survey calendar period; an average household derived 33.6 percent of its income from off-farm employment and 31.6 percent from migration remittances, with farming comprising only 8.8 percent of total income (Fig. 4a). However, income portfolios are highly variable across households: roughly 50 percent of respondents received less than 10 percent of their income from remittances, whereas 20 percent of households received 80 percent or more of their income from this source (SI 3.2). There are also significant temporal trends in the study area: average real household income (adjusted for inflation) increased by 15 percent over the study period, driven especially by growth in revenue from livestock (41 percent growth) and off-farm employment activities (35 percent growth, Fig. 4a). This may reflect increasing industrialization and agricultural commercialization in the Chitwan District, providing farming households with more nearby economic opportunities to diversify income sources.

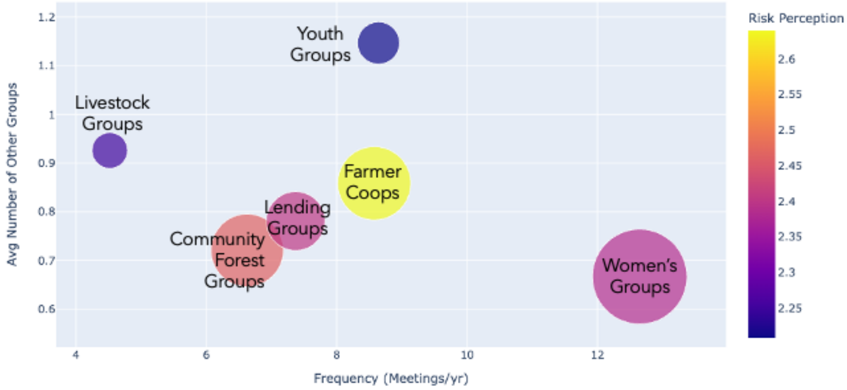


(a) **Salience**

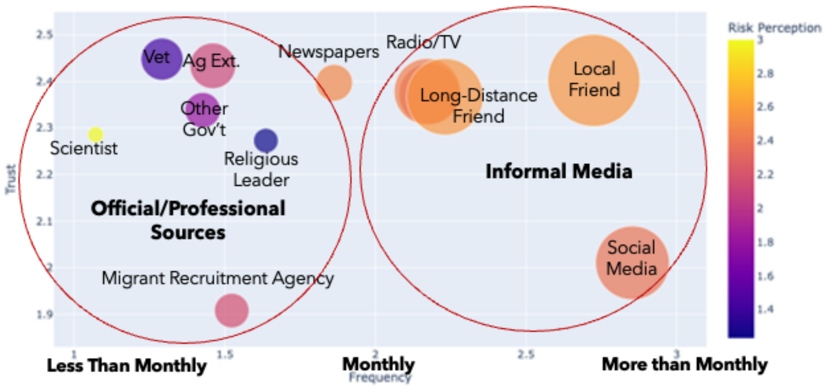


(b) **Risk Perceptions**

Figure 2: **Summary Statistics on Perceived Climate Risk Salience and Direction.** **a)** The heat map illustrates the distribution of survey respondents by the level of salience assigned to each factor on the x-axis with respect to their economic success. For a given factor, the proportion of respondents assigning "Low", "Medium", or "High" importance to a given factor is illustrated by green shading. **b)** Survey respondents generally find that most climate hazards are likely to worsen over the next five years. For each hazard on the x-axis, blue bars indicate the proportion of respondents projecting the hazard's impacts to become worse over the next five years, and orange bars represent the proportion of respondents projecting a hazard's impact to decrease in risk over the next five years. Proportions may not add to 1, as respondents could also answer that "no change" was likely in the hazard. Black dots indicate the sample-wide mean score for each hazard, with 1 representing 100 percent of respondents believing a hazard will diminish in impact, and -1 representing 100 percent of respondents believing hazards will get better. Error bars indicate the 95 percent confidence interval.



(a) **Social Networks**



(b) **Information Sources**

Figure 3: **Breakdown of directional climate risk perceptions (D) by social groups and information sources**. **a)** Social groups are positioned with the x-axis representing the average number of times per year respondents participate in a group. The y-axis position for a group represents the average number of other groups to which its members also have membership. Bubble size corresponds to the proportion of respondents in given group, and color represents the average directional climate risk perception D. For ease of interpretability, D is not standardized in these visualizations. The color scale thus indicates the net number of hazards (out of 7) that consumers of a given source believe will increase in severity in the next 5 years. **b)** Informational sources are positioned according to the average frequency with which they are consulted by respondents (x-axis) and the relative trust that respondents have in them (y-axis, 1 = "Low Trust", 3 = "High Trust"). The size of each bubble corresponds to the proportion of the survey sample that consulted a source at least once in a year. The color of each bubble corresponds to the average directional climate risk perception, D_i, of respondents consulting the specified source at least once in a year.

4 Results

Here, we present the statistical models and most relevant econometric results for the research questions introduced in Section 2.2. In the Discussion, we examine implications of these results for our formal hypotheses and underlying decision-making theories.

4.1 What Factors Shape Climate Risk Perceptions?

To investigate factors shaping farmers' climate risk perceptions, we develop a linear probability model to test for the significance of (i) exposure to past hazards, (ii) access to informational sources, and (iii) access to social groups in affecting farmers' perceptions of climate risk, while controlling for demographic variables. This model has the form:

$$Y_i = \beta_0 + \beta_1 \text{Female}_i + \beta_2 \text{Age}_i + \beta_3 \text{Secondary}_i + \vec{\beta}_{4-8} \cdot \vec{\text{Caste}}_i + \beta_9 \tilde{H}_i + \beta_{10} \tilde{I}_i + \beta_{11} \tilde{G}_i + \epsilon_i \quad (2)$$

where Y_i represents the dependent variable for a household's climate risk perception, which we measure in three ways ($\tilde{D}_i$, $\tilde{S}_i$, and $\tilde{R}_i$) as explained in Section 3.3. Female and Secondary are categorical variables taking on the value 1 if the respondent is a woman and has achieved an education level greater than grade 5, respectively, and 0 otherwise. Age is a discrete variable expressed in years, and caste is a vector of five categorical variables that take the value 1 if the respondent is a member of a specified caste, with Brahmin-Chetri serving as the baseline category. The variables $\tilde{H}_i$, $\tilde{I}_i$, and $\tilde{G}_i$ denote the hazard, information, and social group standardized indices, respectively, as described in Section 3.2. β_0 is a constant and ϵ_i is the error term, which is assumed to be i.i.d.

Broadly, we find that demographic factors and indices of social and informational capital have little explanatory power in shaping generalized farmer climate risk perceptions (Table 4). However, there are two exceptions: the Dalit caste identity is correlated with lower perception of climate risk compared to the baseline Brahmin-Chetri identity ($p < 0.01$), and higher exposure to past climate hazards is associated with a modest but significant increase in climate risk perceptions, as measured by directional ($\tilde{D}$) and composite ($\tilde{R}_i$) risk perception indices ($p < 0.05$). The former is a somewhat counter-intuitive finding, as households belonging to the Dalit caste tend to have lower overall wealth compared to most other castes; one would therefore expect climate risks to be especially relevant for these farmers. However, Dalit respondents in our survey are part of fewer social groups compared to respondents from other castes ($p < 0.01$), and generally have less landholding on average compared to the rest of the survey population ($p < 0.10$). It may be that the social isolation and near-term social and economic pressures experienced by this group diminish the opportunities they perceive from farming and therefore diminish the relevance of climate risks to their livelihoods.

Contrary to hypothesis H1a, neither access to information nor participation in social groups appears significantly correlated with generalized climate risk perceptions across the survey population. One potential explanation is that farmers' risk perceptions differ significantly across specific types of climate hazards. Indeed, 68.6 percent of respondents predicted the impact of at least one type of climatic hazard to worsen over the next 5 years, while also assessing at least one other type of hazard to alleviate in impact over the same time period. In SI 4.2, we further deconstruct the dependent variable $\tilde{D}_i$ into directional risk perceptions of specific hazards. Here, we find that access to greater social and informational capital is significantly associated with perceptions of specific climate-driven hazards, but in different directions. In particular, a 1 standard deviation increase in the number of information sources accessed (approximately 2 additional sources) is significantly correlated with a diminished perceived risk of future droughts (-0.09 points, $p < 0.05$) and groundwater scarcity (-0.07 points, $p < 0.1$). Conversely, greater participation in social groups (participating in 1.0 additional groups) is significantly associated with heightened perception of future groundwater scarcity (0.1 points, $p < 0.01$) and frost (0.06 points, $p < 0.1$). For all hazards except heat and groundwater scarcity, previous experience with a particular hazard was significantly and positively correlated with increased perceptions of its future risk. Regarding demographic variables, female identity was significantly correlated with elevated perceptions of groundwater scarcity ($p < 0.05$), and respondents with at least some secondary school attainment perceive significantly lower risk of drought ($p < 0.1$).

While the positive correlations of specific climate risk perceptions with past exposure and (for some hazards) higher participation in social groups partially supports H1a, the negative correlation of climate risks with access to information is surprising. In the context of this survey population, households with access to greater sources of information typically are ones that have communicated with professionalized services, e.g. agricultural extension officers, veterinarians, migrant recruitment agencies, and other government agencies. In SI 4.4, we test for the specific effect of professionalized vs non-professionalized information sources on generalized and specific hazard risk perceptions. We also conduct alternate specifications of information sources by scope of coverage (i.e. sources that are likely to focus on local vs. national-scale information). While neither alternate specification yields substantially different results for generalized climate risk perceptions, we do find significant correlations between access to local information sources and decreased perceptions of drought and hail risks, as well as access to professionalized information sources and diminished perceptions of drought, flood, and groundwater risks. These results suggest support for the inverse of H1b: access to professionalized sources (especially local ones) appears correlated with lower perceptions of certain slow-onset climate risks. We also test for the specific effect of membership in farming-based social groups in SI 4.5, but do not find substantial deviations from our main results. We next turn to the salience of climate risks for overall perceptions of livelihood risks.

4.2 How Salient are Climate Risk Perceptions to General Perceptions of Livelihood Risks?

We measure the salience of perceived climate risks to generalized risk perceptions of four livelihood strategies: farming cereal crops, raising cattle and buffalo, working off-farm wage labor jobs, and migrating internationally. These are the four livelihood options that respondents found riskiest on average (SI 2.2). As a test for spurious relationships, we also include pension income, which was perceived as the least risky livelihood category and is unlikely to be affected by climate risks.

In this analysis, the dependent variable is respondents' perception of livelihood risk, expressed on a Likert Scale ranging from 1 ("Not Risky") to 3 ("Highly Risky"). This variable is well-suited to an ordered logistic analysis, formalized as:

$$Prob(Y_i \geq j) = \frac{1}{1 + exp(-\alpha_j - \beta_1 * Female_i - \beta_2 * Age_i - \beta_3 * Secondary_i - \beta_4 * \tilde{R}_{10,i} - \beta_5 * \tilde{I}_i - \beta_6 * \tilde{G}_i)} \quad (3)$$

where Prob($Y_i \geq j$) is the probability of household i ranking livelihood Y's riskiness above level j (where j ∈ ["Not Risky", "Somewhat Risky"]). The other variables are the same as in Equation 2, with the exception that here we divide the composite risk index, $\tilde{R}_i$, by 10. This transformation allows for a more meaningful interpretation of the coefficient β_4, which now stands for the log odds that moving 1/10th of the index's range from -1 to 1 (equivalent to 0.2 points) will increase the risk perception of livelihood Y.

Table 5 displays the coefficients and significance levels for each of the five livelihoods assessed. We find that higher perceptions of climate risk, as measured by the transformed composite climate risk index $\tilde{R}_{10}$, are indeed significantly and positively correlated with higher perceptions of livelihood risks for cereal crops, raising large animals, wage labor, and

Variable	Directional Risk ($\tilde{D}_i$)	Salience ($\tilde{S}_i$)	Composite Risk ($\tilde{R}_i$)
Constant	0.395^{***}	0.687^{***}	0.298^{***}
	(0.119)	(0.045)	(0.078)
Gender	-0.0272	-0.013	-0.026
	(0.042)	(0.016)	(0.027)
Age	0.0015	-0.0006	0.0004
	(0.002)	(0.001)	(0.001)
Secondary School	-0.0077	-0.028^{*}	-0.025
	(0.044)	(0.017)	(0.029)
Gurung-Magar-Tamang	-0.0327	-0.027	-0.040
	(0.058)	(0.022)	(0.038)
Dalit	-0.172^{***}	-0.058^{***}	-0.113^{***}
	(0.057)	(0.021)	(0.037)
Newar	-0.0177	-0.016	-0.034
	(0.135)	(0.050)	(0.087)
Tharu-Darai-Kumal	-0.0048	-0.023	-0.043
	(0.044)	(0.017)	(0.029)
Other	-0.0277	-0.0046	-0.0088
	(0.100)	(0.048)	(0.065)
Hazard Index ($\bar{H}_i$)	0.042^{**}	-0.0026	0.029^{**}
	(0.019)	(0.007)	(0.012)
Source Index ($\bar{S}_i$)	-0.011	-0.011	-0.0099
	(0.018)	(0.007)	(0.012)
Group Index ($\bar{G}_i$)	-0.0010	-0.0074	0.0037
	(0.019)	(0.007)	(0.012)

Table 4: **Factors Influencing Generalized Climate Risk Perceptions**, as measured along three dimensions: the perceived direction of future risks ($\tilde{D}_i$), the salience of climate risks relative to other risk factors ($\tilde{S}_i$), and the composite climate risk index ($\tilde{R}_i$), which is a product of these two measures. Significance levels: $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

international migration. An increase of 0.2 points on the Climate Composite Risk scale increases the odds that a household will assign a riskier ranking these livelihoods by 1.17, 1.22, 1.25, and 1.19 times, respectively ($p < 0.01$). In fact, climate risk perceptions are even more salient in driving general perceived risks of raising large animals, engaging in off-farm employment, and engaging in international migration than they are to perceived risks of farming cereal crops. This suggests that rising climate threats may either be directly affecting the viability of these livelihoods, e.g. by making migration trips or outdoor labor more hazardous, and/or indirectly affecting these risks by reducing households' abilities to afford these options. At the same time, this coefficient does not have a significant effect on the odds of pension income being ranked riskier, which matches our intuition.

Informational and social capital are associated with significant reductions in perceived risk levels of different types of livelihoods. Access to more information sources is significantly correlated with a decrease in the likelihood of finding off-farm employment risky ($p < 0.05$), and weakly correlated with a decrease in finding pension incomes risky ($p < 0.1$). Membership in more social groups is weakly correlated with diminished risk perceptions of farming cereal crops, raising large animals, and engaging in international migration ($p < 0.1$). One plausible explanation for these results is that membership in groups e.g. farmer cooperatives and migrant networks help to reduce the long-term risks of these livelihoods, while having more information about off-farm employment opportunities, which are likely more temporary, may be especially important in finding a suitable short-term income source.

In SI 4.2, we further decompose the role of specific hazards in shaping general perceived risks of livelihoods. These results provide strong evidence that farmers perceive climate risks

Variable	Cereal Crops	Large Animal	Intl Migration	Wage Labor	Pension
Gender	-0.047	0.159	-0.388	0.193	0.344
	(0.218)	(0.208)	(0.272)	(0.215)	(0.0214)
Age	0.0007	-0.0084	-0.0052	-0.0084	-0.003
	(0.009)	(0.008)	(0.011)	(0.009)	(0.009)
Secondary School	0.398*	0.060	0.280	-0.137	-0.025
	(0.220)	(0.211)	(0.269)	(0.222)	(0.216)
Composite	**0.160***	**0.200***	**0.227***	**0.177***	**0.0411**
Climate Risk	**(0.037)**	**(0.036)**	**(0.045)**	**(0.037)**	**(0.035)**
Information Sources	−0.104	-0.0527	−0.108	−0.278**	−0.188*
	(0.095)	(0.092)	(0.111)	(0.093)	(0.097)
Social Networks	−0.162*	−0.174*	−0.190*	0.062	0.019
	(0.094)	(0.093)	(0.114)	(0.096)	(0.095)

Table 5: **General Factors affecting Risk Perceptions of Different Livelihoods**. Significance levels: $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

in multifaceted ways. While several climate hazards e.g. droughts, pests, and hail are significantly associated with higher perceived risks of farming, some hazards (droughts, hail, and heat) are also correlated with higher perceived risks of common livelihood alternatives, e.g. livestock, migration, and off-farm employment - sometimes with even stronger effects than they have on perceived farming risk. This complex relationship suggests one understudied mechanism for why previous literature tends to find low uptake of adaptation actions among farmers: as climate change renders farming livelihoods increasingly volatile, it may be seen by farmers as making alternative livelihoods even riskier.

4.3 What Factors Lead to Household Income Diversification?

We next seek to understand how household income sources are related to farmer climate risk perceptions, access to social and informational capital, and experience with climate-related shocks. To do so, we construct a panel model in which we assess drivers of annual changes to households' income sources. This is specified as:

$$Y_{i,t}^{k} = \beta_0 + \beta_1 \text{Female}_i + \beta_2 \text{Age}_i + \beta_3 \text{Secondary}_i + \beta_4 \tilde{R}_i + \beta_5 \tilde{I}_i + \beta_6 \tilde{G}_i + \vec{\beta}_{7-8} \cdot \vec{H}_{i,t} + \delta_t + \epsilon_{i,t} \tag{4}$$

In this model, $Y_{i,t}^{k}$ represents the proportion of household i's income coming from livelihood k in year t. We assess four versions of this model for income coming from farming, livestock, off-farm employment, and remittances. Gender, Age, and Secondary represent the same demographic variables as before. $\tilde{R}_i$ represents household i's general climate risk perception, as above. $\tilde{I}_i$, and $\tilde{G}_i$ represent the information and group index, respectively, for household i. $\vec{H}_{i,t}$ denotes whether household i reported exposure to a particular hazard in time t. For this analysis, we focus on exposure to floods and droughts as two hazards which a moderate proportion of the population reported experiencing in any given year. In alternate models, we test for the 1- and 2-year lagged effect of exposure to floods and droughts by replacing $\vec{H}_{i,t}$ with $\vec{H}_{i,t-1}$ and $\vec{H}_{i,t-2}$, respectively. In SI 4.7, we examine other model specifications and test for possible endogeneity between perceived climate risk and reliance on different livelihoods for income, but do not find strong evidence of reverse causality (i.e. household income composition driving generalized climate risk perceptions). Finally, we add time fixed effects (δ_t) to control for any population-wide temporal trends in income sources. Here, we assume that there are likely unobserved household-level factors that influence how each household adjusts its income to shocks across years and cluster errors at the household level.

Our results indicate that general climate risk perceptions do not seem to significantly affect long-term income portfolio strategies, running counter to our hypothesis of increased diversification as a function of perceived climate risk (H2a). However, other factors may partially explain households' decisions to diversify their income portfolios (Table 6). Membership in social groups is correlated with an increase in the proportion of income coming from farming livelihoods ($p < 0.05$). Access to information sources is significantly associated with deriving more income from remittances ($p < 0.05$) and less from off-farm employment ($p < 0.05$). These results provide mixed evidence for H2b. Increased access to social and informational capital appear to be relevant to farmers' livelihood decisions, but at least in the case of social networks, membership in multiple local groups may be giving households more confidence in their ability to secure income through farming livelihoods, and/or applying peer pressure to conform to predominant livelihood practices in their immediate surroundings, instead of further diversifying household income. In fact, an alternative specification of social networks that only accounts for farming-specific groups is not sufficient to explain this effect (SI 4.5), suggesting that broader localized social networks (e.g., membership in women's groups, community forestry user groups, and youth groups) are contributing to keeping households rooted in local farming livelihoods. Conversely, greater access to diverse information sources, including friends living outside of Chitwan, migrant recruitment agencies, and media, may provide households with more confidence that migration is a viable strategy to diversify their income. In endogeneity checks, we find weak evidence for the possibility that household income sources may exert a causal effect on information sources, but stronger support that income sources could affect membership in social groups (SI 4.7).

In addition to time-invariant factors in our model, e.g. informational and social capital, our analysis also indicates that experiencing climate-driven events is significantly associated with an increase in reliance on farming income (Table 6). Specifically, exposure to a flood is significantly associated with a 4.0 percentage point increase in the proportion of household income coming from farming ($p < 0.05$), and exposure to drought is associated with a similar increase of 2.9 percentage points ($p < 0.1$). Exposure to drought is also significantly associated with a 6.5 percentage point decrease in the proportion of household income coming from off-farm employment ($p < 0.05$). These effects also appear to persist or even increase in magnitude in subsequent years after a household experiences such a shock. For example, exposure to drought or flood is associated with significant increases in the proportion of income coming from farming even two years after experiencing such an event, while exposure to drought is associated with an even more substantial decrease in the income proportion coming from wage labor in the two years following the event (Fig. 5). Exposure to drought is also associated with a significant increase in the proportion of household income derived from livestock two years after a household reports experiencing this event, whereas it does not significantly alter this proportion in the same year of drought exposure, suggesting that investments in livestock may be a longer-term adaptive strategy. Exposure to natural hazards were not significantly associated with the relative proportion of household income from migration remittances.

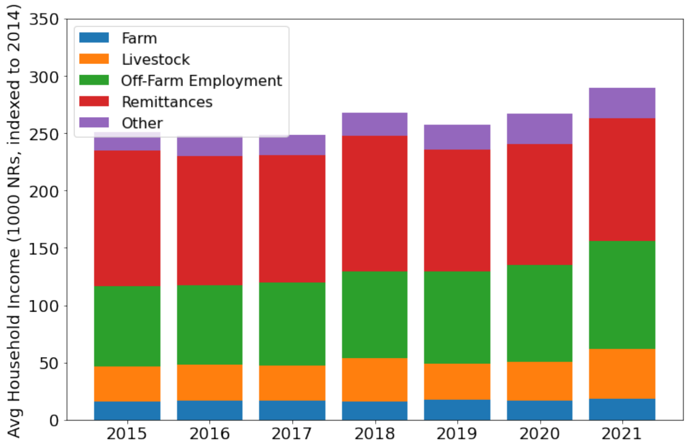
Our panel model therefore points to a counter-intuitive result: exposure to natural hazards that would clearly affect the viability of crop yields actually further deepens farmers' reliance on this livelihood for income. This could reflect at least two mechanisms: (i) financial constraints (i.e., a natural hazard-driven shock reduces households' disposable incomes, and thus their ability to diversify livelihoods in a given season) and/or (ii) psychological responses (i.e., a shock induces households to "hunker down" and focus even more financial and labor resources to produce a suitable harvest). We attempt to further disentangle these mechanisms by disaggregating results by income quartiles. If financial constraints were the dominant mechanism driving an increased reliance on farming income during hazards, we would expect this effect to be more pronounced in lower quartiles and less pronounced in higher quartiles. By contrast, if psychological responses drove this behavior, we would expect little difference in effect across quartiles, and perhaps even more of a "hunkering down" effect among farmers in higher quartiles, who may have more resources to re-deploy to farming in a given season.

Our results illustrate quartile-specific effects that differ by hazard in diverging ways (Fig. 6 and SI 4.6). Specifically, exposure to floods are associated with an especially strong reliance on farming income among the lowest income quartile, increasing this proportion by 8.7 percentage points ($p < 0.05$, SI 4.6). By contrast, exposure to floods is not significantly associated with changes in income composition for the middle quartiles, and weakly associated with a small increase in farming income among the highest income quartile (4.4 percentage points, $p < 0.1$). This result suggests that financial limitations may indeed be constraining poorer households' capabilities to diversify income sources away from farming during flood-driven income shocks. However, drought exposure exhibits a different effect: only the highest income quartile shows a significant, positive relationship between exposure and increased reliance on farming income (4.0 percentage points, $p < 0.1$). No other quartile exhibits a significant relationship between these variables, and the lowest quartile is the only one for which the coefficient is negative. We consider implications of these results in the Discussion.

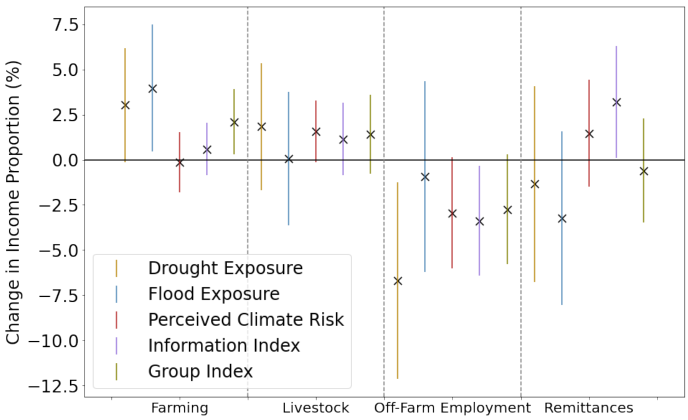
Additional quartile-specific results also suggest further insights. Demographic factors and membership in social groups exhibit stronger correlations for the income composition of lower-income households, while information sources exhibit stronger effects for higher-income households (Fig. 6). This provides further evidence that financial constraints may be a key determinant of livelihood strategies for lower-income households, whereas providing accurate information on climate and other livelihood risks becomes increasingly influential once households have some ability to redeploy resources in response to that information.

Variable	**Farming**	**Livestock**	**Off-Farm Labor**	**Remittance**
Constant	0.91^{***} (0.21)	-0.0001 (0.20)	-0.059 (0.27)	0.64^{**} (0.29)
Gender	-0.022 (0.019)	0.0020 (0.024)	-0.010^{***} (0.036)	0.090^{***} (0.033)
Age	-0.000095 (0.001)	0.0040^{***} (0.001)	-0.0059^{***} (0.001)	-0.0009 (0.001)
Secondary School	0.015 (0.019)	0.022 (0.022)	-0.14^{***} (0.038)	0.027 (0.035)
Composite Climate Risk ($\tilde{R}$)	-0.0049 (0.034)	-0.088 (0.034)	-0.077 (0.060)	0.038 (0.059)
Social Networks ($\tilde{G}$)	0.021^{**} (0.009)	0.015 (0.011)	-0.029^{*} (0.015)	-0.0052 (0.015)
Information Sources ($\tilde{I}$)	0.0059 (0.007)	0.011 (0.010)	-0.033^{**} (0.015)	0.031^{**} (0.016)
Flood Exposure	**0.040**** **(0.018)**	**0.0018** **(0.019)**	**-0.012** **(0.027)**	**-0.031** **(0.024)**
Drought Exposure	**0.030*** **(0.016)**	**0.018** **(0.018)**	**-0.065**** **(0.028)**	**-0.014** **(0.028)**
Year	-0.011^{***} (0.003)	-0.0004 (0.003)	0.011^{***} (0.003)	-0.0054 (0.004)

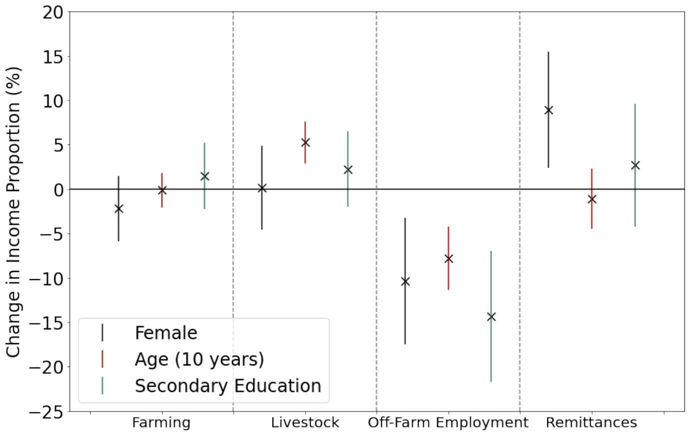
Table 6: **Factors affecting household income composition.** Results from a series of ordinary least squares regressions on factors associated with changes in the proportion of income coming from farming, livestock, off-farm labor, and remittances. Dependent variables, along with the Flood and Drought Exposure variables, are expressed at the household-year scale. Other variables are household-level properties and are time-invariant in this model. The variable Year represents annual fixed effects to capture community-scale temporal trends in livelihood incomes.



(a) **Average Household Income by Year**

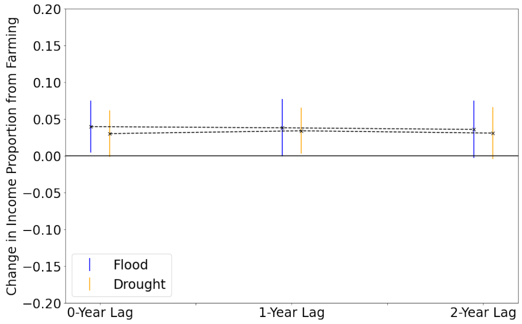


(b) **Effects of Hazards, Risk Perception, and Social Capital**

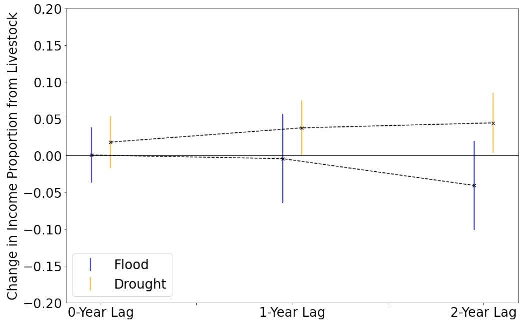


(c) **Demographic Effects**

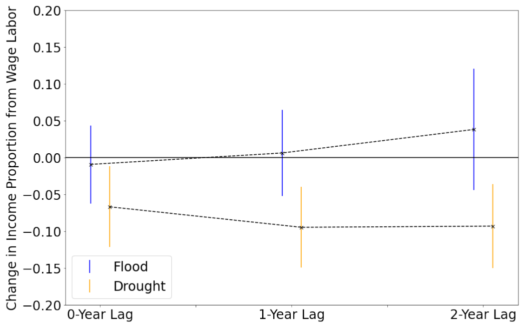
Figure 4: **Household Income Composition by Livelihood Activity.** **a)** Bar chart displays the average income composition of households from 2015-2021 by specific economic activity, expressed in thousands of 2014 Nepali rupees. On average, Chitwan farming households exhibit high diversity of economic activities, with farming only accounting for 8.8 percent of total reported income during this time. The most significant income-generating activities include: remittances from international migration (27.2 percent); off-farm employment, which includes wage labor (14.8 percent) and salary jobs (11.8 percent); and revenue from selling meat and milk (10.2 percent). **b)** Tick marks indicate the effect size of key independent variables on proportion of household income coming from (left-right) Farming, Livestock, Off-Farm Employment, and Remittances, with error bars representing the 95 percent confidence interval of the effect sizes. **c)** For the purposes of illustration, tick marks indicating effect sizes of demographic variables on the proportion of household income coming from each indicated livelihood are shown separately here. Non-binary variables (Perceived Climate Risk, Information Index, Group Index, and Age) are standardized to facilitate comparison.



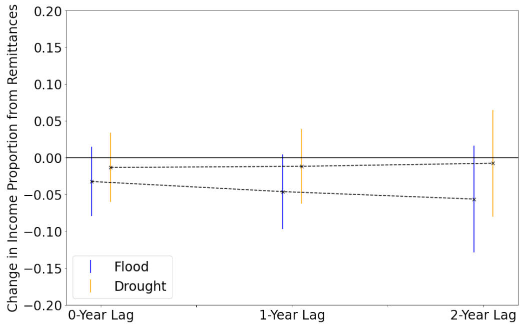
(a) **Farming**



(b) **Livestock**



(c) **Off-Farm Employment**



(d) **Remittances**

Figure 5: **Size and significance of exposure to climate-linked hazards over 2-year period.** The effect size of exposure to drought (orange) and flood (blue) on the proportion of income coming from **a-d)** farming, livestock, off-farm employment, and remittances are shown for three time periods: income in the same year a household reports exposure to the event, income from 1 year after, and income from 2 years after experiencing the event. In some cases (e.g. livestock and off-farm employment), exposure to a hazard is associated with an even greater effect on income proportions two years after the event. Error bars represent the 95 percent confidence interval.

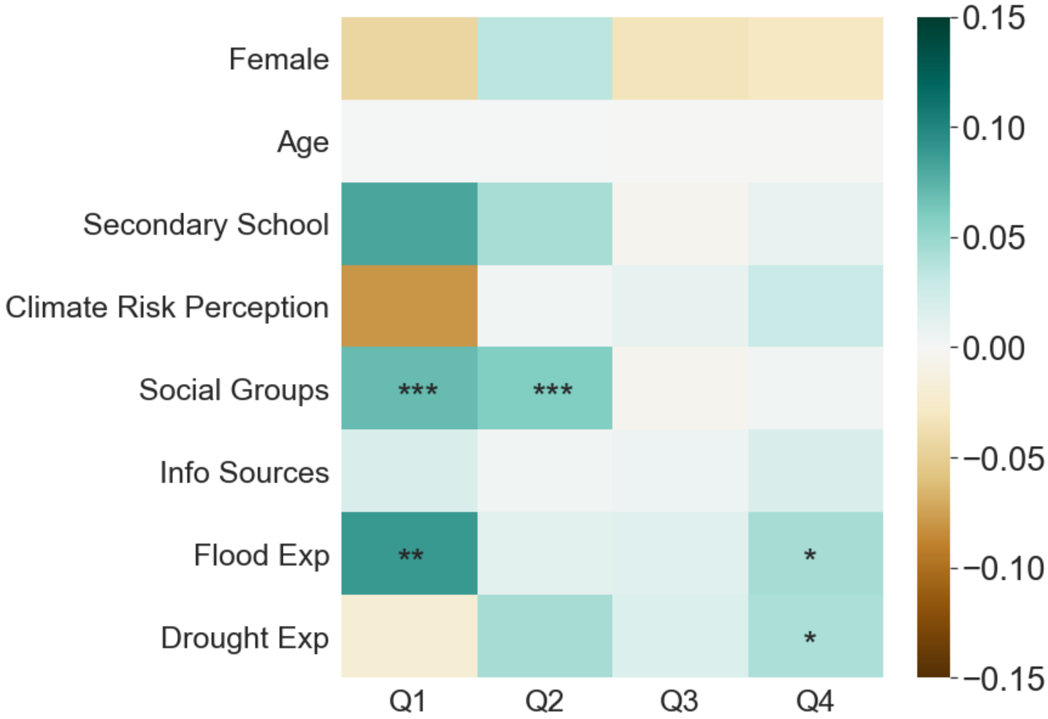


Figure 6: **Effect Sizes and Significance on Income Proportion by Quartiles.** Heatmaps display the direction (blue = positive, brown = negative), strength (colorbar), and significance ($^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$) of effects of each variable on the y-axis on the proportion of household income coming from farming activities. Columns represent effects disaggregated for each income quartile, with Q1 representing the lowest income quartile, and Q4 the highest quartile. Similar results for income from livestock, off-farm employment, and migration remittances are shown in SI 4.6.

5 Discussion

Increasing climate risks to agriculture are likely to require substantial and sometimes swift changes to subsistence livelihoods in the coming decades. This is especially true if regional and global ecosystem tipping points are breached [Morton, 2007, Keller et al., 2008, Rockstrom et al., 2009], resulting in large-scale changes to water availability, soil fertility, and temperature and precipitation patterns. Farmers have had to contend with highly volatile livelihoods for decades, and in some respects are well positioned to cope with uncertainty. As this analysis has demonstrated, smallholder farmers already exhibit highly diversified income portfolios that are malleable in the face of shocks. Yet, long-term climate change introduces new sources of uncertainty for farmers, and the current success of climate information services appears mixed with respect to incentivizing systematic transitions to climate-smart agriculture, including livelihood diversification.

While previous work has elaborated various factors that impact farmers' climate risk perceptions and adaptation choices, here we investigate how heterogeneity in informational and social capital affect these perceptions, and how climate risk perceptions factor into farmers' evaluation of a range of livelihood strategies. We derive three main conclusions from our analysis. First, climatic conditions appear to be highly salient to farmers' overall perceptions of livelihood risks, including farming and non-farming occupations (Sections 3.3 and 4.2). Further, climate-related risks appear to drive even higher perceived risks of common alternative livelihood options to farming, e.g. international migration and off-farm employment. Second, we find that access to a higher diversity of information sources and social networks does not necessarily lead to higher perceptions of climate risks (Section 4.1). In fact, for specific hazards e.g. droughts and groundwater scarcity, access to more information actually dampens perceived climate risk. This may reflect access to local institutions - both formal (e.g. agricultural extension offices) and informal (e.g. friend and migrant networks) - that are well-suited to providing technical help to farmers, even if they are not in a position to implement large-scale strategic shifts in the agricultural sector. Finally, we find that even when households perceive high climate risks, they may in fact "hunker down" on farming-based activities during periods of acute climate shocks (Section 4.4). This behavior persists across multiple years, and appears to be driven by both financial constraints that impede lower-income households from quickly diversifying income sources and a psychological desire among farming households to avoid harvest losses.

Our findings provide some additional nuance for each of the three main theoretical frameworks that informed our hypotheses (Table 7). On the one hand, we find that rural households generally maintain diversified income portfolios, in line with NELM. On the other hand, in times of acute income shock, rural households may intensify their farming livelihoods - providing more support for the SP/A framework, which emphasizes the goal of meeting a basic aspiration level. These nuances align with recent findings on drivers of income diversification across a variety of subsistence farming contexts. Specifically, farmers that experience sustained and severe climate-linked hazards appear more likely to diversify income portfolios [Ma and Maystadt, 2017, Wuepper et al., 2018, Arslan et al., 2021, Antonelli et al., 2022], whereas households experiencing short-term, anomalous shocks are likely to respond through intensifying current agricultural practices [Ma and Maystadt, 2017, Antonelli et al., 2022]. Further, households that already maintain highly-diversified portfolios are generally less likely to further adjust income sources in response to a climate-linked shock [Arslan et al., 2021]. Our findings contribute to this literature by identifying the role of climate-driven hazards in heightening risk perceptions of livelihood alternatives as another factor that contributes to divergent outcomes on diversification. We also find some support for PMT in that past experience with climate hazards appears to make climate risk a more salient threat, and that access to informational and social resources could enhance farmers' perceived capacity to implement livelihood diversification strategies to reduce this threat. However, increased access to information also may diminish perceptions of climate threats, perhaps because it engenders greater confidence that such threats can be success-fully managed.

Our findings also lead to insights that could help improve the effectiveness of climate information services in agriculturally-dependent countries. First, investments in expanding access to climate information services should be paired with financial resources that provide low-income farmers with improved capability to diversify livelihoods. We find that while access to information sources can promote livelihood diversification, this effect tends to be limited to higher-income farmers who presumably have more resources to act on the information they receive. Policy packages that pair dissemination of climate information with subsidized crop insurance, cash transfers, or migration assistance may be more effective in encouraging livelihood diversification [Choquette-Levy et al., 2021]. Second, climate information services should focus not just on risks to farming crops, but also on climate risks to alternative livelihoods, e.g. livestock, off-farm employment, and rural-urban migration. Our results point to a strong correlation between farmers who are concerned about climate change and who believe that livelihood alternatives are also highly risky. These perceptions may reflect real risks, e.g. heat stress that makes off-farm labor work more dangerous and extreme events that make migration trips perilous or less profitable. Policymakers should therefore take a broader view of climate information services such that these provide accurate information about risks to livelihood alternatives, and ideally point to less risky opportunities to diversify incomes during shocks. Third, officials can consider deepening investments in mechanisms that spread crop yield risks over multiple harvests and/or reduce yield volatility, e.g. irrigation infrastructure, cooperatives, grain silos, and food banks. Although policy approaches to agricultural climate risks often assume that farmers will self-insure through migration and other forms of livelihood diversification, our findings of "hunkering down" behavior during climate-linked shocks suggests a fundamental desire to maintain harvests. Therefore, risk-sharing mechanisms tailored to the agricultural sector may provide rural households with both financial and psychological security to pursue alternative income-generating activities. However, such mechanisms may become less effective over time, if rising climate risks lead to increasingly correlated losses across households and across seasons.

There are several considerations that temper the strength of our conclusions. First, our survey comprised a relatively small sample of 500 households, which limits our statistical power to investigate interactions between multiple factors. The survey was also conducted in 2022 following two severe waves of COVID-19, which may have influenced respondents' assessments of various livelihood options, particularly the riskiness of migration. Second, although our sample likely shares demographic similarities with many other farming communities in South Asia (e.g. high working-age male out-migration), it was skewed compared to the overall demographic composition of the Chitwan District and Nepal, and may not be representative of more industrialized areas. Further, we only included households that were currently farming as of the year of study (2022) and therefore did not observe households that may have exited farming in previous years [Ghimire et al., 2021], which likely lead us to underestimate the effects of climate risks on livelihood change. Third, it is difficult for our research design to reject the likelihood of reverse causality for certain hypothesized relationships. While we test for endogeneity between household livelihood choices and risk perceptions (SI 4.7), we cannot fully discount the possibility that risk perceptions and livelihood income choices co-evolve. An ideal research design could disentangle the direction of causality by collecting data on farming households' risk perceptions over multiple survey waves. Fourth, our survey design is subject to multiple potential sources of measurement error. In particular, we encountered several nuanced choices about how to measure risk perceptions, including whether to assess risk as a belief about the probability and severity of specific events or to also measure the salience of such hazards, and whether to combine beliefs about multiple climate risks or keep them disaggregated. A further nuance is how to assess adaptation: should engaging in risky off-farm employment count as adaptation, even if this is done as an option of last resort to make up for income shocks? These questions especially highlight the difficulty of assessing respondents' perceived level of agency in their decision-making, which may be a more direct indicator of whether a strategy could be considered adaptive.

Nevertheless, our findings point to avenues for future analysis and theoretical development. From an analytical perspective, it would be fruitful to integrate the data we collected from mostly close-ended survey questions with qualitative insights from in-depth interviews and focus group discussions. Questions on how farmers compare risks across different livelihood options and the type of information that is obtained from different sources would be especially relevant to this analysis. Expanding the survey area to different agro-ecological regions of Nepal, particularly farming areas in the Himalaya and mid-Hills, could also provide useful insights on how different types and degrees of climate risks are shaping farmers' livelihood choices. In this regard, the Government of Nepal's forthcoming Agricultural Census may offer valuable national-scale data on farmer climate adaptation. Finally, further exploring rural households' basic aspirations and how these might during an income shock, e.g. a drought or flood, may facilitate more nuanced theoretical development.

Framework	**Relevant Hypotheses**	**Supporting Evidence**	**Contradicting Evidence**
Protection Motivation Theory	H1a-b; H2b	Climate hazards correlated with perceived livelihood risks	Information sources correlated with decreased risk perceptions
New Economics of Labor Migration	H2a	Households maintain diversified income portfolios	Households "hunker down" on farming during shocks
Security-Potential /Aspiration	H3	Farmers depend more on farming during shocks	"Hunkering down" behavior more evident for slow-onset risks

Table 7: Theoretical Frameworks - Application to Smallholder Farmer Climate Adaptation

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