Farmer adaptation to reduced groundwater availability

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Abstract

The sustainability of agriculture in the American West depends on the capacity of farmers to adapt to water resource constraints. Most US studies of agricultural adaptations measure farmers’ willingness to adopt various water use reduction strategies, meaning we have little empirical data on which strategies farmers implement and how these decisions impact their farms. We use survey data from 265 farmers in southeastern Idaho who, beginning in 2016, were required to cut annual groundwater withdrawals by 4%–20% to identify (1) the adaptation practices farmers implemented; (2) how reported crop yields and farm income were impacted; and (3) how adaptation practices varied by farm and farmer characteristics. We found the most commonly used adaptations were reduced spending, installation of more efficient irrigation systems or less frequent watering, and changing crop rotations. Farmers reported losing on average 7.6% of their yield and 8.4% of their income over the first two years of the water cuts. We found no systematic variation based on specific farm or farmer characteristics. Drawing on these results and prior research, we present a typology of adaptation categories intended to inform future research, allow comparisons to adaptation strategies elsewhere, and assist policymakers in designing effective policy interventions.

Introduction

The sustainability of agriculture in the American West depends on the capacity of farmers to adapt to future water resource constraints. Climate change, land use changes, and a growing population coupled with diminishing groundwater resources are all expected to alter the timing and amount of water available for agriculture in the coming years (Elliot et al 2014, du Bray et al 2018, Niles and Wagner 2019). Given the reliance of local economies on agriculture along with the effects of farming on local land and water resources, the adaptation choices and overall success of farmers in the American West have important implications for the social-ecological sustainability of the region (Eakin et al 2016). There is a critical need to empirically investigate how farmers are impacted by reduced water availability, through environmental, social, and policy change (social-ecological change hereafter), and the types of adaptation decisions they make to address those impacts.

Research on farmer adaptation to climate and other forms of social-ecological change in the United States (US) has largely focused on farmers’ willingness to adopt various adaptation strategies, and few studies have tracked actual implementation (see Mase et al 2017 for an exception). This literature has demonstrated how risk perception, belief in climate change, attitudes about technology and available adaptation practices, and path-dependencies associated with cropping choices influence farmers’ intentions to adapt (e.g. Niles et al 2013, Chatrchyan et al 2017, Running et al 2017, Gardezi and Arbuckle 2018, Lane et al 2018, Roesch-McNally et al 2018). But more
empirical research documenting how US farmers are impacted by and adapt to climate and other forms of social-ecological change (such as Carlton et al (2016)) is important if the goal is to create future policies that are synergistic with existing formal and informal agricultural institutions (Agrawal 2010, Engle and Lemos 2010, Burnham and Ma 2016).

Beginning in 2016, farmers in southeastern Idaho were required to cut annual groundwater withdrawals by 4%–20%. In this exploratory paper, we use data from a survey of 265 of those farmers to understand (1) how reported crop yields and farm income were impacted by water cuts, (2) the adaptation practices farmers implemented; and (3) whether adaptation choices varied by farm and farmer characteristics. In response to critiques that most research characterizing, monitoring, and evaluating adaptation lacks a standardized approach, thus limiting comparability and generalizability across systems (Ford and Berrang-Ford 2016), we also present a typology of adaptation behaviors expanded from existing literature. Doing so enables us to report our results in a standardized way that is comparable with other research efforts examining adaptation practices (see Agrawal 2010, Burnham and Ma 2016, Fischer 2018, 2019, Ford and Berrang-Ford 2016 for more on the importance of typologies in adaptation research).

Adaptation typology

Several conceptual frameworks and typologies that highlight the function, origin, timing, and purpose of different adaptation actions have been developed. Within them, adaptation actions are frequently conceptualized as binaries: either autonomous or planned, private or public, pro-active or reactive, and incremental or transformative (Tompkins and Eakin 2012, Thorn et al 2015). While competing definitions of adaptation exist, in the context of agriculture, adaptation is typically defined as changes in beliefs, values, and actions that help farmers mitigate the impacts of change and increase a farm’s harmony within its social-ecological context (Carr 2008). Adaptation is often distinguished from coping responses, defined as shorter-term, quickly implemented behaviors designed to reduce stress and regain livelihood stability (Osbahr et al 2008). However, simplistic distinctions between adaptation and coping fail to consider that those experiencing social-ecological stressors do not necessarily recognize the dichotomy (Osbahr et al 2008). Moreover, with repeated exposure to social-ecological stressors, coping and adaptation strategies are often employed simultaneously and the boundaries between them, as well as between pro-active and reactive adaptation and other binary categories, blur (Osbahr et al 2008, Agrawal 2010, Burnham and Ma 2018).

The adaptation practices catalogued in this paper are a mix of planned, long-term behavioral shifts (often considered adaptation) and shorter-term, incremental and reactive behaviors (often considered coping). We thus develop a typology that incorporates both adaptation and coping within a single classification system, focusing on risk reduction rather than timing. Further, our typology calls attention to the various ways farmers reduce risks posed by social-ecological change beyond changing their farm management practices and allows for comparison across case-studies. Understanding how farmers employ multiple risk reduction strategies simultaneously is essential for developing adaptation policy that does not contradict extant forms of risk management and can help policymakers avoid unintended consequences. Our approach builds on a conceptual typology created by Agrawal (2010) and extended by Burnham and Ma (2016) and focuses on how social-ecological change poses risks to farmers’ ability to maintain operations across time, space, asset classes, and households. Thus, we categorize farmers’ adaptation practices into one of the following six analytical risk management categories that identify the mechanisms through which farm-level risks are experienced and addressed: (1) mobility, or the distribution of risk across space; (2) storage, or the distribution of risk across time; (3) diversification, or the distribution of risk across asset classes; (4) communal pooling, or the distribution of risk across households, (5) market exchange, or the purchase and sale of risk via contracts and other processes, and (6) environmental management, or the reduction of risk through changes in management practices.

Though this typology was originally developed through examination of adaptation practices in the Global South, we add a suite of risk management strategies relevant to US industrial agriculture not reflected in the six-category typology laid out above (see table 3). First, we retitled the ‘environmental management’ category ‘operations management,’ and gave it four sub-categories. The first is technology, or the reduction of risk through technology adoption (e.g. center pivot irrigation), in which farmers update their operations with new technologies rather than manipulating those they already use. The second is water, or the reduction of risk through changing on-farm water management (e.g. change irrigation schedule). The third is crops, soil, and environment, or the reduction of risk through changes in farm management practices not captured by the first two sub-categories (e.g. change crop rotation), and finally assets, or the reduction of risk through changing how income and savings are managed. We recognize the potential overlap between these categories, a risk inherent in the development of any typology, and suggest researchers employ their best judgement when categorizing adaptation practices in their own studies while keeping in mind that the mechanism of risk reduction allowed by the broader operations management category is more analytically important than to which sub-category an individual strategy belongs. Second, we changed the category ‘diversification’ to ‘income diversification’ to more accurately label farmers’ adaptation strategy of...
distributing risk across income sources. Finally, we added two categories to the typology: capacity building, or the reduction of risk through learning and other ways of increasing management skills, as well as exiting farming altogether.

Below, we summarize the ecological and economic characteristics of our study site, as well as the 2015 water settlement agreement that led to the mandatory annual groundwater reductions to which the farmers are adapting. We then outline our data collection process and present descriptive statistics of the adaptation behaviors farmers reported using to meet their water usage reduction requirements. We end with a brief discussion.

Methods and data

Study site and policy context

Idaho’s Eastern Snake Plain Aquifer (ESPA) region is a primarily agricultural area that covers most of southern Idaho and contributes substantially to the global agricultural market (UIE 2016), producing about 33% of the potatoes, 20% of the sugar beets, and 10% of the total wheat in the United States, and about 72% of Idaho’s market value in agricultural commodities (USDA 2014, Li et al 2019). Income from agricultural activities also accounts for almost two-thirds of the median household income in the region (UIE 2016).

In 2015, negotiations between representatives of surface water and groundwater users culminated in an overhaul of existing water policy in Idaho and a new water management agreement that requires groundwater irrigators in the ESPA’s eight groundwater districts to reduce total irrigation water consumption by an average of 240 000 acre-feet (AF) (or about 29.6 trillion m$^3$) or about 13% annually, calculated from mean annual water usage over the last five years (1 AF = 1233.48 m$^3$). As long as each farmer maintains membership in their groundwater district and follows its rules for meeting the reductions, individuals are protected from lawsuits by surface water users (most of whom have legally senior water rights) for the five-year agreement. According to the state’s water policy, prior appropriation, water rights are assigned a priority date stipulating that senior water rights holders receive their full allotment before junior water rights holders when water access is curtailed. Without the 2015 agreement, water rights would be fulfilled annually following their priority dates, with the earliest water rights holders legally able to demand their full water share despite diminishing water resources.

Groundwater district managers were given some autonomy in implementing the agreement. Figure 1 shows a map of these eight groundwater districts, each of which were allowed to allocate specific reductions...
between various water rights holders and monitor compliance among their own members. Most districts developed a tiered system requiring groundwater withdrawal reductions by certain percentages depending on a water right's seniority, while a few districts required the historically highest using farmers to reduce the most. The agreement went into effect in 2016 and will be re-examined and potentially renegotiated in 2020 (for more detail on the agreement, see du Bray et al. 2018).

**Survey**

Our data come from a mail survey sent to farm operators in the eight affected groundwater districts, administered from February to April 2018 (Burnham et al. 2019). To construct our sample, we identified water rights holders in each district using the Idaho Department of Water Resources (IDWR) online water rights locator tool. This process yielded 800 farm operator addresses. Because the tool acknowledges the database of water rights is incomplete, we supplemented by crosschecking addresses from an IDWR curtailment order sent on 17 January 2017 to water rights holders in the ESPA with rights junior to 20 June 1989. This resulted in a total of 1398 unique addresses.

We employed the standard Tailored Design Method (Dillman et al. 2014) to administer the survey. We included a $2 incentive in the first survey mailing. Respondents had the option to respond online, though less than 10% did. One hundred and seventy-nine surveys were returned as undeliverable, and an additional 85 were returned with a note from the respondent stating they no longer farmed or owned that land, resulting in an adjusted sample size of 1133. In total, we received 265 surveys for a final response rate of 23%. While fairly low, we suggest this number is acceptable given our focus on developing our conceptual typology rather than statistical generalization, as well as the general decline in household survey response rates in the United States (Stedman et al. 2019). All data were entered using CSPro and then analyzed using R (R Core Team 2018) and Stata 15.

**Table 1.** Descriptive statistics summarizing farm and farmer characteristics.

| Variable                          | Measure       | Percentage |
|----------------------------------|---------------|------------|
| Gender                           | Male          | 93%        |
|                                  | Female        | 7%         |
| Education                        | High school   | 21%        |
|                                  | Technical school/some college | 26%        |
|                                  | College       | 37%        |
|                                  | Graduate degree | 16%        |
| Average net farm income over last 5 years | Less than 25 000 | 27%        |
|                                  | Between 25 001 and 50 000 | 21%        |
|                                  | Between 50 001 and 100 000 | 21%        |
|                                  | Between 100 001 and 250 000 | 15%        |
|                                  | Between 250 001 and 500 000 | 7%         |
|                                  | Between 500 001 and 1000 000 | 7%         |
| Average yearly farm expenses over last 5 years | Less than 25 000 | 22%        |
|                                  | Between 25 001 and 50 000 | 11%        |
|                                  | Between 50 001 and 100 000 | 17%        |
|                                  | Between 100 001 and 250 000 | 19%        |
|                                  | Between 250 001 and 500 000 | 0          |
|                                  | Between 500 001 and 1000 000 | 0          |
|                                  | More than 1000 000 | 32%        |
| Average percent income from different sources | Agriculture | 53%        |
|                                  | Livestock     | 14%        |
|                                  | Other         | 32%        |
| Political ideology               | Liberal       | 3%         |
|                                  | Moderate      | 21%        |
|                                  | Conservative  | 76%        |
| Percent growing crop             | Alfalfa/hay   | 7%         |
|                                  | Barley        | 23%        |
|                                  | Corn silage   | 8%         |
|                                  | Seed corn     | 1%         |
|                                  | Potatoes      | 18%        |
|                                  | Sugar beets   | 17%        |
|                                  | Irrigated wheat | 12%        |

| Variable                           | Average       | Min–Max       | Standard deviation |
|------------------------------------|---------------|---------------|--------------------|
| Acreage farmed                      | 1252 (5.07 km²) | 0–16 000 (64.75 km²) | 2270 (9.19 km²) |
| Acreage owned                       | 1316 (5.33 km²) | 1–15 000 (60.70 km²) | 2166 (8.77 km²) |
Table 2. Descriptive statistics summarizing impacts of required water cuts.

| Impact                                      | Average | Min–Max  | Standard deviation |
|---------------------------------------------|---------|----------|--------------------|
| Percent water cut                           | 11.9    | 0–80     | 12.7               |
| Percent yield lost                          | 7.9     | 0–100    | 11.9               |
| Percent farm income lost                    | 8.6     | 0–80     | 11.8               |
| Number of well meters purchased             | 3.7     | 0–49     | 5.6                |
| Well meters that still need to be purchased | 1       | 0–75     | 5.5                |
| Acres taken out of production in 2016       | 68 (0.28 km²) | 0–4500 (18.21 km²) | 419.2 (1.70 km²) |
| Acres taken out of production in 2017       | 74 (0.30 km²) | 0–4500 (18.21 km²) | 405.6 (1.64 km²) |
| Money spent to meet requirements in 2016    | $11 174 | $0–200 000 | $24 851.14         |
| Money spent to meet requirements in 2017    | $13 849 | $0–400 000 | $40 122.24         |

| Water rights type | % with water rights type | Average % of water rights portfolio |
|-------------------|--------------------------|-------------------------------------|
| Junior            | 60%                      | 25%                                 |
| Senior            | 79%                      | 52%                                 |
| Surface           | 45%                      | 24%                                 |
| Dual rights       | 80%                      | 8%                                  |

### Analysis

Our first analytic step was developing a strategy to deal with item-level missingness in the responses, which was 12% across the entire dataset and about 17% across the adaptation actions analyzed in this paper. Although this level of missingness is common in survey research, 183 of 264 observations would have been lost if we had used listwise deletion. Therefore, we performed multiple imputation to retain all responses for our analysis. Multiple imputation is a class of methods designed to enable unbiased analysis of datasets with data missing at random (Rubin 1987). We used the Multivariate Imputation by Chained Equations (mice) package in R (van Buuren and Groothuis-Oudshoorn 2011) because it allowed for flexibility in the imputation method and mechanisms of imputation quality checking. We conducted five imputations (frequently suggested as the minimum threshold for effectively representing variability in the prior distribution from which imputations are sampled (Lall 2016)), yielding a 97.65% on the Rubin’s score for relative. We then calculated descriptive statistics from this imputed dataset to identify how farmers have been impacted by the required water reductions and which actions farmers had undertaken in each category in our typology.

### Results

Descriptive statistics for farm and farmer characteristics among our 265 respondents are reported in table 1. On average, respondents farmed 1252 total acres (~5.07 km²). The primary crops grown were typical for the region, and included alfalfa/hay, barley, corn for seed or silage, potatoes, sugar beets, and both irrigated and dryland wheat. Most farms held a diverse portfolio of water rights with respect to both type and seniority. Specifically, 80% of respondents reported holding dual water rights—a mixture of surface and groundwater permits that can be used on the same land. Sixty percent of respondents held some junior water rights, while 79% held some senior water rights.

### Adaptation actions

Respondents reported an average required water cut of 11.9%; table 2 summarizes the overall impact. Average yield loss was 7.9% and farm income loss was 8.6%. An average of 33 acres (0.13 km²) were taken out of production in 2016 and 41 acres (0.17 km²) in 2017. On average, $11 173 was spent in 2016 (and $13 848 in 2017) to meet the required water cuts. The most common expenses were putting in required water meters and improving the efficiency of current irrigation systems or switching to a new system, followed by purchasing canal water rights or recharge credits and hiring an outside consultant to provide technical help or perform an efficiency review of farm management practices.

Our survey included a list of 27 possible adaptation actions farmers could have implemented to reduce water use since the settlement agreement or mitigate the impacts and risk the settlement agreement posed to their farm, with two blanks for ‘write-in’ strategies where 49 farmers identified strategies not included in our list of possible adaptation actions (table 3). Most respondents reported implementing more than one action (mean = 9). Among the ‘write-in’ actions, the three most frequently reported strategies were renting out all or part of their land (9 farmers or 3%), reducing the proportion of the farm work done by hired laborers (6 farmers or 2%), and retiring (5 farmers or 2%). Of the 27 adaptation actions provided, the two most commonly adopted were improving irrigation system efficiency (77%) and reducing spending (67%). Irrigating less frequently (59%), changing crop rotation...
(53%), and switching to a more efficient irrigation system (53%) were also actions taken by more than half of respondents. The least commonly adopted adaptation actions (with fewer than 10% of respondents reporting their use) included selling land (8%), joining a co-op (8%), and the most extreme strategy available, exiting farming altogether (6%).

We used our typology to categorize adaptation actions and evaluate what types of risk reduction strategies were most and least used among farmers. The most used type of adaptation was modifying water-related operations management, with 88% of our respondents reporting the adoption of at least one strategy to use less water. The specific actions farmers undertook to reduce water usage in this category were not watering the corners of farm fields (48%), irrigating less frequently (59%), turning off the end guns on their center pivot systems (42%), and planting less water-intensive crops (44%).

The next most common type of adaptation involved changes in technology-related operations management. Here, 85% of respondents reported having made some sort of technology-supported efficiency improvement, with improving irrigation efficiency being the most common (77%), switching to more efficient irrigation systems fairly common (53%), and adopting precision agriculture somewhat less common (21%). Similarly, about 79% of respondents adjusted one or more of their crop, soil, or environment-related operations management practices, with 53% changing their crop rotation schedules, 43% their tillage practices, and 36% taking land out of production.

Beyond the operations management changes related to water, technology, crop, soil or environment, a majority of respondents (67%) also used market-based strategies to mitigate the water cut’s impacts. These strategies included planting higher value crops, contracting more or fewer crops, selling land or enrolling in government conservation programs (most of which pay farmers), and/or purchasing water or water rights in some way, though each of these individual strategies were only used by 10%–20% of respondents. Additionally, 67% of respondents reported reducing spending on either farm-based or personal expenses (even noting forgone vacations, movies, or dinners out in their optional written answers), and about one-third diversified their household income either by taking an off-farm job or starting a new business.

### Table 3. Typology of Adaptations with percent adopting in each category.

| Adaptation type                              | % Adopting category | Adaptation action                                      | % Adopting action |
|----------------------------------------------|---------------------|--------------------------------------------------------|-------------------|
| Income diversification                       | 34                  | Took an off-farm job                                   | 21                |
|                                              |                     | Started a new business                                 | 14                |
| Communal pooling                             | 8                   | Joined a coop                                          | 8                 |
| Market exchange                              | 67                  | Planted higher value crops                             | 18                |
|                                              |                     | Contracted more crops                                  | 22                |
|                                              |                     | Contracted fewer crops                                 | 14                |
|                                              |                     | Sold land                                              | 8                 |
|                                              |                     | Put land into CRP or other government program          | 14                |
|                                              |                     | Purchased recharge credits                             | 18                |
|                                              |                     | Purchased or rented canal shares                       | 19                |
| Operations management-technology             | 85                  | Improved irrigation system efficiency                  | 77                |
|                                              |                     | Switched to more efficient irrigation system           | 53                |
|                                              |                     | Adopted precision agriculture                          | 21                |
| Operations management-water                  | 88                  | Dried up corners                                       | 48                |
|                                              |                     | Turned off end guns                                    | 42                |
|                                              |                     | Irrigated less frequently                              | 59                |
|                                              |                     | Planted less water intensive crops                     | 44                |
|                                              |                     | Used canal water to meet requirements (mitigate)       | 37                |
| Operations management-crops, soil, and environment | 79                | Changed crop rotation                                  | 53                |
|                                              |                     | Switched to or added dryland acres                     | 25                |
|                                              |                     | Took acres out of production                           | 36                |
|                                              |                     | Changed tillage practices                              | 43                |
|                                              |                     | Reduced livestock herd size                            | 13                |
| Operations management-assets                  | 67                  | Reduced spending                                       | 67                |
| Capacity-building                             | 28                  | Hired consultant for technical help                    | 28                |
| No adaptation                                | 29                  | Did not do anything                                    | 12                |
| Exit (removed exposure to risk)               | 6                   | Stopped farming                                        | 6                 |
Discussion and conclusions

Our research findings address a critical need in planning for the future of agriculture in the American West: understanding how farmers are impacted by and responding to changing water availability, one of the most important forms of social-ecological change in the region. Water availability can change due to policy drivers, such as the water settlement agreement analyzed in this paper, environmental drivers such as climate change, or social drivers such as in-migration and the associated development that many previous studies have documented. In an agricultural context, adaptation to these changes involves producers making farm-level operations adjustments, and most previous research in the US has focused on practices that in our typology fall under the operations management category (e.g. Mase et al. 2017). However, our research shows that farmers’ adaptive responses to social-ecological change in the form of a new requirement to reduce groundwater irrigation may be more heterogeneous than past research suggests. Specifically, surveyed farmers employed a range of practices to address the ways that social-ecological change poses risk to their livelihoods across time, space, asset classes, and household. Moreover, correlational assessments completed in the course of our data analysis revealed no clear pattern between individual farmer or farm-level characteristics and adaptation actions, suggesting farmer adaptation decision-making may be more associated with regional environmental or socio-political context than individual farmer and farm-level differences, as much of the adaptive capacity and vulnerability literature suggests (Grothmann and Patt 2005, Adger 2006, Eakin and Lemos 2010, Lemos et al. 2016).

What we did find is that the vast majority of farmers in our study have undertaken at least one adaptation action to meet the required water cuts, and on average, farmers used nine out of 27 possible options in our survey. Even though a few types of adaptation strategies are more commonly used (e.g. changes in operations management, changes related to market exchange) than other types (e.g. income diversification, capacity building, or communal-pooling), every possible strategy listed in our survey and all of the more generalized adaptation categories were chosen by at least some farmers. This finding suggests that many farmers address risk in a more holistic way than simply employing one-off on-farm management adaptations, and they tend to select a combination of adaptation practices that also reduce temporal, spatial, asset-related or community-based risk. As such, it is important for policymakers who seek to incentivize agricultural adaptation to be aware of this diversity of possible choices and how practices they decide to promote may create synergies or incompatibilities with the local farming practices already in use (Agrawal 2010).

A close look at the common types of adaptation used by our surveyed farmers shows that changing operations management was the most widely used category of adaptation practice. It may be that this type of adaptation requires the least amount of new investment or knowledge (with the possible exception of changing crop rotations, if all of the crops had been grown by the farmer before) and thus may be considered the ‘low-hanging fruit’ of adaptation choices. In particular, our results show modifying on-farm water use as the most used adaptation strategy, likely because it is an action that has a measurable outcome with clear short-term effects and does not require any new investments. However, adopting this strategy may not be available to farmers who already irrigate efficiently because there would be little room for further reductions (du Bray et al. 2018). Technological upgrades, the second-most commonly adopted change in operations management, may be similarly appealing to some farmers because they require little change to existing practices while still offering long-term efficiency gains. But, new technologies such as more efficient irrigation systems or technologies that support precision agriculture are expensive and highly dependent on economic resources or the ability to access lines of credit or cost-share programs. Moreover, the capital outlay required to purchase new technologies likely reduces the financial capacity of adopters and thus their ability to deploy economic assets to mitigate new forms of risk. As such, researchers, practitioners, and policy makers should pay particular attention to the justice implications of promoting certain adaptation strategies and identify how and when adaptation to one stressor could potentially expose farmers to new forms of risk or reduce their ability to adapt in the future (Osborne et al. 2008, Feola et al. 2015, Taylor 2015, Burnham and Ma 2018).

Finally, we want to again emphasize our most hopeful finding to date, which is that, despite average yield losses of about 7.9%, and average farm income losses of 8.6%, the vast majority of farmers faced with the irrigation restrictions required in Idaho’s 2015 water settlement agreement have successfully found adaptation strategies that allow them to continue farming without having to sell off farmland or leave the farming business. Still, there are farmers who seem to farm at the margins of profitability and who may not be able to absorb much more in the way of losses if future policies require additional cutbacks or another social-ecological challenge emerges. Further, farmers’ ability to continue adapting may become more constrained over time as climate change increasingly threatens water availability and growing human populations accelerate demand. Eventually, such changes may result in more farmers choosing to leave agriculture which may generate significant second-order effects, including changes to crop prices, the loss of ag-related businesses in a region, and exurban...
development, thus reducing local employment opportunities in rural areas and hastening the deterioration of rural communities. It is also important to follow up with exiting farmers to assess the longer-term livelihood implications for those individuals.

All of this suggests that, in order to avoid adverse unintended consequences, understanding the adaptation actions farmers select and why, including decisions to exit farming or sell off farmland, may be necessary to prevent negative socioeconomic effects or cultural consequences. This remains an important area for future research, with the broad literature on adaptive capacity providing a fruitful starting point for examining the structural and individual factors that shape how farmers adapt to social-ecological change.

In addition, on the policy front, results from these studies and those documenting how policies affect human communities and ecosystems provide an opportunity for future policymakers to draft evidence-based policies that both complement existing adaptation behaviors and balance impacts to farmers with long-term environmental sustainability.

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Data availability statement

The data that support the findings of this study are openly available at: https://doi.org/10.7923/3cjg-wy61.

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