FARM RESILIENCE TO WATER SUPPLY VARIABILITY:

AN ECONOMETRIC ANALYSIS OF RISK MANAGEMENT STRATEGIES

IN THE MEXICALI VALLEY, MEXICO

By

Elizabeth Schuster

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STATEMENT BY AUTHOR

This thesis has been submitted in partial fulfillment of the requirements for an advanced degree at The University of Arizona.

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APPROVAL BY THIS THESIS DIRECTOR

This thesis has been approved on the dates shown below:

___________________________________ ________________

Bonnie Colby, Ph.D. Date
Professor of Agricultural and Resource Economics

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The statements, findings, conclusions, and recommendations are those of the author and do not necessarily reflect the views of the Walton Family Foundation, interviewees and survey respondents, or the individuals who have supported and reviewed this thesis.

DEDICATION

To all the farmers we surveyed in the Mexicali Valley,

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Abstract

In the lower Colorado River in the western United States and northern Mexico, water supplies are being constrained by increasing competition from urban populations, ecosystems, and the pressures of climate change. Regional stakeholders are interested in how farmers could reduce consumptive use of water and/or water diverted while still maintaining profitability. Two promising risk management strategies have been highlighted, the adoption of cement lining of parcel-level canals and the diversification of crop portfolios by adding a crop with a lower consumptive use of water. Yet little is known about the economic feasibility of these options and current adoption patterns. This thesis, focused on the Mexicali Valley of Mexico, is the result of multi-faceted research over two years including numerous interviews with water managers and other stakeholders as well as 180 detailed farm household surveys conducted in 2012. The results provide insights into the questions of regional water supply reliability and farm resilience to uncertainty in irrigation water supplies. The study finds evidence that crop diversification and cement lining of parcel-level irrigation canals are often considered economically feasible by farmers at the farm level. Specifically, past problems with water supplies are positively associated with investment in the two strategies. Irrigation water delivery delays are more likely to lead to crop diversification while irrigation delivery shortfalls are more likely to be associated with the adoption of water conserving technology. These conclusions provide valuable information to a wide range of stakeholders that can lead to more effective water management at the regional level.

Chapter One - Introduction and Background

1.1 Introduction

Water supplies are fully allocated across much of the western United States and northern Mexico. The Colorado River is no exception, and consequently no unclaimed water is available as water demand increases. Problems of water supply reliability are being exacerbated with the intensification of agricultural production, and an increasing demand from growing urban populations and water-dependent ecosystems. In the arid Mexicali Valley of Baja California, Mexico, located in the lower Colorado River, agriculture has the highest consumptive use of water. However, water is also a critical input in agriculture since precipitation levels are negligible in terms of maintaining agricultural production and farmers are entirely reliant upon surface and groundwater for irrigation. And because water is a critical input in crop production, even slight changes in irrigation water deliveries can directly impact agricultural profitability. Given the challenges in predicting future regional water supplies both temporally and spatially, adaptive strategies to water supply variability that allow farmers to maintain productivity during a wider range of conditions are crucial.

In addition to the increasing pressures on water supplies in the Mexicali Valley due to a rise in demand, the region also represents an interesting case study due to recent shocks that have impacted regional water supplies. Yet, little is known about the differences and magnitudes of shocks that impact water users within a single region and how farmer responses to shocks differ. The "Easter" earthquake of 2010 destroyed 600 kilometers of canals and drainage ditches and is one type of shock that tested farmers' capacity to respond to water supply variability. About 140,850 irrigated acres (57,000 hectares) were affected, with the primary damage concentrated in irrigation Modules 10, 11, and 12. Approximately 88,958 acres (36,000 hectares) were brought back into production in the first phase of repairs, with both government and individual investments contributing to the reconstruction of canals and ditches, laser leveling of agricultural parcels, and improvement of soils through application of soil amendments. The remaining acreage is still in the process of water delivery system reconstruction.

The lining of the All-American Canal in southern California (completed in 2010) is another example of a shock to the water supply in the Mexicali Valley. The cement lining prevented water seepage, which had previously recharged the aquifer for Mexicali Valley farmers located in the northern perimeter of the district. Although the long-term impacts on groundwater levels are not yet well understood, experts in the region predict that the true impacts may not be seen until 5-10 years after the lining of the All-American Canal.

The word “drought” is often an inaccurate representation of the issues at hand because there is little change in precipitation levels each year and because it overly simplifies the issue as being a matter of quantity. The emphasis on drought fails to capture the role of the volume of water available for irrigation, the timing of irrigation deliveries, and the variability of the quantity and timing. At times, uncertainty in water supplies is due to water management issues, while at other times the water supply is not the issue, but the lack of storage capacity, implying that water supply variability may be a more appropriate way to frame the issue, instead of focusing on drought.

This thesis examines regional water supply variability, and focuses specifically on decision making at the farm level. How do farmers select among multiple risk management strategies that increase their ability to respond to water supply variability? Do farmers respond differently to *general threats* to water supplies (*i.e*. long-term shortfalls in irrigation deliveries) as they do to unexpected *shocks* to their water supplies (*i.e*. the Earthquake of 2010)? Given the heterogeneity among farmers in terms of wealth, access to resources, and where they cultivate within the district, it becomes clear that heterogeneity is likely in the risk management strategies of farmers. Nonetheless, little is known about how heterogeneity among farmers influences their choice of risk management strategies.

1.2 Background on irrigation and crop production in the Mexicali Valley

The following paragraphs describe the Mexicali Valley Irrigation District, resources, and constraints for crop production and irrigation. This background provides an important overview of information that is relevant to the farm-level decision-making process. The Mexicali Valley Irrigation District, referred to as Irrigation District 014-Río Colorado, is an arid region that receives less than four inches of precipitation annually (Brun *et al*. 2010). In the 1944 Treaty between the United States and Mexico, Mexico was allocated 1.5 million acre-feet of water per year from the Colorado River. In 1973, Minute 242 was added to the treaty to address water quality, requiring that salinity levels be less than 130 ppm (+/- 30 ppm); such as addition was important because when salinity levels of irrigation water are sufficiently high, they can lead to severe losses in agricultural production. The Colorado River is the primary source of water for the Mexicali Valley Irrigation District, and the remaining water is pumped from groundwater aquifers. The wells in the district yield around 567,500 acre-feet per year (700 million cubic meters) (Medellín-Azuara, Lund and Howitt 2007). Of the 725 total wells, 422 are federal wells managed by the irrigation offices, 236 are private wells, and the remaining 67 are for urban use.

Established in 1938, the irrigation district was decentralized and privatized in the early nineties into the 22 irrigation modules that exist today. All registered water users who own land in the region in which the office is located are considered owners of the irrigation module. The modules are managed by an elected board of directors and a manager who is hired by the board of directors. A new board of directors is elected every three years. Of the 576,620 acres (233,350 hectares) in production in the Mexicali Valley Irrigation District in 2010, the majority of acres (88%) are in the state of Baja California and the remaining 12% of acres are in the state of Sonora (SAGARPA 2010a; SAGARPA 2010b).[1] The district had about 16,000 registered water users in 2011, though the number fluctuates from year to year and not all water users are active.

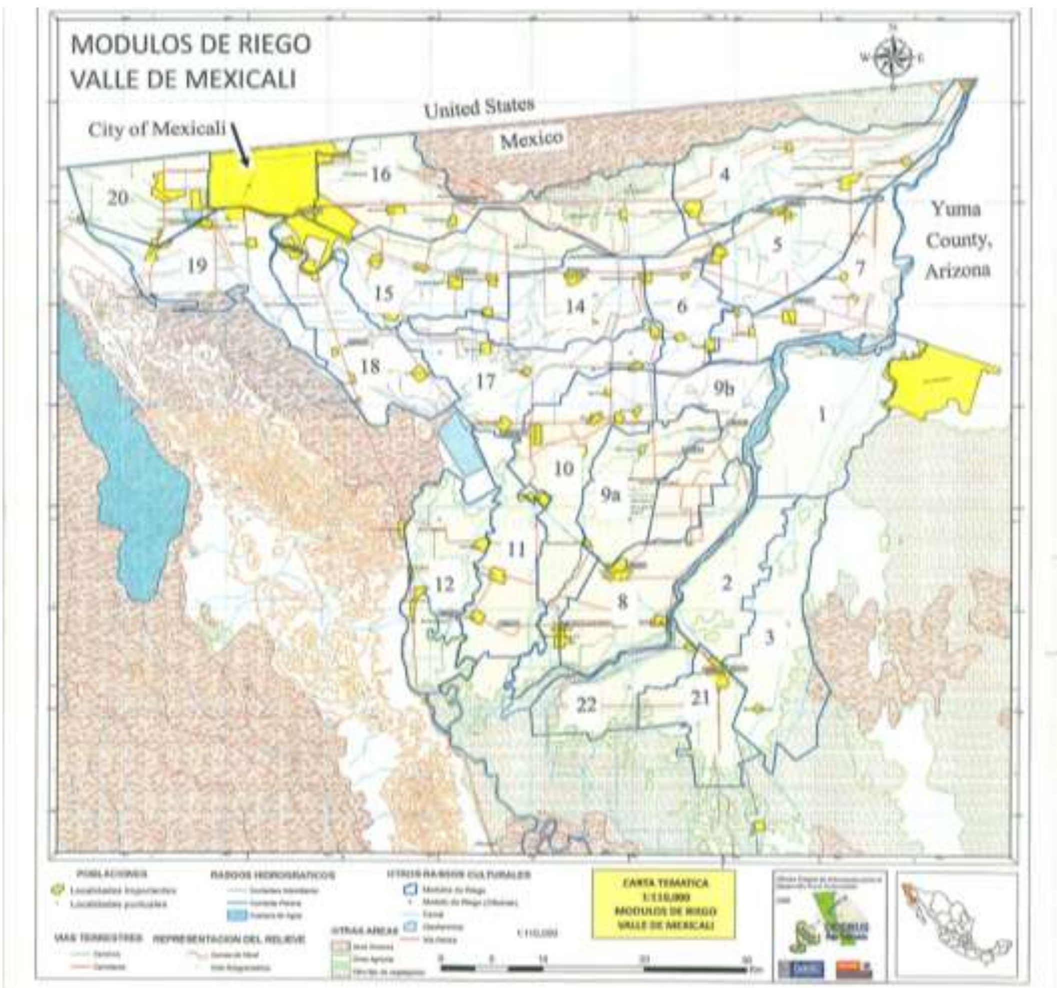
The irrigation module offices manage the extensive network of canals and drainage ditches in the Mexicali Valley at the parcel and module level (refer to the blue lines in figure 1.1, which outline the perimeter of each irrigation module).[2] Mexico's National Water Commission (CONAGUA) and the Water User's Association (Sociedad de Responsibilidad Limitada, or S. de R.L.) manage the major distribution canals in the valley. Because of the tight constraints on the

[1] Only 208,000 hectares in the Mexicali Valley have legally designated water rights for irrigation (Medellín-Azuara, Lund and Howitt 2007). Thus the 233, 350 hectares grown in 2010 further highlights the constraints placed on the regional water supplies.

[2] In this thesis, we use parcel as a general term that refers to the plots of land where farmers cultivate, and these plots of land cultivated by a single farmer may or may not be connected.

volume of water in the Mexicali Valley, CONAGUA devotes a significant amount of resources to planning agricultural water use a full year in advance, and submits a water plan to the United States in December of the previous year for the upcoming year. The exact quantities are adjusted throughout the year. Water is ordered from the United States every seven days based upon the anticipated water needs, and must travel 164 miles to arrive in the Mexicali Valley (via Parker, Imperial, and Morelos Dams) (Robles Van dyck 2011).

Figure 1.1 Map of the 22 irrigation modules in the Mexicali Valley (SAGARPA 2011)



Crops have different seasons in which they are planted, and each crop has a different consumptive use of water, meaning that farmers are expected to purchase a permit to grow a specific crop and commit to planting that crop at a specific time of year. The permit system in the Mexicali Valley is important to understand because it likely impacts a farmer's ability to respond in the short-term to changes in price signals, such as rising or falling crop or input prices. In the Mexicali Valley farmers are also required to obtain a water permit for double cropping, and these permits are not always granted to farmers, so crop permits for double cropping add additional constraints as a farm manager allocates resources. Finally, farmers reported that it is challenging to obtain a new permit to plant alfalfa, leading to incentives to continue growing alfalfa to maintain possession of the alfalfa permit, despite fluctuating alfalfa prices and yields. Alfalfa has a higher consumptive use of water than other crops in the region, making this a key crop of interest in this research.

Government support programs also play a role in agricultural production.[3] Multiple types of government programs and price controls exist, which may serve to either incentivize or constrain agricultural production decisions. One example is PROCAMPO, a federal agricultural cash transfer program implemented in 1993 to increase competitiveness of the Mexican agricultural sector after NAFTA. Other examples of government support include subsidized crop insurance and programs which provide partial funding for agricultural equipment, irrigation improvements, and machinery investments. Although these programs likely incentivize farmers (to a certain degree) in their cropping and investment decisions, farmers often report substantial delays in the government payments, issues regarding eligibility, and high transactions costs from participating in these programs. The implication is that the programs are not as influential in decision-making behavior as they otherwise would be.

Additional constraints for agriculture may result from the legal framework in Mexico, which differs greatly from the legal system governing water rights in portions of the lower Colorado River north of the US-Mexico border. Water law in Mexico is governed by the National Water Law (LAN), and although the government officially owns all water rights in the country, the LAN establishes the conditions under which the government can award these water rights to beneficial use via concession. Water allocation is ranked, and priority is first granted to domestic use, then municipal use, followed by cattle, agriculture, environmental flows, generation of electricity for public use, industrial, aquaculture, generation of electricity or

[3] Government programs may contain state-level and federal-level components, so although there are many similarities in the agricultural programs available in Baja California and Sonora, we might expect to find some differences in the specific programs offered; only irrigation Modules 1, 2, and 3 are located in the state of Sonora.

private use, leaching salts from soils, tourism and recreational activities, and multiple uses (Carrillo-Guerrero 2009).

Understanding value chains and production systems in the Mexicali Valley also provides background for better understanding the impacts that affect a farmer's ability to respond to a shock to a water supply. A large variety of crops are grown in the Mexicali Valley and the primary crops are shown in tables 1.1 and 1.2 using data from Mexico's Ministry of Agriculture, Livestock, Rural Development, Fisheries and Food (SAGARPA).[4] Table 1.1 ranks the top crops in terms of total *value* of production whereas table 1.2 ranks the top crops in terms of total *area* in production. These two ways of presenting data serve to highlight that certain high value crops, such as green onions, contribute significantly to the total value of production despite being a small percentage of area.

Table 1.1 Value of Top Crops in the Mexicali Valley (SAGARPA 2010a)

Crop	Value of Production (1,000 MXN)	**Percent of total value of production**	Percent of total area planted
Wheat	1,584,924	**35.8%**	56.2%
Cotton, unprocessed	691,576	**15.6%**	12.0%
Onion, green	542,081	**12.2%**	2.2%
Alfalfa	539,824	**12.2%**	15.7%
Asparagus	201,782	**4.6%**	0.8%
Lettuce	172,456	**3.9%**	0.8%

Table 1.2 Area Harvested for the Top Crops in the Mexicali Valley (SAGARPA 2010a)

Crop	Area Harvested (Hectares)	**Percent of total area planted**	Percent of total value of production
Wheat	87,321	**56.2%**	35.8%
Alfalfa	24,432	**15.7%**	12.2%
Cotton, unprocessed	18,659	**12.0%**	15.6%
Sorghum Hay	5,585	**3.6%**	14.8%
Onion, green	3,466	**2.2%**	12.2%
Rye Grass	3,420	**2.2%**	1.3%

[4] For reference, SAGARPA listed 99 different crops in cultivation in 2010 (SAGARPA 2010a).

However, the distribution of crops grown across the irrigation district is heterogeneous, varying with location and farm size. Only 30 large farms, cultivating a range of approximately 250 to 7,900 acres each (100-3,200 hectares) dominate the region in terms of acres cultivated and value of total production (Brun *et al.* 2010). Larger farms are more likely to have access to markets for high value crops, such as asparagus, where 50% of production is controlled by only six producers (Brun *et al.* 2010). Mexico is oft-cited for the bimodal distribution of farm size and large farms are a distinct contrast to the small-scale land tenure systems in the Mexicali Valley (Gómez Tovar *et al*. 2005). Two types of small-scale tenure systems exist: the *ejidal* land system and the *colonial* land system. The *ejidal* land system has been in place in Mexico since 1917, and traditionally small-scale farmers cultivated and owned the land communally, though were restricted from selling the land or using the land as collateral. Since 1992, *ejidal* lands have been reformed and most *ejidatarios* now possess a legal certificate establishing their right to cultivate the land and their right to water. *Colonial* land, in contrast, was the land ownership system that allowed small-scale farmers to own 20 hectares of land with a legal land title.

Small-scale land owners are most likely to grow wheat, as wheat has lower variable costs than cotton and requires less specialized machinery than alfalfa, and it is interesting to note that although 56% of acreage is dedicated to wheat, only 36% of the value of total production comes from wheat (SAGARPA 2010a). Although poverty in the Mexicali Valley is less than the other parts of Mexico – in Mexicali household incomes are on average 15% higher than average income in Mexico - rural poverty is still a concern (Medellín-Azuara, Lund, and Howitt 2007). Poverty rates in the Mexicali Valley are close to 50% (Carrillo-Guerrero 2009), and we might expect that a shock to the water supply for a farmer closer to the poverty line can have a more severe impact than a shock to a farmer with more resources available.

Water and soil resources vary not just at the farm level but also at the irrigation module-level. Table 1.3 provides general statistics on the 22 irrigation modules, revealing differences in total of hectares with water rights and in surface and groundwater allocations. Data on wheat production for 2009 and 2010 was included to demonstrate differences in production and yields. Also, the Easter earthquake occurred in the Mexicali Valley on April 4, 2010 shortly before the wheat harvest. The impact was greatest on modules 10, 11, and 12 and is likely a factor in the drop in wheat yields in those modules from 2009 to 2010. The earthquake also resulted in liquefaction, where sand and saline water erupted from underground, flooding many fields and reducing the soil quality in the areas where it occurred.

Table 1.3 General statistics on irrigation modules and wheat pre- and post-earthquake[5]

Module #	Hectares w/ water	MM^3 surface water	MM^3 federal wells	Number of federal wells	Wheat Yields (mt/ha)	
					2009	*2010*
Module 1	10,000	2,732	97,433	84	6.3	8.2
Module 2	5,086	46,630	11,827	11	6.3	8.2
Module 3	8,845	90,921	12,025	11	6.3	8.2
Module 4	9,930	2,896	98,581	87	7.2	8.0
Module 5	9,372	1,361	95,565	70	7.2	8.0
Module 6	6,127	23,490	42,505	36	7.2	8.0
Module 7	7,117	4,612	69,268	56	7.2	8.0
Module 8	8,311	102,752	0	0	6.9	7.7
Module 9a	7,120	51,370	22,844	19	6.9	7.7
Module 9b	7,129	53,710	26,620	22	6.9	7.7
Module 10	13,135	114,105	7,993	44	6.6	6.1
Module 11	9,140	39,983	0	0	6.6	6.1
Module 12	9,569	41,815	0	0	6.6	6.1
Module 14	8,896	106,478	0	0	6.3	7.6
Module 15	12,690	146,046	0	1	6.3	7.6
Module 16	11,889	121,987	4,342	7	6.3	7.6
Module 17	9,188	96,398	10,976	8	6.1	5.9
Module 18	8,250	92,360	0	0	6.1	5.9
Module 19	7,000	88,796	0	0	6.1	5.9
Module 20	4,700	57,088	0	0	6.1	5.9
Module 21	4,987	59,349	0	0	6.2	6.3
Module 22	4,851	18,597	0	0	6.2	6.3

[5] Table 1.3 was compiled by the authors with data collected from the field, from the Mexican governmental Agency for Agricultural Development (Secretaria de Fomento Agropecuario, SEFOA, 2011), and from visiting SAGARPA's *Cader* office in Mexicali in 2011. SAGARPA reports agricultural production statistics at the *cader* level, where they consider together the Sonoran Modules 1-3, and the Baja California Modules 4-7, 8-9a, 10-12, 14-16 and 21-22 on an aggregate level. Also, note that MM^3 stands for million cubic meters, *mt* for metric ton, and *ha* for hectare.

1.3 Regional water supply variability and the Colorado River Delta

Farmer decision making is impacted by the environment in which the farmers live. Farm systems by their nature are interconnected with biological processes, weather patterns and climate, natural resources, and ecosystem services. Therefore, understanding the surrounding social-ecological systems provides background information on what may be impacting farm systems. Due to the interconnectedness of farm and ecological systems, farmers and environmental groups alike will benefit from understanding farmer decisions that affect on-farm water use.

The Colorado River Delta region, where the Colorado River previously united with the Pacific Ocean, was once a region of nearly 200,000 million acres of wetlands (Zamora-Arroyo *et al*. 2005). A Sonoran Institute report (2007) stated that only 8% of the Delta remains (Lellouch, Hyun, and Tognetti 2007), and experts in the field believe that the percent of quality habitat remaining is much lower. The Colorado River endured a period from 1932 until 1981 where the Delta received very little water. An increase in flows after 1981 allowed for a revitalization of certain ecosystems. Also, in 1977, brackish run-off from the Wellton-Mohawk Irrigation and Drainage District (WMIDD) began supplying water to the wetlands of the Ciénega de Santa Clara, which is about 4,200 hectares (10,378 acres) and possesses rich biodiversity, including the endangered species such as the Yuma clapper rail (Glenn *et al.* 2001).

The Colorado River Delta began receiving significant attention in the early 2000's, and a successful binational collaboration of individuals from institutions in the United States and Mexico resulted in the publication of a landmark document in 2005, the "Conservation Priorities in the Colorado River Delta, Mexico and the United States" (Zamora-Arroyo *et al.* 2005). The Conservation Priorities document details information on the more than 350 bird species, fish and marine species, habitat, and vegetation that depend on water for survival. The collaborative efforts of these institutions have raised awareness of the need to secure flows to protect the ecosystems of the Colorado River Delta before the last remaining biodiversity is lost. Given that run-off from the irrigation districts is currently the main source of water for the remaining wetlands in the Delta, collaborations are beginning to involve farmer groups as well.

Ecosystem services provided by the Delta serve as an additional link between agriculture and the environment. Anecdotal evidences suggests that ecosystem services that benefit farmers in the Colorado River Delta can include hunting and fishing, employment generated from tourism, flood control, water quality filtration, as well as cultural services such as family visits to the river over *Semana Santa*. Given the rate of decline of ecosystems in the Delta, a wide variety of stakeholders are interested in the quantification of ecosystem services to better understand the benefits offered to the region of having additional flows remain in the river. Despite the fact that accurate quantification of ecosystem services is limited at this time, quantifying ecosystem services (provided to and provided by agriculture) can encourage the creation of incentive-based policies to increase the production of these important services (Swinton *et al*. 2007).

Market-based water transfers are another link between ecosystems and agriculture and can serve as a voluntary method for reallocation of water. Fallowing payments to farmers for transferring agricultural water to other uses can serve as an additional tool for farmers for managing risk. Fallowing payments are a certain source of income, so the addition of these payments to a crop portfolio may be appealing to risk averse farmers for reducing variance in agricultural net returns. However, although this is a potential option for increasing regional water supply reliability, it is useful to explore a wider range of options that that could allow farmers to reduce the volume of water consumed while maintaining productivity and profitability.

Ultimately, coordination among environmental groups and farmers is an opportunity to increase water supply reliability for both groups through more efficient management. Coordination could involve reallocation through water transfers or other indirect strategies to improve water supply reliability such as collaborative research. Better collaboration can improve water resource allocation, particularly because environmental groups are often willing to accept lower quality water supplies that may not be appropriate for agriculture. Other researchers have proposed that collaboration can lead to better management of natural resources, such as water, while promoting sustainable livelihoods (Plummer and Armitage 2007).

Collaboration involves transaction costs, such as travel costs and time expended in meetings, yet because of the high dependence that farmers and ecosystems in the Delta have on scarce water resources, the benefits of collaboration are likely to outweigh the costs (Ostrom 2009). This is consistent with the recent trend in the literature on irrigation in arid and semi-arid regions, which has been to demonstrate that improvements in irrigation technology alone are insufficient to increase water use efficiency, and that collaboration and social networks are proving to be of increasing importance (Lam and Ostrom 2010).

Demand from urban areas exerts additional pressure on regional supplies. Baja California's major cities, Mexicali, San Luis Río Colorado, Tijuana-Rosarito and Tecate, depend upon the Colorado River and groundwater aquifers for water resources. Urban regions have been increasing water use while agricultural water demand has remained more constant, thus uncertainty about future urban growth is an important consideration when considering regional water supplies. For instance, the urban demand in Mexicali is predicted to increase from 70,000 acre-feet/year (86 million cubic meters/year) to 82,128 acre-feet/year (100.9 million cubic meters/year) which will directly impact regional water supplies. Planning is challenging when compounded by uncertainty in urban, agricultural, and environmental demand and climate change (Medellín-Azuara *et al.* 2009).

Given the constraints on the total water supply in the Mexicali Valley, agricultural consumptive use of water is a pressing concern for all stakeholders. If agriculture had less water available in the future, could farmers maintain profitability? Is it economically feasible for farmers to adopt strategies to reduce agriculture consumptive use, such as adding a crop to a farmer's crop portfolio that consumes less water, or adopting water conserving irrigation or conveyance technology? Can we look at past behaviors to determine under which conditions these strategies have been feasible in the past to gain insights into possible future behaviors? All of these questions are explored in this paper, with implications for water management across the region.

1.4 Contribution of research

This study provides several contributions to the literature. Primary data collection resulted in 180 farm household surveys, 30 interviews with water managers, and 12 interviews with government officials and experts in the region. This data gives rise to ample information on regional water supplies, major impacts on agricultural profitability, and common responses to water supply variability. Crop diversification and cement lining of parcel-level irrigation canals are targeted as key risk management strategies of interest. From the perspective of stakeholders interested in regional water supply variability, these two strategies are important as methods for farmers to maintain productivity if water supplies were to decrease further in the future. The survey results indicate that both crop diversification and cement lining being adopted at the farm level, implying that they have the potential to be economically feasible at the farm-scale under certain circumstances.

We use an econometric analysis based upon the survey data to assess which factors are associated with the selection of three risk management strategies in the Mexicali Valley: crop diversification, cement lining of parcel-level canals, and geographic diversification. This study contributes to the literature in that it provides a method for the quantification of water supply variability into two separate components – timing (delivery delays) and volume (delivery shortfall). We find that farmer risk management strategies - either crop diversification or cement lining of parcel level canals - vary depending on the *type* of variability in water supply. Geographic diversification, analyzed in a third econometric model, is a risk management strategy that involves increasing the radius in which agricultural parcels are distributed to increase the probability that at least one parcel can avoid a shock. Geographic diversification, in contrast to the previous two risk management strategies, is less successful as a risk management strategy in response to water supply variability given constraints on land in the Mexicali Valley.

We use a mixed-methods approach involving quantitative survey questions and empirical analysis, as well as qualitative survey questions and the literature review. The value of the qualitative survey questions are that it we find a wide range of responses to water supply variability and low profitability. It is important to understand the full range of responses, beyond the common risk management strategies cited in the academic literature, as each response may have a different impact on regional water supplies. We also have increased the understanding of biggest impacts on agricultural profitability in the region. These findings on actual farmer risk management strategies and top impacts on profitability from the Mexicali Valley will help in the creation of more effective policies and incentives in the region to increase water supply reliability. Also, this research has increased our understanding of the role of irrigation deliveries and uncertainty in the farm-level decision-making process. Further, we apply an innovative method for exploring farm resilience by surveying farm households who had recently experienced a 7.2 magnitude earthquake which damaged irrigation canals. The incorporation of farm resilience into a risk management framework itself is another contribution to the literature.

Chapter two of this paper is a review of the literature on risk management strategies, with an emphasis on crop diversification, adoption of new technology, voluntary water transfers, and geographic diversification. The latter portion of the literature review explores farm resilience definitions, thresholds, indicators, and strategies. Chapter three presents the framework, conceptual model, and the economic theory behind the research. Chapter four explains the data collection methods, survey design, and sample selection. Chapter five includes the summary and description of variables and the descriptive statistics. Chapter six presents the econometric models, results, and discussion of the three econometric analyses. Chapter seven discusses implications for farmers, policy makers, and environmental organizations, and entails the conclusion, limitations and future research.

Chapter Two - Literature Review

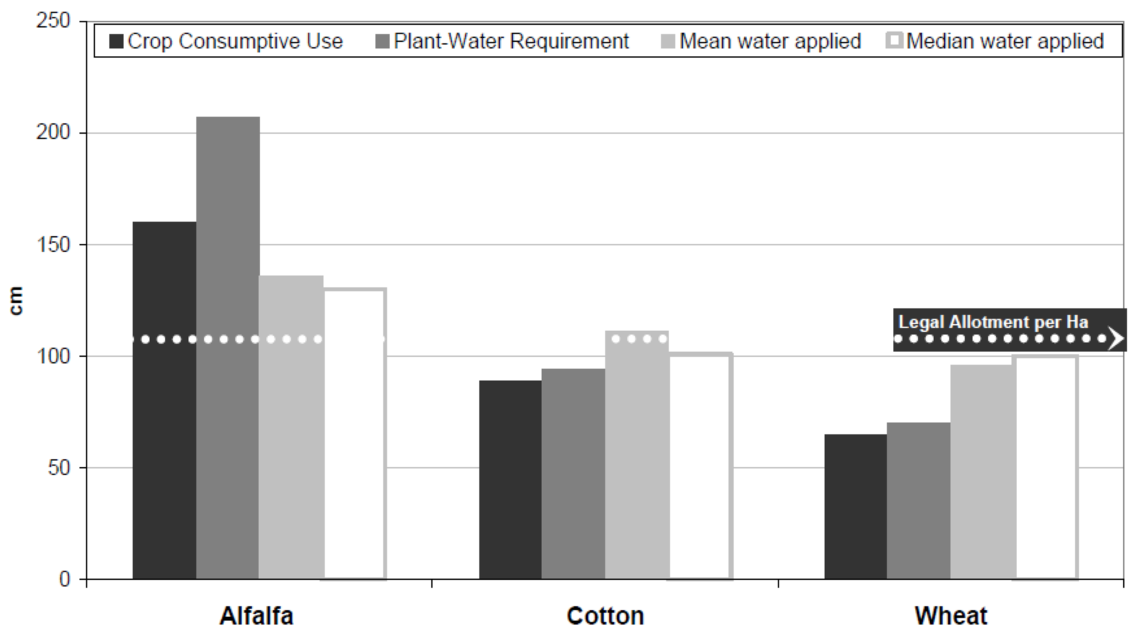
This chapter begins with general literature from the region on irrigation and water management. The next sections explore the academic literature on common risk management strategies for water supply variability, which include crop diversification, water conserving technology, voluntary water transfers, and geographic diversification. The final section in this chapter explores characteristics of farm resilience to better classify which risk management strategies are more successful at maintaining productivity under a wider range of circumstances.

Much of the current literature from Mexico on farmer response to water supply variability is related to climate change and vulnerability to natural disasters and markets. Weather index insurance has received much attention as a successful farmer response to drought. This is an insurance mechanism that is activated when a predetermined unfavorable weather threshold (such as low precipitation) is crossed. While important, weather insurance is an *ex post* solution to risk management and often, retroactive responses are more costly than preventative measures. Weather insurance in Mexico is also partially funded by the federal government, and the government has been reducing agricultural funding since the early nineties. Weather insurance also has had unintended consequences, by incentivizing farmers to invest only in insured crops (Fuchs and Wolff 2011). Weather index insurance is not currently available for farmers in the Mexicali Valley, though a similar type of catastrophic insurance is expected to be available starting this year, which would cover drought, earthquake, and other disastrous events that are outside of the protection of standard crop insurance (Pérez Vega 2012). Thus, though weather index insurance is one possible response to water supply variability, other risk management strategies have the potential to be more cost-effective and to be more appropriate for increasing farm resilience.

Carrillo-Guerrero (2009) conducted an empirical analysis of farmers in the Mexicali Valley regarding water use efficiency and farmer perceptions towards water conservation. The research utilized a GIS analysis to assess farmer water use and Carrillo-Guerrero's analysis of 321 farmers concluded that farmers use on average 4% more than their allotment of water, though that figure varies spatially and by crop. Although the researcher did not assess economic aspects, the study is one of the only prior studies that provides farm-level data from the Mexicali Valley. It may be useful to define key terms referenced in her analysis, as the subtle differences do have implications for risk management strategies. *Allotment of water* refers to the legal entitlement of volume of water per hectare, which in the Mexicali Valley is defined as 117 liters/second per 24-hour period, which extrapolated over a year is equal to 3.31 acre-feet per acre per year. *Crop consumptive use* is the quantity of water absorbed by the plant through development, growth, and evapotranspiration and does not include the water returned to the system due to run-off and infiltration. The *plant-water requirement* is water required for consumptive use of the plant plus the additional quantity needed to compensate for soil type and the leaching requirements for salinity. The *water applied* refers to the actual volume of water used by farmers in irrigation, independent of consumptive use and plant-water requirement. Although the term has many definitions, a basic definition for *water use efficiency* is a reduction in the volume of water used per unit of output of irrigated cropland (Carrillo-Guerrero 2009, 82). The data presented in figure 2.1 comes from Carrillo-Guerrero's analysis in the Mexicali Valley and shows graphically the difference among the three major crops in the area and their crop consumptive use, plant-water requirement, water applied, and legal allotment. Alfalfa producers' water applications are on average 35% greater than their allotment (but less than the estimated plant-water requirement), cotton producers apply on average 10% greater than their allotment, and wheat producers do not exceed their allotment.

The author concluded that almost 80% of farmers in the region should be able to improve water use efficiency. The most cost-effective method for improving water use efficiency would simply be to reduce the water applied to equal the plant-water requirement. Thus, it follows that in the face of water shortages, a farmer might first change behaviors to maximize efficiency of available water resources, by using "every drop" of water available and reducing waste. Yet, a percentage of farmers (largely those located closer to the end points of the distribution canals, those with problems with salinity, and those producing alfalfa) in her survey already use less water than the plant-water requirement, meaning that additional approaches would be necessary. The additional strategies suggested in Carrillo-Guerrero's study resulted from survey questions asking farmers what options they would recommend to improve irrigation efficiency, with land leveling ranked as the preferred option, followed by pressurized irrigation and then parcel-level cement lining of irrigation ditches. However, the question was formed in hypothetical: 1) Do you think you could improve your irrigation practices in your field? 2) If yes, how do you think you could improve it? These preliminary findings informed the design of survey questions for this paper, where we can now analyze data on how farmers have already responded to water supply problems and what factors influence their decisions. In addition, Carrillo-Guerrero assessed *volume* of water and not *timing* or extent of delivery delays, so this thesis expands the research to include a larger range of water supply variability issues facing farmers and the economic implications.

Figure 2.1 Comparison of crop consumptive use, plant-water requirement and water applied in the Mexicali Valley (Carrillo-Guerrero 2009, 100)



Saldaña-Zorrilla (2008) conducted surveys in southern Mexico on farmer coping capacity with respect to natural disasters, where the majority of natural disasters are related to water (flooding or drought). The analysis entailed a survey of 151 farm households in three communities, and results found that the majority of farmers produced a single crop, increasing their exposure to natural hazards and to sudden decreases in crop prices. The surveys revealed that the most common coping strategy of farmers was *ex post* financial instruments, with "relatives in the community" being the most common source, followed by government aid, and then neighborhood solidarity. Saldaña-Zorrilla's analysis consisted of descriptive statistics and correlations between key variables of interest. The researcher also used contingent valuation, framing questions such as, "How are you expected to finance the recovery costs from the next natural disaster?" and "Do you have plans to diversify your crops?" rather than basing conclusions on historical behaviors.

Luers *et al*. (2003) conducted a quantitative analysis of farmer vulnerability to water supply variability in the Yaqui Valley of Sonora, Mexico, a region that neighbors the Mexicali Valley to the southeast. Using remote sensing to obtain yield estimates from four different years, the authors found that management decisions such as fertilizer application and irrigation, tillage practices, pest control, soil management, and also soil quality were all important variables in determining vulnerability. However, the goal of the research was to provide a framework for assessing vulnerability to water supply variability, and was not on providing information on profitability or risk management strategies employed by the farmers.

Frequently, the existing literature focuses on vulnerability. The challenge with focusing on vulnerability is that the emphasis is on the problems facing agriculture rather than the solutions. Lance Gunderson, an expert on resilience, stated that we already know more about what erodes resilience than what improves it, thus greater benefits may result from studying successes and innovations (Gunderson 2011). Hart Bise Barham *et al*. (2011) provide an informative analysis of successful risk management strategies used by Texan cotton farmers in the Lower Rio Grande Valley, where similar to the Mexicali Valley, even irrigated agriculture does not guarantee water supply reliability. The researchers test combinations of risk management strategies, following up on previous literature that showed that while forward pricing and crop insurance are complements, irrigation technology is a substitute for crop insurance. Utilizing a Monte Carlo simulation allowed the researchers to systematically test multiple combinations of rainfall variability and up to 16 different risk management strategies. This provided a unique opportunity to demonstrate how farmers might combine multiple risk management strategies, and they found that the number of irrigations together with option contracts was the top ranked preference in terms of expected profit. Although the authors' simulation relied upon aggregate data and not on household level surveys, the study is beneficial for highlighting optimal combinations of risk management strategies and number of irrigations. However, the authors did not analyze the relation between actual water supply variability at the farm level and how that influences which risk management strategies are selected.

2.1 Crop diversification

Farmers must make decisions each day with incomplete information, and in years with no unexpected events, they may be skilled at estimating their crop yields. Nonetheless, farmers are not able to predict all potential impacts on yields, including uncertainty resulting from pests, plant diseases, levels of salinity and sodicity, soil quality, and climate variables such as temperature, rainfall (which can have a negative impact directly after planting in the Mexicali Valley), hail, and wind. Moreover, the challenge of prediction is magnified when attempting to simultaneously predict yield and market prices – gross revenues. And, although the literature often focuses more on uncertainty in gross revenues, rapidly rising fuel and fertilizer prices in recent years may increase the importance of uncertainty in input prices and quantities (survey data suggests that even supposedly "required" inputs can decrease in quantity due to rising costs and other constraints). Thus, the cumulative impacts on net returns are what motivate farmer decision making and the net returns from agricultural production will vary depending upon which crops are grown.

Crop diversification is a strategy for reducing the variance in net returns. Under risk aversion, farmers will prefer a crop portfolio with lower variance in net returns, all else equal. However, focusing exclusively on net returns and variance in a crop portfolio is insufficient. Farmers make cropping decisions based upon expectations regarding input and output prices, and also based upon managerial knowledge and experience, specialized machinery, and labor requirements. Lavee (2010) also found that farmers were less likely to diversify crop portfolios into capital intensive crops (such as orchards) under water supply uncertainty, though the analysis was at an aggregate level and not the farm level.

Two other motivations for crop diversification decisions, but not directly related to risk management, are the role of crop rotations and of economies of scope (defined in the following paragraph). Discussion on crop portfolio diversification often does not emphasis these additional factors, which have implications for farm resilience. Although the difference is subtle, rotations change the seasonal timing of planting of crops, and for purposes of coping with seasonal variability in water supply, this may be an effective strategy.

Also, the common perception is often that producing crops with a higher expected return is typically riskier, meaning that a reduction in risk in the crop portfolio through diversification could necessarily result in a reduction of expected returns. Moreover, economies of scale in acres planted of a single crop can lead to lower average costs. Therefore, economics of scale might provide an incentive for specialization of crops, furthering the argument that diversification would potentially lead to lower net income. However, this assumption may not be true in the presence of economies of scope. Also called complementarities, the economic argument is that economies of scope exist if the total cost of growing crops A and B together is less than the total costs of growing A alone and B alone. Chavas (2011) refers to “economies of diversification” as the combined benefits of economies of scope, risk management, and learning and develops a conceptual model (discussed in greater detail in chapter 3 of this thesis) that allows researchers to explain certain tradeoffs that economic agents make between diversification and specialization.

Bradshaw *et al.* (2004), for instance, found in an analysis of over 15,000 operations in Canada, farmers are becoming more specialized, not diversifying, and the trend is more pronounced in smaller farms. In contrast, Chavas and Di Falco (2012) conducted an empirical analysis of farm household surveys in Ethiopia, using panel data for 2000, 2002 and 2005, and then used those values to run a simulation that allowed them to separate the benefits of economies of scope and risk management motives for diversification. Their analysis revealed a scale effect, where increasing scale had a negative and statistically significant impact on crop diversification. However, they estimated that the net benefits of diversification were positive, with the expected return for an average farm for diversifying crop portfolios at 17%. This debate does not expose a contradiction in agricultural decision making; rather, it helps to elucidate the tradeoff between specialization and diversification.

Helmers *et al*. (2001) add to the literature by teasing out the differences between crop rotations and crop diversification. Their research on Nebraskan agriculture postulates that it is plausible to see corn-soybean diversification and corn-soybean diversification with rotation, and these two scenarios have different implications for risk and net returns. Rotations can result in greater complementarity benefits to crop diversification. Benefits include increased soil fertility and increased productivity, as well as lower production costs. They found that cumulative extent of negative net-return events were reduced over a 14-year period for farmers employing both rotation *and* diversification. These debates on the tradeoffs between specialization and diversification and the reasons why farmers may choose one option over the other are crucial for understanding agriculture in the Mexicali Valley and for assessing the potential for greater crop diversification into crops with a lower consumptive use of water.

Very few empirical studies exist analyzing crop diversification as a risk management strategy either in Mexico or in the lower Colorado River basin, so we include studies from other regions. Hansson, Ferguson, and Olofsson (2010) conducted an empirical analysis on farm businesses in Sweden, assessing the specific question of diversification and specialization tradeoffs in 900 farms from 2000-2007. Their use of a comprehensive analysis with panel data enables them greater depth into the questions of diversification or specialization over time. They define agricultural diversification as diversification into new market activities. They conclude that considerable path dependence occurs, where the previous year’s level of diversification largely determines the following years’ level. It appears that farmers choose a business strategy and continue with that choice, either going in a specialization or diversification direction, embedded in the structure of the business. They also find diversification to be positively associated with farm size and negatively related to age. While these results are fascinating, they fail to address the role of shocks, and whether a significant shock could motivate a farmer to change business strategies.

Seo (2010) completed an empirical analysis on crop portfolio diversification in Africa, focusing on the addition of livestock to the portfolio and then uses simulation to compare the relative profitability under a variety of climate scenarios for 2060. Although the diversified portfolio, with crops and livestock, does become more profitable under the 2060 climate scenario, any simulation will be based upon assumptions about unknown conditions, and the actual behaviors of farmers may vary significantly in practice.

Bezabih and Sarr (2010) assess crop diversification decisions in Ethiopia with respect to rainfall variability and risk aversion, and their empirical analysis involves a count index (representing the number of crops) as a dependent variable over two time periods. A substantial portion of their analysis is devoted to eliciting risk preferences from farmers, and although they do find that higher risk aversion is related to higher likelihood to diversify, the relation is weak. They find that a decrease in total rainfall leads to greater specialization, while an increase in variability of monthly rainfall increases likelihood of crop diversification.[6] These results at first seem puzzling, but when looking at the idea that farmers focus on a smaller number of crops that are likely to produce well in low water conditions (*i.e.* specialization), and that diversification is a risk management response to reduce variance, the results seem logical. This methodology, the comparison of both volume and variability in the regression model, is relevant because it clearly elicited different responses in each case. However, the variability calculation was an aggregated value, both in terms of time (monthly) and space (regional level) that misses daily changes at the farm scale. Aggregation fails to capture the role of shocks and variability in timing (that is, delivery delays) and quantity that are associated with irrigation canals and water deliveries.

Lien and Hardaker (2001) researched factors that influence diversification decisions in Norway, using a two-way fixed effects panel regression, and find that unlike other studies, risk-aversion had no impact on cropping decisions. Rather, labor availability, market factors (such as

[6] They calculated variability as the ratio of the mean over variance in rainfall.

existence of a contract), and subsidies were more important in cropping and livestock decisions. They concluded that this was probably due to high levels of subsidies and geographic constraints that exist in Norway, which created incentives that were more influential than the role of risk aversion. This study has important implications and does not contradict other studies that show the importance of risk aversion, but rather highlights the existence of cases where other factors may be more decisive than risk aversion as a determinant in diversification decisions.

Another risk management strategy is through crop biodiversity, described as "genetic variation within species and within population [which] increases the ability to respond to the challenges of environmental stress" (from Mainwaring 2001, as cited in Di Falco and Chavas, 2008, p. 84). Di Falco and Chavas (2008) focus not on decisions to diversify but on productivity increases due to crop biodiversity, and found in an empirical analysis that crop biodiversity buffers and in certain cases can even reverse productivity losses during times of decreased rainfall. Although crop biodiversity has the potential to be a powerful strategy for farmers in arid and semi-arid regions to increase farm resilience, limited access to diverse seeds as well as limited market demand for the alternative varieties can be a constraint.

2.2 Adoption of new technology and innovation

Much literature exists on the role of new technology in economic development and the factors that lead to adoption of innovations. Under the induced innovation hypothesis, research will be motivated by "opportunities to generate higher returns by taking advantage of resource endowments," yet the hypothesis may not hold true with respect to uncertainty in future water supplies (Antle and Capalbo 2010, 10). If uncertainty is seen as high, then the incentive to invest in new technologies and research will be lower. The question arises, under what conditions do farmers choose to adopt water conserving technology?

In the western United States in 2003, 58% of irrigated acres used pressurized sprinkler or drip systems, and 40% of those systems were low-pressure, water conserving systems (Schaible, Kim, and Aillery 2009). In contrast, in the Mexicali Valley over 95% of wheat and alfalfa farmers and 63% of cotton farmers use gravity-flow systems (basin irrigation for wheat and alfalfa; furrow irrigation for cotton; Carrillo-Guerrero 2009). Despite the close proximity of the Mexicali Valley to the US-Mexican border and relatively easy access to new technology, the levels of adoption of pressurized irrigation systems are substantially lower south of the border. In the Mexicali Valley, in addition to improved irrigation systems, the other most promising technological approach for water conservation is through improvements in conveyance structures (cement lining of irrigation canals to prevent infiltration of water into soil). Laser leveling of land is also considered an important aspect of improving water efficiency in irrigation, since having land completely leveled reduces run-off of water and therefore reduces wasted irrigation water. However, laser leveling is quite common in the region of study, supported by government programs, and generally accepted as good practice, so it is not an area that warrants considerable additional research.

Adoption of water conserving technologies can decrease variance in net returns by allowing for higher output when applying the same quantity of water. Although it appears that technological innovations can be a useful tool for risk management, a debate exists on whether technological solutions actually improve farm resilience or not. However, this thesis focuses more heavily on which options farmers have in response to water supply variability (regardless of whether the options succeed in increasing farm resilience or not) and what influences decision making, and we do not take a stance in the debate.

Because water conserving technologies also can increase mean agricultural returns, we might hypothesize that not only risk averse farmers interested in reducing variance will adopt, but that risk neutral and risk loving farmers may also choose to adopt new technologies due to the increase in mean returns. Therefore, we would expect that risk aversion is not the only factor that will influence adoption. Koundouri, Nauges and Tzouvelekas (2006) conducted a comprehensive empirical analysis of the adoption of irrigation technology by 265 farms in Crete, Greece. They find that, in addition to level of risk aversion being significant, level of information (measured by education level and number of extension visits) also has a positive impact on adoption, while age has a negative impact. However, they do not consider the extent of past irrigation delivery shortfalls as a variable. Given that information is a key variable in their model, and one would expect that past information would inform future decisions.

Foudi and Erdlenbruch (2011) also investigate the factors that impact decision to adopt irrigation technology, analyzing 248 observations on corn-producing farmers in France. Although they also find that risk aversion is positively related to the decision to adopt irrigation technology, they note that all farmers in the study were risk averse, meaning that level of risk aversion is not a particularly useful variable for predicting technology adoption among a given group of farmers and that additional variables that are more effective at differentiating among farmers might be more useful. Likewise, their contribution that higher risk aversion can lead to higher volumes of water used in irrigation does not provide additional insights into the behavior of farmers in regions with constraints on the volume of water available. Their more significant contribution to the literature is that they provide evidence that irrigation technology is successful at reducing variance, calling irrigation a form of "self-insurance."

Other forms of technology that can reduce risk include management innovations, as technology is simply the application of knowledge to solve a problem. For instance, improved management of flood irrigation can bring water use efficiency from 35% to close to 80% efficiency (Schaible, Kim, and Aillery 2009).[7] Yet, in many cases, research is necessary before implementing technological and managerial innovations. In most cases, research by the public sector is appropriate. For instance, proper irrigation management interacts with salinity management, as water is a key input required for overcoming problems of salinity. Farmers with soils with a high clay content and insufficient drainage may have limitations in the crop choices for portfolio diversification and may be interested in additional research on salt-resistant crops. Also, because larger volumes of water are generally the foundation of salinity management, research on improved salinity management under water shortages may be necessary. Therefore, the question becomes, "What is the economic value of research and adaptation to water supply variability?" Antle and Capalbo's (2010) focus on the cost of adaptation and research as an investment is a noteworthy addition to the literature on climate

[7] For comparison, pressurized systems have a water use efficiency of 50 to 90-95% and drip/trickle systems have water use efficiencies of as high as 85-95% (Schaible, Kim, and Aillery 2009).

change and adaptation, and is relevant to our discussion on water supply variability, as both involve substantial uncertainty related to future agricultural production. Indeed, the Mexicali Valley is facing multiple forms of uncertainty related to future water supplies. However, while adaptation to climate change is largely based upon predictions and guesses about future climate, many farmers in the Mexicali Valley have already experienced delivery shortfall s and delivery delays and have already adopted water conserving irrigation technologies (a broad category that includes irrigation systems and cement lining of parcel level canals). Because we assume that farmers are rational and profit maximizing, we can look at past behaviors and if farmers adopted water conserving technology, then we can assume that the technology is economically feasible at the farm-level. This allows us to avoid the issue of estimating possible future costs of adoption under uncertainty.

2.3 Geographic diversification

Geographic diversification is defined in this paper as the expansion of agricultural parcels to be distributed over a wider geographical area, and can occur through the purchase or leasing of non-adjacent agricultural parcels. Geographic diversification as a risk management tool with the potential to increase farm resilience to water supply variability has not received much attention in the literature. Wilson, Thompson, and Cook (1997) use surveys to analyze the ways in which farmers in the produce industry in the southwestern United States have used geographic diversification to reduce risk and take advantage of unique market windows allowed by diverse micro-climates. Krueger *et al*. (1999) also tout the benefits of geographic diversification for taking advantage of seasonal market windows and expanding the growing season. The link to risk management is that by allowing producers access to these unique market windows, this allows producers to avoid windows where the market supply is flooded and corresponding low market prices are more likely, thus reducing variance in net returns. Wilson and Thompson (2003) expand the concept to a phenomenon called “time integration”; they classify geographic diversification as within season, whereas time integration allows farmers to move production into multiple seasons throughout the year. Among the grower-shippers interviewed in western United States, Florida, and Mexico (western Mexico and Baja California), they find that time integration as a risk management strategy is common, with 40% of the sample growing year-round. Using a Poisson regression, with number of months per year shipping product as the dependent variable, variables that were positive and statistically significant are size, geographic diversification and crop diversity. One might hypothesize that an active market for leasing land would facilitate higher levels of geographic diversification, and Wilson and Thompson's results corroborate this hypothesis, with 44% of grower-shippers interviewed owning no land and leasing 100% of their land.

Nonetheless, for risk management in response to water supply variability in our study area, diverse micro-climates may be beneficial but should not be considered crucial. The goal of geographic diversification for managing water supply variability is slightly different than the goal for growing produce over a greater number of months in a given year. Geographic diversification simply increases the likelihood that one of a farmer's parcels of land will avoid a shock such as earthquake. Also, heterogeneity exists in the management of water resources depending upon the management of each irrigation office and upon the productivity of wells. Thus, in a region such as the Mexicali Valley, where the district is divided into 22 irrigation modules, each with different management, geographic diversification could be considered diversification of fields by module. Research on management of common pool resources led by Ostrom and Gardner (1993) brought greater attention to the issue that "tailenders" (farmers located at the endpoints of the distribution canals) bear a disproportionately high percentage of the water outages that the irrigation district faces. Under a farm resilience framework, having land in multiple locations across the region would help farmers manage risk by increasingly likelihood of avoiding shocks.

A related subject is the role of redundancy, which refers to the existence of more than one source for providing the same function. Functional redundancy has its origins in the ecological resilience literature, which describes how the existence of multiple species in an ecosystem increases the possibility that if one species goes extinct, the ecosystem will continue to provide necessary services (Folke *et al*. 2010). Geographic diversification could be thought of as a form of redundancy to increase farm resilience. Geographic diversification also may entail higher costs. Having parcels of land in close proximity can facilitate management, whereas managing parcels that are geographically disbursed may have higher transaction costs, especially when considering transportation of machinery and equipment.

2.4 Voluntary Water Transfers

Market-based solutions such as voluntary water transfers can be an effective method for responding to water supply variability that avoids the challenges associated with legal reform. Voluntary water transfers are a method for augmenting water supplies and include both permanent and temporary transfers of water rights from one water user to another. Markets are considered an efficient mechanism for transferring resources from one user with a surplus to another who is willing to pay a higher value for that resource. Also, in Mexico (similar to other parts of the Colorado River basin), water rights can be legally traded separately from the land with which they are associated. The value of water will vary dependent upon a variety of factors. For instance, the initial cost of a permanent water transfer may be higher than the cost of a temporary water transfer, though a decision maker would need to consider the per unit benefit over time to get a more accurate assessment of the total cost. The cost of water, if leased in conjunction with the land, will vary depending upon the soil quality of the parcel. If water transfers were sufficiently low-cost and consistently available for farmers at the desired timing, then this would be the primary risk management strategy needed to respond to water supply variability. However, various constraints exist on water supply available for transfer and the cost of transferring water can be high.

Having access to irrigation water supplies from more than one source may also be a risk management strategy. Having redundant and uncorrelated water sources increases the likelihood that if one has a shock to one water supply (for instance, the surface water supply) then he has access to a back-up supply (for instance, groundwater). Land values are likely to reflect, to a certain degree, the reliability of the water sources. A parcel of land with access to both surface and groundwater is likely to have a higher land value, which means that increasing farm resilience by acquiring land with multiple sources of water could involve higher costs and affect profitability. Thus, there may be tradeoffs between maximizing profitability and minimizing variance.

Thus, continuing with the theme from Antle and Capalbo (2010), what is the economic value of adaptation? There may be a cost to augment water supplies, and these costs could be seen as an investment or a type of self-insurance. An important caveat to mention is regarding supply availability. The decision to lease or purchase additional water supplies may not only be in response to price. In arid regions such as the Mexicali Valley, where substantial constraints exist on the total volume of water available for all users in the region, farmers may be willing to pay for additional supplies. Yet the surplus water supplies may not be available for purchase. Therefore, although augmenting water supplies in response to water supply variability would typically be considered an effective solution, it may not be feasible in all circumstances. For this reason it is important to consider the full suite of risk management strategies.

2.5 Farm resilience: overview and definitions

Farm resilience is the ability of a farm system, after a shock or stress, to recover farm productivity and household wellbeing and to avoid shifting to a less desirable equilibrium. Although the definition emphasizes resilience of the farm system, it is recognized that in cases where farms are family-owned, that other sources of income at the household level may contribute to household wellbeing, thus the focus on the household unit. Farm resilience is related to the ability to effectively respond to unexpected shocks that go beyond the standard coping capacity of a farm business. Shocks can include sudden disruptions such as earthquake, hail, fire, frost, flooding, pests and disease, or an E-coli outbreak. Shocks can also include unpredicted events such as a sudden shortage in irrigation water, a spike in salinity, a change in policy or regulation, a change in labor markets, a drop in crop prices, or a rapid increase in input prices. By definition, shocks are unable to be predicted, so a fundamental characteristic of farm resilience is being prepared and able to maintain household wellbeing under a wider range of circumstances.

Perhaps the largest influence on the economic farm resilience literature is the area of research known as ecological resilience thinking. Darnhofer, Fairweather and Moller (2010) provide a theoretical framework, carefully connecting farm and ecological resilience literatures. Also, the reader will benefit from referring to Parsonson-Ensor and Saunders (2011) for a comprehensive explanation of the relevance of ecological resilience thinking to farm system resilience, in addition to a qualitative analysis involving farmer interviews. The subject of ecological resilience, while gaining in recognition in recent years, was first developed in its current context by Holling in 1973, who recognized the need for better frameworks for representing the uncertainty inherent in complex, integrated, nonlinear systems with multiple stable states (Holling 1973). Ecological resilience is “a measure of the amount of change or disruption that is required to transform a system from being maintained by one set of mutually reinforcing processes and structures to a different set of processes and structures” (Peterson, Allen, and Holling 1998, p. 10). The comparison between ecological systems and businesses is important because the conventional definition for economic resilience encompasses only the ability to quickly return to the initial state. For instance, one author describes resilience in business as “their ability to, and the speed at which they can, return to their normal performance level following a high-impact/low-probability disruption” (Sheffi 2005, p. ix). Yet, as ecological resilience emphasizes, multiple steady states can exist – farms can be transformed into a new state after a sufficiently large shock. Economic poverty traps are one example of a lower, less desirable equilibrium that may be “sticky,” or hard to surpass.

These subtle differences in definitions of farm resilience can result in tangible impacts on farmer decision to invest in resilience. Under a framework such as Sheffi’s business resilience definition, there is less incentive to invest in preventative measures. The emphasis is heavily on speed of recovery. However, certain farmers do invest in water conserving technology and others do not. Could this be because farmers who do not invest in the technology have not yet experienced water outages, or that they believe that any outages are temporary and recovery of previous levels of performance is still possible? And, might it be that farmers who do invest in the irrigation technology have experienced shocks to their water supplies which lead them to believe that the system variables may be changing- that a permanent change in water supply is a possibility in the future?

An example that illustrates the difference in definitions of resilience relates to irrigation infrastructure at the irrigation district level. This region-scale example highlights a similar process that may be occurring with farm resilience at the farm-scale. The Mexicali Valley experienced a smaller, 5.8 magnitude earthquake in December, 2009, and the government's response followed the Sheffi resilience definition- they rebuilt the canals as quickly as possible to return to normal performance levels. The government had a different response to the April, 2010, earthquake. They increased flexibility of the system in various ways, such as through a binational agreement with the United States to allow for storage of water in Lake Mead (Pitt and Crowley 2010) during reconstruction of canals.[8] CONAGUA, together with the Water User's Association, have also approved the use of flexible materials in the construction of the new canal in the Mexicali Valley (previously called the Nuevo Delta Canal, the new name is the *4 de abril* canal, which will soon be constructed in the zone most impacted by the earthquake, thus named in its honor) (Robles Van dyck 2012). These flexible materials are part of a category of geosynthetic barriers, which can be used in conjunction with cement lining of the canal and can also be used for reservoir and landfill lining (Zanzinger 2007). Although use of these materials dates back to the 1940s, their use in the *4 de abril* canal would be the first time geosynthetic barriers would be used in canals in the Mexicali Valley. They are beneficial in that they lengthen the life of the cement and if the frequently occurring smaller magnitude earthquakes succeed in cracking the cement lining of the canal, the geosynthetic membranes would prevent leakage and allow the canal use to continue. Thus, through increased storage capacity and increased flexibility of canals, the irrigation district was able to improve the infrastructure in a way that will increase ability to respond to future shocks. This implies that learning occurred in the government from the earlier earthquakes, and after the Easter earthquake the focus changed instead of recovery, to recognition of the existence of new processes and system variables, and an understanding that investments are necessary as a preventative approach. The response of the Mexican government is consistent with the idea from Holling's approach to resilience,

[8] The agreement of the United States to allow for storage of Mexican's Colorado River allotment in Lake Mead is temporary, though serves to set a precedent and makes it more likely that a similar agreement could be reached after a future disaster. This is considered by NGOs working in the region as a good example of a successful binational collaboration (Pitt and Crowley 2010).

where he demonstrated multiple cases where random shocks helped to increase system resilience, and in contrast, stable systems that never experienced shocks were not likely to be resilient (Holling 1973).

A farm resilience framework also highlights the temporal component of risk management. An ability to recover from shocks will necessarily be dependent upon the number of shocks received in the recent past – that is, the exposure of a farm system to shocks. Because of the interrelated nature of shocks, which can exhibit a ripple effect of consequences, considering risk management and farm resilience over time is important. For instance, after the April 2010 Easter earthquake destroyed water conveyance infrastructure, the frost in February 2011 that decreased yields in the Mexicali Valley Irrigation District may have had a larger impact. And after those two cumulative shocks, a minor illness for the owner of a farm could be enough to turn the net farm income from positive to negative. Mueller & Osgood (2009) document this phenomenon –where the impact of shocks lasts over multiple periods - in an empirical analysis of labor markets in Brazilian agriculture and the long-term impacts of drought. Their analysis showed that the impacts of drought on wages can last up to five years after a drought, even when controlling for economic recession. One likely interpretation of this result is that farmers tap into capital reserves to cope with drought, and require several years to recover.

The economic literature on farm resilience is fairly new, and few quantitative studies have been published. An innovative empirical assessment of farm resilience in the beef industry in Australia was done by Kaine and Tozer (2005), providing a valuable framework for quantitative assessment. Kaine and Tozer developed a set of thresholds for grazing systems and the economic components, and found that tradeoffs exist between stocking rates, cash flow, and resilience to shocks. Although the study is specific to the pasture-based grazing in Australia, the framework is a good starting point for research involving thresholds and the tradeoffs that face decision makers. Other empirical studies on farm resilience to drought in China (Simelton *et al*. 2009) and Africa (Seo 2010) are useful for their methodologies but do not look specifically at decision making at the farm level, nor at which factors influence which risk management strategies farmers will adopt.

Antle, Stoorvogel, and Valdivia (2006) provide an empirical analysis of agricultural system resilience with a focus on soil management. Their multiple-equilibrium framework is valuable in a resilient context, clearly elucidating the role of thresholds and the possibility for a high productivity equilibrium and a second low productivity equilibrium. Using an econometric simulation model, the authors identify the existence of a soil threshold: beyond that threshold, soil quality drastically affects yields and can become economically unfeasible to improve. Thresholds are a major focus in the farm resilience literature. Antle and Capalbo (2010) define farm resilience with respect to the ability to maintain production of valued outputs. This description directly connects farm resilience to maintaining levels of productivity, and the authors emphasize the importance of determining thresholds, "beyond which [farms] experience large losses or even complete failure" (p. 389). The quantification of thresholds is a useful method for assessing resilience, because it explains an otherwise peculiar phenomenon: why can a farm household endure low or negative net returns in some circumstances, and in other cases a seemingly minor event leads to a farm going out of business? The reason must be the existence of a threshold, which was crossed.

It is feasible to quantify thresholds related to physical processes, such as in the Antle, Stoorvogel, and Valdivia article on soil thresholds. However, quantifying a threshold for the entire farm system where, if crossed, the farm becomes unviable, is nearly impossible. One can envision the theoretical existence of a farm household wellbeing threshold or tipping point. The cumulative impact of crossing over multiple farm-level thresholds can lead to a crossing below that tipping point, after which the household can no longer meet their desired levels of health, education, basic needs, and overall utility. For every farmer, the decision to exit from agriculture is based upon a conglomerate of factors and on personal expectations and perceptions of the value of wellbeing for that farm household. Thus, we can only truly measure farm resilience *ex post*.

2.6 Farm resilience classification: thresholds and indicators

Nonetheless, it is useful to understand a range of thresholds and indicators, which provides a useful framework to aid researchers and farm managers in estimating farm resilience. The proximity of a farm household to certain thresholds can help stakeholders better understand which households will be at risk of crossing below the tipping point after a shock. Indicators can aid in the prediction of which farmers are more likely to have the capacity to respond to a shock and which will not. Difference thresholds for physical processes, which directly impact farm yields, exist for soil, temperature and pests (Antle and Capalbo 2010). Irrigation water thresholds exist, though because many crops can withstand a lower quantity of water than the plant-water requirement while maintaining production, should be considered in conjunction with profitability. The water requirements for each crop in the Mexicali Valley, such as those calculated by Carrillo-Guerrero (2009), and will vary according to soil type and salinity of soils. Temperature and timing of irrigation deliveries also play a role in the extent to which a shortfall in irrigation water impacts crop yields. A salinity threshold exists as well, and also varies by crop. For instance, the salinity threshold for lettuce is estimated at 0.90 dS/m, while for cotton the threshold is 5.1 dS/m, exemplifying the wide range between different crops (Williams 2005).

Economic thresholds can include cash flow (Kaine and Tozer 2005) and debt to asset ratio (Darnhofer 2009). Management decisions impact both yields and costs and are more challenging to quantify, as they encompass timing of fertilizer application and irrigation, tillage practices, pest control, soil management (Luers *et al*. 2003), and farming systems and technology (Antle and Capalbo 2010). Management and technology decisions can be captured indirectly, however, through the net income threshold, which incorporates the following variables (where price and yield are vectors of all crop prices and corresponding yields of each crop in the portfolio):

$$\text{Net Income} = \Sigma(\text{Other income}) + (\text{Price} * \text{Yield}) - \text{Variable Costs} - \text{Fixed Costs}$$

In the net income threshold, a single value captures crop prices, yield, and costs during one time period. Crossing below the net income threshold can manifest itself though short-run shutdown for a particular crop during one season. Nonetheless, estimation of a quantifiable farm resilience threshold is fairly subjective, and will change by household and over time. The purpose of understanding economic thresholds, then, is not for explaining causal relationships, but rather for improving management and to aid in identifying farms with a higher likelihood of not being able to respond to shocks.

In other cases, classification of farm resilience is facilitated through indicators. Indicators are numeric measurements of qualitative variables and are used to make relative comparisons between cross sectional units or within cross sectional units over time. Parsonson-Ensor and Saunders (2011) encourage the quantification of various types of capital indicators as a useful tool for contrasting differences among farms. Changes in these indicators over time can assist in better assessment of farm resilience. Natural capital consists of resources such as land, soil and water, as well as other types of ecosystems services and processes (United Nations Economic Commission for Europe 2009). Physical capital consists of assets such as tractors and other types of machinery, buildings, processing facilities, and vehicles. Human capital can include formal education, health, and training received in soil management and disaster planning. And social capital includes trust, shared values, and norms (Parsonson-Ensor and Saunders 2011), access to farmers' organizations, technical assistance organizations, and connections to government agencies which may facilitate access to government programs. Nonetheless, there is increasing evidence that social capital can have either positive or negative impacts in terms of economic growth. Thus, the definition proposed by Dasgupta (2005), "interpersonal networks," removes any positive or negative connotations. Yet, in the case of farm resilience, a primary goal of social networks would be for assistance in recovering from shocks, not exclusively for economic growth. Thus, in cases where social networks can be utilized for recovery, then we would expect farmers with higher levels of social capital to have a higher capacity to regain agricultural production after a shock.

While it is important to control for the thresholds and indicators listed thus far, assessing management responses to water supply variability can be the most direct way to characterize farm resilience. The presence of (or lack of) key responses or strategies can give important insights into the resilience of a farm. Not all management responses, both preventative and retroactive, increase farm resilience. Certain responses might even decrease farm resilience, and the presence of these responses can also provide a good picture of the level of farm resilience. Anderson and McLachlan (2012), who conducted a study which surveyed Canadian farmers to determine responses to bovine spongiform encephalopathy (BSE), use a similar approach, where they classify responses to shocks along a spectrum. This approach clearly highlights the phenomenon that not all responses increase farm resilience.

The presence of a diversified crop portfolio, with appropriate combinations of uncorrelated crops, could be a good indication of farm resilience, particularly if the farm also cultivates a mix of crops with a higher and lower consumptive use of water. However, other strategies do not automatically increase farm resilience. Becoming an elected member on the board of directors could result in an increase of social capital, resulting in fewer delays in irrigation water deliveries, but also could lead to higher transaction costs without any subsequent effect on farm resilience. Increasing acreage cultivated could lead to higher net returns and greater capacity to respond to shocks, or could lead to a greater number of water outages and higher debt. Liquidating cattle before optimal time for sale is likely to result in lower profitability and a reduction in the diversity of the agricultural income portfolio, and is therefore unlikely to increase farm resilience.

Another strategy that has been suggested as a potential response to water supply variability that can also increase farm resilience is deficit irrigation. Deficit irrigation is frequently mentioned among lower Colorado River stakeholders as a potential method for decreasing consumptive use of water in agriculture without reducing agricultural profitability (Smith and Pritchett 2010). Regulated deficit irrigation is the process of choosing to irrigate crops with less water than the recommended quantity, which may result in slightly lower yields, but when controlled, still allows for crop production to be economically feasible. In other words, deficit irrigation has the potential to increase farm resilience by enabling greater flexibility for farmers to respond to temporary decreases in volume of water delivered - without significant decreasing profitability. Success of deficit irrigation varies depending upon water table, crop type, and soil characteristics (Ottman 2010). In the Mexicali Valley, a more important constraint exists: many farmers are already practicing deficit irrigation by default. For instance, alfalfa has a higher plant-water requirement than the legal allocation in the Mexicali Valley, meaning that many alfalfa farmers are forced to deficit irrigation (Carrillo-Guerrero 2009). In other words, farmers may not be choosing to deficit irrigate in the same way in which they choose other risk management strategies; rather, deficit irrigation is a constraint that the farmers are not actively choosing. Thus, although in specific cases deficit irrigation may be an effective response to water supply variability it cannot be considered a primary risk management tool in this region for increasing farm resilience.

In summary, farm resilience is a concept that is slowly gaining popularity in the agricultural economics literature in the past few years. Thus, the definitions of key terms and the measurement of farm resilience at the farm household level are still in the process of being developed. We have proposed a list of relevant thresholds and indicators to assess farm resilience. In a given region, targeting specific risk management strategies that are expected to either increase or decrease farm resilience is also informative. The presence or absence of these key strategies is an additional method for classifying farm resilience.

Chapter Three - Framework and Conceptual Model

3.1 Risk management and decision making under uncertainty

Decision making under uncertainty is a constant challenge for profit maximizing agricultural managers. Profit, also referred to as net returns, is calculated as follows:

Net returns = (Crop price **x** yield) – (Input price **x** quantity) – fixed costs

Where Crop price **x** yield = Gross revenues, *and*

Input price **x** quantity = Variable costs

From this equation, it is clear that a decrease or increase in any single component will have an impact on net returns. Uncertainties can come in many forms - uncertainty in crop prices and price of inputs, uncertainty in weather, water supplies, yields, and uncertainty in government policies. Given a budget constraint in a multi-period model, where a negative net return in one period can carry over into future periods, uncertainties of one type are tightly related to other types of uncertainties. For instance, imagine a farm where a low market price for wheat leads to a negative net return the first time period. Therefore, in period two, a farmer may be repaying debt and more vulnerable to a shock to the water supply. Consequently, in the third period, that farmer might not be able to invest in water conserving irrigation as a response to water supply variability. Thus, decision making is a multiple-period process.

Moreover, decision making in response to uncertain water supplies has added complexities. Risk theory assumes risks to have a known probability distribution, or one that can reasonably be estimated. The assumption that the probability distribution can be estimated facilitates calculations of expected utility, which is a function of the expected value of net income. However, with climate and water uncertainties we cannot assume stationarity, and must recognize that predictability is compromised (Milly *et al*. 2008). By definition, a shock is an unexpected event in a system. In addition to shocks to water supplies, the impacts on agricultural net returns resulting from slow onset drought, climate change, and increasing demand for water can also be challenging to accurately predict, given the intrinsic uncertainty in each of these factors.

Good risk management is broadly accepted as being crucial in business management, and particularly so for agribusiness management, given that agriculture is intrinsically full of uncertainties. Despite the fact that proper risk management is assumed in agribusiness management, little is known about what influences the decision-making process: why does a farm manager select some risk management strategies while ignoring others? For instance, while crop diversification is a common risk management strategy for reducing the variance of agricultural net returns, is there an economic rationale for why a farmer may choose not to diversify his crop portfolio?

One might assume that wealth is a factor in risk management, and to a certain degree, greater wealth will likely be correlated with a higher level of farm resilience. However, is wealth the primary determinant of farm resilience or might other factors be more important? In the Mexicali Valley, of 16,000 registered water users, only about 25% of these water users are active farmers. The remaining three quarters of water users are no longer involved in agricultural production and they lease their water rights to active farmers. Having a sufficient level of wealth may have been one factor in keeping the remaining 25% of farmers in agricultural production, we postulate that other factors play a role as well. What innovations have these active farmers adopted that have helped them maintain productivity despite multiple shocks in recent years? What can policy makers, water managers, and farm managers learn from these successful active farmers?

Further, while risk management focuses on the tools available for maximizing expected returns while reducing variance of net returns, positive outcomes are not guaranteed. Risk management alone does not assess the success of each farmer at reducing risk, nor the capacity that a farmer has for adopting various risk management strategies. *Farm resilience* is a term that incorporates two components: 1) risk management strategies, with 2) the capacity to respond under a wide range of circumstances. As defined in chapter two, farm resilience is the ability of a farm system, after a shock or stress, to recover farm productivity and household wellbeing and to avoid shifting to a less desirable equilibrium. The definition includes shocks *and* stresses because limiting the definition to “shocks” – that is, a type of uncertainty that is beyond what farmers are able to predict – is insufficient. The survival of the farm system also encompasses the ability of a farm to respond to and recover from substantial stresses. A stress could be thought of most generally as an impact that results in lower than average net returns for the farm household. Then, a sufficiently high stress is a shock. Examples are extreme heat, low crop prices, or serious health problem for the farmer.

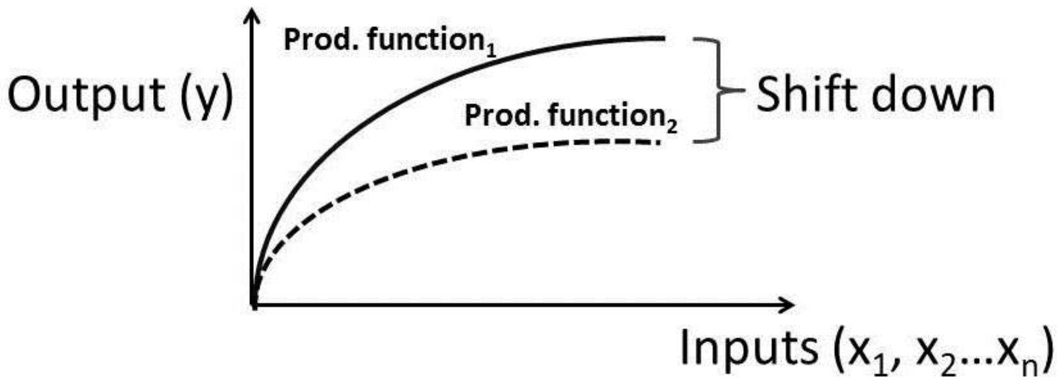
Household wellbeing can be evaluated with respect to net income and utility derived from that income, and more broadly encompasses the health, education, quality of life, and consumption levels of the household. One method of describing the optimal farm household equilibrium is in reference to poverty traps, such as presented in Banerjee and Duflo's book *Poor Economics* (2011). Farm households in what the authors call the *poverty trap zone* are unable to invest and increase their household income level. Rather, in the poverty trap zone, farm households have *less* income in each future period, which leaves them in a place where they are unable to improve their wellbeing. Farm households who have exited from the poverty trap zone have reached a minimal level of income where they *are* able to invest. These farmers experience an increase in income over each time period, until a point. Therefore, the optimal farm household equilibrium is one where the farm household has sufficient income to be outside of the poverty trap zone, to meet basic needs, and to improve household wellbeing.

There exists a direct relationship that can lead from a shock to a water supply to loss of profitability, a shift to a lower equilibrium, and a negative impact on household wellbeing. Risk management models are not designed to explain systems where multiple equilibria are possible, but rather, these models assume that after a shock, normal performance levels can be achieved once again. In reality, a shock of sufficient magnitude is capable of propelling a farm system into the poverty trap zone. For this reason, the definition for farm resilience includes the ability of the farm household "to avoid shifting to a less desirable equilibrium."

The *market equilibrium* is usually described as the price-quantity combinations where supply equals demand. Although this is a dynamic process, under perfect competition we expect the market to return to the equilibrium after a disruption. In households, we can think of a similar process occurring. Households will optimize utility for a given income, and equilibrium is where a state of balance occurs between consumption and net income. Again, the process is dynamic and net income will fluctuate over time, but all else equal, the equilibrium will remain within a constant upper and lower bound over time. A shock resulting in a shift to a lower equilibrium has an important implication: when a system shifts, the system variables change and farm households may no longer be able to maintain satisfactory levels of wellbeing. For instance, a shock to a farm system could propel the farm household into the poverty trap zone. A shock that leads to a permanently lower water supply would be an example of how the system variables might change. Once the system is changed, adaptation is necessary.

Equilibrium is a concept applied to the *household* level, though a shift often first occurs with respect to net returns of a *single income-generating asset*. Using a generic graphical representation for agricultural production, such a change could be represented as a shift down in the production function. A production function is a relationship between different input bundles and the output (yield per hectare) per unit of input. In figure 3.1, production function 1 has a higher output at every possible combination of inputs, while production function 2 has lower output in every case. A farm that was unable to avoid a shift from production functions 1 to 2 has a lower level of farm resilience. Production function 2 could represent the case, such as given in the example, where a shock to a water supply leads to a permanent change in irrigation water supplies, resulting in lower output. Then, the cumulative negative impacts on the net returns of multiple income-generating assets can lead to propelling the entire household over a tipping point. Crossing below the tipping point indicates a household with low levels of farm resilience, and can push a farm household into the poverty trap zone. The following paragraphs discuss income diversification, crop portfolio diversification, and technological innovations as risk management strategies that have the potential to increase farm resilience. Worded another way, these targeted strategies can improve the likelihood of avoiding a shift to a lower equilibrium, into the poverty trap zone.

Figure 3.1 Shift down in a production function



The graphical representation in figure 3.1 models a farm with only one source of income. Farm households may have multiple sources of income, which may serve to increase farm resilience by giving the household an alternative if agricultural production fails. Income diversification can take several forms – diversification of farm income (into high value markets, livestock, or dairy sales), diversification of household income into earning wages by working on other farms, and diversification of household income into non-farm income sources. Diversification of farm income sources may involve risk, as the same variables that influence one type of farm income may also impact other farm income (for instance, a water shortage will impact both crop production and livestock production), whereas a water shortage may not impact a job in manufacturing. Thus, households manage portfolios of income sources with varying degrees of risk.

The type of income source may also affect household wellbeing dependent upon the utility a farmers gains from different types of work. For instance, a farmer main gain a level of utility from being a farmer, coming from a combination of factors such as the autonomy of being a business owner, the short commute for farmers who live on the land that they cultivate, and cultural aspects of a family history of agriculture. Therefore, it should be recognized that although risk management and expected net income may be factors in seeking sources of non-farm income, they will not be the only consideration.

Income-leisure models provide a different but equally useful framework for analyzing decisions to seek off-farm income. These models elucidate the fact that family farms are constantly making decisions about number of hours worked on-farm, number of hours worked off-farm, and the opportunity cost of leisure time. In a family farm, family labor will be more productive given costs from principal-agent dilemmas. The principal-agent dilemma is that the principal (in this case, the farm owner or manager) cannot be certain that the agent (the employee or farm-wage earner) who he hires will be working with the same interests in mind, but instead the agent may be pursuing his own interests. Yet in a family farm, family members who work on the farm are likely to have the same interests (higher profitability for the farm) as the owner or manager of the farm. Farmers may be considering the productivity of family labor in off-farm income decisions. Seeking off-farm income may serve for income smoothing during the slow season, but during active agricultural production, off-farm income can result in the need to hire non-family labor. Farmers must assess the tradeoffs of the increased off-farm income versus the potential for lower productivity when hiring non-family labor on farm.

Although ample evidence exists showing that non-farm income sources are gradually increasing as a share of household income in agricultural regions (Reardon *et al*. 2006), less is known about how the additional income is invested. Does non-farm income increase farm resilience? Or is non-farm income an exit strategy, eventually leading to retiring from agricultural production? Pfeiffer *et al.* (2009) analyze 1,668 household surveys from Mexico and find that non-farm income has a negative impact on agricultural output, but a positive impact on the purchase of agricultural inputs. Their results are intriguing and lead to further questions about farm resilience – are farmers with an off-farm income source more likely to invest in strategies that can increase farm resilience? Or, because farmers with off-farm income are more likely to have lower output, are they less likely to make long-term investments in agriculture?

Another strategy that could improve farm resilience is crop diversification. Because figure 3.1 represents a farm with a single type of output, an increase in the number of crops in the crop portfolio could increase farm resilience by providing an alternate source of output for a farm in the event that a shock impacts only the farmer's principal crop. Crop portfolio diversification is a strategy employed by farmers to reduce risk in net returns through choosing crops with uncorrelated or negatively correlated net returns, though the exact combination chosen by a farmer will depend upon a farmer's financial goals and level of risk aversion. All else equal, risk averse farmers will prefer a crop portfolio with lower variance. By definition, risk averse farmers prefer a certain payoff to a risky payoff with the same expected value.

As an example, we have compiled table 3.1, which shows the correlations of the gross revenues for several of the major crops in the Mexicali Valley (gross revenues are used instead of net returns because of data gaps). The higher the correlation, the less desirable the combination of crops would be for a risk averse farmer. For instance, an alfalfa-wheat combination, with a correlation of 0.93, is not a recommended combination for reducing variance in gross revenues.

Table 3.1 Correlations of Gross Revenues, Mexicali Valley, 2002-2010 (SAGARPA 2010a)

	Alfalfa	Cotton	Sorghum	Wheat	Radish	Safflower
Alfalfa	1	0.38	0.54	0.93	0.25	0.32
Cotton		1	0.21	0.51	0.89	0.95
Sorghum			1	0.37	0.27	0.29
Wheat				1	0.35	0.45
Radish					1	0.94
Safflower						1

The coefficient of variation for crops is another common measurement of risk, and a useful tool for comparing the riskiness among different crops when expected return is not the same. A risk averse farmer will prefer crops with a lower coefficient of variation, defined as the ratio of the standard deviation to the mean, which allows for a standard deviation per unit of return (Valvekar *et al*. 2011). The coefficient of variation has been calculated for the major crops in the Mexicali Valley in table 3.2. The implication is that in order for crop diversification to be successful at increasing farm resilience, decision makers need to carefully consider the coefficient of variation and correlations in crop revenues or net returns. Otherwise, crop diversification will not be as effective at increasing capacity of a farm to recover from a shock.

Table 3.2 Coefficient of Variation, Mexicali Valley, 2002-2010 (SAGARPA 2010a)[9]

Variable	Gross Revenues, Mean (MXN)	Standard Deviation	Coefficient of Variation
Alfalfa	21,747	5,185	0.24
Cotton	17,735	8,869	0.50
Sorghum	11,856	1,451	0.12
Wheat	12,589	5,343	0.42
Radish	44,811	26,037	0.58
Safflower	4,769	2,033	0.43

In regions with unreliable water supplies, crops that depend upon a larger quantity of water will be more at risk to a delivery shortfall or delivery delay than crops that have a lower water requirement. Therefore, effective risk management may involve the addition of a crop with a lower water requirement to the crop portfolio, particularly if a farmer has a large number of hectares of alfalfa, which has the highest water requirement of any crop grown in the Mexicali Valley. Safflower is a crop that has been promoted by SAGARPA due to its low consumptive use of water, and in table 3.1 the correlation of gross revenues of alfalfa and safflower are shown as 0.32. Therefore, alfalfa-safflower is an attractive combination for risk averse farmers who seek to increase farm resilience. The values in tables 3.1 and 3.2 are useful for understanding general differences in levels of risk among crops. In practice, however, farmers make decisions based upon net returns, as we expect farmers to consider total costs per hectare as well.

Finally, a third strategy for increasing farm resilience involves technology. In the literature, technology is considered one factor that can shift the production function. In response to shocks to the water supply, technological innovations that increase output for the same quantity of water applied will assist farmers in maintaining productivity in the face of water supply variability. Yet, making long-term investment decisions regarding adaptations to an uncertain water supply also involves risk. Thus, the question becomes, what is the cost of investing in adaptation to water supply variability under uncertainty? On the one hand, for instance, an investment in water conserving irrigation technology before the water supply diminished results in a sunk cost that cannot be recovered if the prediction was incorrect and

[9] Data compiled and calculations computed by the author in tables 3.1 and 3.2.

the water supply does not decrease. In contrast, delaying the decision can lead to losses if a shock to a water supply occurs after costs have been sunk into the production cycle during the season. Like any investment decision, a farmer will calculate the expected return before making the investment. That decision will be derived from his expectation of the shape of the probability distribution and his perception of the tradeoffs between risk and rewards.

3.2 Portfolio Allocation under Uncertainty

Next we consider the role of variance and net returns of the crop portfolio. Although the equations presented in this section are not explicitly part of the conceptual model that informs the econometric regression models, the economic theory they offer provides crucial background information on the decision making process of farmers in terms of crop selection and farming systems. In section 3.3 we build a conceptual model that incorporates expected utility of income and the risk premium. The general form for calculating the net returns from agriculture can be written as follows:

Net returns from agriculture = Σ(Total crop revenues) + Σ(Other agricultural revenues) - Σ(Variable Costs) - Σ(Fixed Costs)

Crop revenues are a function of price multiplied by yield, and yields are a function of management and technology, climate and weather (temperature, wind, and precipitation), water, soil, pests and diseases, and salinity. However, given yield and price uncertainty, net returns fluctuate each year and are difficult to predict. Moreover, the net returns of the crop portfolio will differ depending on the crop mix selected. Therefore, assessing crop returns with respect to share of each crop in a portfolio is appropriate. Because eliminating uncertainty is impossible, selecting crop mixes that reduce variance in net returns is an optimal risk management strategy.

Let r_i be equal to the expected returns of each crop, livestock, or other source of agricultural income (*i*=1,2…n). Let z_i equal the share of returns from each agricultural source *i.* Let expected agricultural returns (R) be equal to the following:

$$R=\sum_{i=1}^{n} z_i r_i \qquad \textit{(Equation 1)}$$

If all else equal, a risk averse farmer would prefer a crop portfolio that reduces variance. From Moss (2012) we would consider an optimal portfolio as one that minimizes the variance of the portfolio with respect to share of each crop, as shown in equation 2. This is subject to an average return constraint, selected by the economic agent, to be greater than or equal to A. The constraint, A, could be defined as an agricultural returns financial goal and can vary depending upon whether a decision maker strives for rapid growth or for more stability. Then, the variance equation is written to be summed over n crops over time (t=1,…12, representing twelve months in the year).

$$\underset{z}{Min} \;\; V\left(\sum_{i=1}^{n} z_i r_i\right) \qquad \textit{(Equation 2)}$$

$$\text{s.t.} \quad \begin{aligned} &\sum_{i=1}^{n} z_i \bar{r}_i \geq A \\ &\sum_{i=1}^{n} z_i = 1 \end{aligned} \qquad \textit{(Equation 3)}$$

$$\begin{aligned} &v\left(\sum_{i=1}^{12} z_i r_i\right) = \sum_{t=1}^{12}\left(\sum_{i=1}^{n} z_i r_{it} - \sum_{i=1}^{n} z_i \bar{r}_i\right)^2 \\ &\bar{r}_i = \frac{1}{12}\sum_{t=1}^{12} r_{it} \end{aligned} \qquad \textit{(Equation 4)}$$

The existence of correlations of net returns among crops in a crop portfolio is one of the fundamental premises behind the field of risk management. The net returns of crops will be correlated at varying levels, and negative correlations are less common, since all crops will be affected by many of the same factors. Thus, when considering two crops with higher correlation of net returns, the variance of the portfolio will increase. Similarly, crops with lower correlation in net returns will reduce the variance of the portfolio. Equations 1-4, where farmers minimize with respect to *shares* for each crop in the portfolio, do not directly consider crop *correlations*. The equations are presented for their mathematical simplicity and ease in calculation. If the reader seeks a mathematical approach, sophisticated methods have been developed using linear programming, which enable researchers to process a wider range of information on risk and uncertainty in a farm household portfolio,

Yet, for the purpose of this thesis, the goal of this chapter is to provide a greater understanding into the decision-making process, providing economic theory as to what farmers might be considering when making cropping decisions. A farmer first seeks portfolio diversification as a risk management strategy. Then, when selecting specific crops for the portfolio, a risk averse farmer chooses combinations of uncorrelated or less correlated net returns with the goal of reducing variance of net returns. Looking at an example from the field work in the Mexicali Valley, 45% of the sample had only one crop in their portfolio, and the remaining portion of the sample had between two and ten crops in their October 2010 – October 2011 crop portfolio. Among those growing two different crops in their portfolio, the most common combinations were wheat-cotton mixes and wheat-alfalfa mixes. For those farmers growing wheat and cotton (12% of the sample) the average share of wheat was 58%, minimum share was 27% and maximum share was 94%. For those growing wheat and alfalfa (6% of the sample), the average share wheat was 52%, minimum share was 32% and maximum share was 85%. This example highlights that even within a small region, where we do not expect to see high variation among farmers with input and output prices, there still remains great variety in the designation of shares in the crop portfolios. This could be due to personal goals, risk preferences, soil quality, labor constraints, and level of experience, among other factors.

To further explore the concept of variance minimization in a crop portfolio, we use an example to illustrate how the share of each crop in a portfolio affects the riskiness of the portfolio. Using the coefficient of variation (CV) to measure risk in a two crop portfolio of wheat and cotton, we can assess this question using survey data and SAGARPA data on annual yields and prices (in this example we make simplifying assumptions that yields are the same for all farmers in the region and that farmers maintained the same share of each crop in the portfolio over the duration of the period considered). Table 3.3 shows the data from the 21 farmers in the sample growing a wheat-cotton crop mix combined with the SAGARPA data on gross revenues (gross revenues are used instead of net returns because of data gaps).

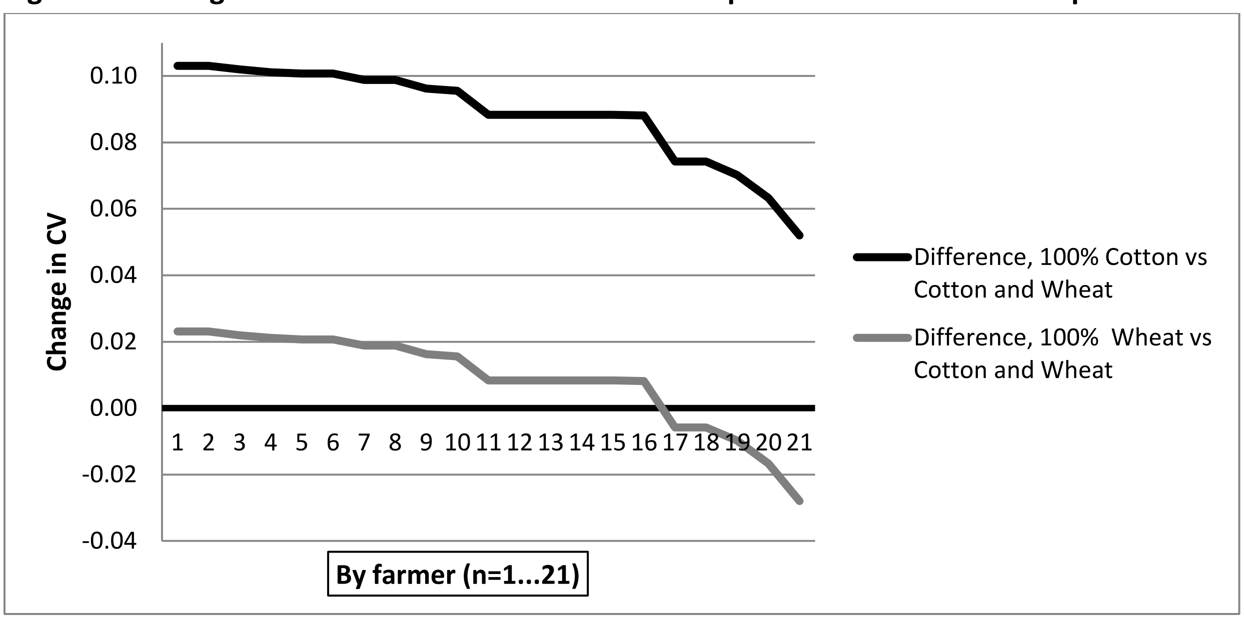
Table 3.3 The relationship between crop share and risk in a wheat-cotton portfolio

Farmer ID	Wheat (ha)	Share of Wheat	Cotton (ha)	Share of Cotton	Total hectares	Mean of Gross Revenues (MXN)	SD of Gross Revenues	CV
1	40	0.67	20	0.33	60	858,246	340,631	0.40
2	80	0.67	40	0.33	120	1,716,493	681,262	0.40
3	60	0.82	13	0.18	73	985,874	392,402	0.40
4	50	0.83	10	0.17	60	806,782	321,774	0.40
5	20	0.63	12	0.38	32	464,593	185,508	0.40
6	100	0.63	60	0.38	160	2,322,967	927,539	0.40
7	15	0.60	10	0.40	25	366,180	146,905	0.40
8	60	0.60	40	0.40	100	1,464,720	587,621	0.40
9	20	0.57	15	0.43	35	517,798	209,049	0.40
10	40	0.89	5	0.11	45	592,221	239,507	0.40
11	8	0.50	8	0.50	16	242,589	99,863	0.41
12	10	0.50	10	0.50	20	303,237	124,829	0.41
13	10	0.50	10	0.50	20	303,237	124,829	0.41
14	10	0.50	10	0.50	20	303,237	124,829	0.41
15	30	0.50	30	0.50	60	909,711	374,487	0.41
16	230	0.94	15	0.06	245	3,161,413	1,302,122	0.41
17	80	0.40	120	0.60	200	3,135,296	1,334,967	0.43
18	100	0.40	150	0.60	250	3,919,121	1,668,709	0.43
19	60	0.38	100	0.63	160	2,528,823	1,086,776	0.43
20	30	0.33	60	0.67	90	1,441,762	629,591	0.44
21	7	0.27	19	0.73	26	425,086	190,426	0.45

The mean of the gross revenues is calculated over the time period of 2002-2010. It is interesting to note that though the table is sorted in increasing order by CV, the share of wheat is not consistently decreasing. That is, as the share of wheat decreases, in general the CV or riskiness increases but not always. The correlation between the share of wheat and CV is not a perfect negative correlation at -0.74. The reason is simply mathematical, due to the calculation of the CV (standard deviation divided by the mean), where an increasing mean can decrease CV even if share of wheat increases, all else equal.

In figure 3.2, we calculate the difference between a specialized and a diversified portfolio. The expectation would have been that crop diversification decreases the risk of a portfolio (in this case, as measured by the CV). Yet, did level of riskiness decrease by switching from a specialized to a diversified portfolio? The CV for the portfolios of 100% cotton and 100% wheat were obtained from table 3.2 in the previous section of this chapter. The CV for gross revenues of a portfolio with 100% cotton is 0.5, and the upper curve in figure 3.2 is calculated by subtracting the actual CV per farmer from 0.5. The lower curve is calculated by subtracting the actual CV per farmer from 0.42, which is the CV for gross revenues of a portfolio with 100% wheat. If the value is greater than (or equal) to zero, then the wheat-cotton portfolio is less (or equally) risky than the specialized portfolio. If the value is less than zero, then diversifying into a wheat-cotton portfolio actually increased riskiness of gross revenues.

Figure 3.2 Change in coefficient of variation between specialized and diversified portfolios



We see that in the case of a specialized cotton portfolio compared to a wheat-cotton portfolio, in all 21 cases the diversified portfolio was less risky than the specialized portfolio. Thus, a cotton farmer who adds wheat to the portfolio does meet the expectation that diversification reduces risk (that is, a reduction in the value of the CV). However, when compared to a specialized wheat portfolio, diversification was not always beneficial in terms of reducing risk. In cases where the share of wheat is 40% or less of the portfolio (for farmers 17-21), the addition of cotton results in a diversified portfolio that is actually *riskier* than a portfolio with only wheat. This simple example reaffirms the conceptual model shown in equations 1, 2, and 3, validating the concept that the share of each crop in the portfolio has a direct relation to the riskiness of the portfolio. The example also illustrates that diversification alone is not guaranteed to reduce risk if correlations in crops revenues are not considered.

In addition to crop shares and variance in crop portfolios, Van Nieuwerburgh and Veldkamp (2009) highlight the role of information in portfolio allocation choice. Information is a constraint which can lead to underdiversification. Information is considered on a per-asset basis and would therefore be an aggregation of information gained on all crops in a portfolio. In a multi-period model, we might expect that information obtained over more than one period results in learning. Even when not developing a multiple period model, it is still possible to analyze the role of information and learning through different variables in the empirical model, such as through years of experience growing each crop, education, and information on past water supply variability.

Chavas (2011) developed an alternative conceptual framework for assessing portfolio diversification and decision making under uncertainty in response to the "underdiversification puzzle." The underdiversification puzzle refers to the observation that many investors are not sufficiently diversified. He develops an innovative approach for assessing the role of economies of scope, risk management, and learning under one model. The model has a time constraint, where time spent on labor is divided among the farm, leisure, and off-farm wages. The time constraint is used to calculate the budget constraint, consisting of initial wealth and all types of income, minus costs and investment. Then, between periods one and two, learning can occur, represented by a conditional probability given a certain piece of information, as per the Bayes theorem. Such a model is useful under a resilience framework, where we might expect that a shock could change the shape of the probability density function. Chavas' model is able to capture if a decision maker is able to incorporate the new information under learning and change behaviors. Under this two-period expected utility model, the risk premium is considered the willingness-to-pay to minimize profit risk. Risk preferences are automatically included in the risk premium through the sign: positive for risk aversion, zero for risk neutral, and negative for risk loving. Then, economies of scope are captured by the certainty equivalent, which is the expected profit with risk removed. The firm has economies of scope if the certainty equivalent of the diversified firm minus the certainty equivalent of a specialized firm is greater than one.

Chavas' comprehensive, multiple period model demonstrates that it is possible to analyze risk management and risk aversion, the value of information, and economies of scope under a single conceptual model. Chavas' approach is useful for understanding tradeoffs in specializing versus diversification, though it does not fully elucidate the role of minimizing variance in a crop portfolio. Thus, the calculations in equations 1, 2, and 3 help the reader visualize the process of allocating land and resource shares to different crops in the crop portfolio. Consequently, although the Chavas model may be useful in future research where panel data is available and where the research question is more explicitly focused on the role of economies of scope, a simple one-period conceptual model is sufficient to answer our current research questions on factors that influencefarmer decision-making process, as shown in the next section.

3.3 Expected Utility Models

Without the presence of uncertainty, one might use a profit maximization or utility maximization conceptual model. With decision making under uncertainty, the expected utility approach is preferred, due to the fact that farmers make *ex ante* decision on cropping systems and input use, without knowing net returns at the end of the season. For instance, the values listed in table 3.3 were calculated after the fact, and farmers would not know prior to selecting crop shares what the actual variance would be of their net returns; thus, we need tools for evaluating how farmers make decisions about the future. Expected utility takes into consideration the probability of multiple outcomes. Also, under a farm household analysis, the household will consider overall wellbeing in addition to profitability, making the emphasis on utility appropriate.

It is common to assume that fixed costs do not affect the short-run decision making process, and we also make the assumption regarding fixed costs. Likewise, it is common in the literature to assume that input and output prices are known and only yield is random, a simplifying assumption we apply to this research a well, since water supply variability directly impacts yields.

Let the expected utility function U=E[u(y)] be a Von Neumann-Morgenstern utility function, where y represents income, *u(y) is a Bernoulli utility function* increasing in income (u'>0) and concave (u''<0). Income is divided into two components, non-farm income (I) and agricultural income (R). Agricultural income is a function of yield (Y) and price (P). Building upon conceptual models used by past researchers, we define yields by separating out the production function f(X), where X can be inputs such as seeds, fertilizer, and water costs; g(X) is the variance of the function; and the stochastic component of the yield is represented by ε, as follows (Di Falco, Chavas, and Smale 2007; Foudi and Erdlenbruch 2011; Chavas and Di Falco 2012):

$$Y = f(X) + g(X)\varepsilon \qquad \textit{(Equation 5)}$$

Net returns (R) is equal to the sum of net returns from all crops in the crop portfolio, though in a generalizable form can be written as follows, where output price is $p=(p_1, p_2,\ldots p_m)$ for *m* agricultural outputs; input price is $r=(r_1, r_2,\ldots r_n)$ and input quantity equals $X=(x_1, x_2,\ldots x_n)$ for *n* inputs:

$$R = p^*(f(X) + g(X)\varepsilon) - rX \qquad \textit{(Equation 6)}$$

The expected utility as a function of income (π) is represented by the following:

$$\underset{X}{Max}\, EU[\pi] = \underset{X}{Max}\, EU\left[I + p\left(f(X) + g(X)\varepsilon\right) - rX\right] \qquad \textit{(Equation 7)}$$

The certainty equivalent (CE) is equal to the expected value of income, which is the value of income with risk removed, or:

$$CE = E[I + p^*(f(X) + g(X)\varepsilon) - rX] \qquad \textit{(Equation 8)}$$

Let the budget constraint equal *h*=(time, land, information, initial wealth, regulations). As with crop diversification, we expect information to play a role with technology adoption (Koundouri, Nauges and Tzouvelekas 2006) and decisions to diversify geographically. Land available is a constraint, and is particularly relevant in the geographic diversification regression. Governmental and irrigation district level regulations may also impact the decision making process and therefore are included as a constraint, either as programs that incentivize certain crops and types of production systems, or through the permit process (such as in the case of the Mexicali Valley) that may impede farmers' crop choices.

The risk premium (RP) is considered the maximum amount that an economic agent would pay for a certain income, calculated as *max*(EU) – CE = RP *(Equation 9)*. Again, recall that risk preferences are automatically included in the risk premium through the sign: RP>0 for risk aversion, RP=0 for risk neutral, RP<0 for risk loving. Therefore, under risk aversion, a farmer will invest if the cost of the less than or equal to the value of the risk premium.

All three econometric models are influenced by a common conceptual model as they focus on the same fundamental question: what is the value of investment in three key risk management strategies? Ultimately, farmers will only adopt the three strategies of focus – crop diversification, cement lining of parcel-level irrigation canals, or geographic diversification – if the strategies are perceived as economically feasible at the farm level. Thus, referring again to Chavas (2011) and equations 4-8, the risk premium is considered the willingness-to-pay to minimize profit risk and is the conceptual model applied to the three econometric models. We expect that if adoption of these three strategies occurred in the past, then the cost of the investment was less than or equal to the risk premium, and that farmers are more likely to invest if they consider the investment a form of self-insurance. The following two chapters outline the data which is used in the econometric models. The econometric models take a deeper look into the decision-making process, highlighting which factors are associated with farmers who adopt different risk management strategies.

Chapter Four - Data and Research Methods

This chapter begins with a description of the research methodology and survey design. Then, the chapter details the data collection and data cleaning processes. We employed a mixed-methods approach, which includes a quantitative and qualitative analysis. The quantitative analysis was comprised of structured interviews with water managers, farmers, and other stakeholders quantifying regional and household statistics, data acquired from Mexican governmental offices, as well as the econometric analysis. The qualitative research included a literature review, the selection of principal findings to apply to the study area, and categorical survey questions such as those asking farmers which innovations they had adopted in response to past waters supply variability.

The interviews were completed from Fall 2010 through Spring 2012, consisting of 12 interviews with experts and government officials (from the Mexicali Valley and Yuma, Arizona) and 30 interviews with water managers from the Mexicali Valley. The farm household surveys were designed based upon the preliminary results from the expert interviews, and 20 surveys were pretested in the field in January 2012. Feedback was incorporated from farmers and water managers, enabling us to improve the survey instrument such that it was carefully constructed to the specific topics and issues facing Mexicali Valley farmers. The survey was implemented by a team of two bilingual enumerators led by Elizabeth Schuster, and a total of 180 surveys completed. The final number of surveys for the analysis is 168. Five surveys with farmers who have exited from agricultural production were used for qualitative aspects but were not included in the regression models which focus on active growers. An additional 7 surveys were removed from the empirical analysis due to missing information. For four of the seven cases, the survey was conducted with a farm manager who was not the owner and was not active in the decision-making process, meaning that we were missing age, educational attainment, household size, and other important information about the actual owner of the business. For two surveys removed from the analysis, the motivation was that the farmer had only been involved in agricultural production for one year, meaning that we were unable to assess the response to water supply variability over time. The final survey was removed because the farmer was missing the share of hectares per crop.

The interviews with water managers were less structured and followed a protocol that targeted areas such as information on major crops, total hectares, number of registered water users and active water users; quantity of groundwater wells; which improvements had been made to module-level irrigation infrastructure; soil quality and salinity issues; and the costs of water and land leases in that module. Interviews lasted between one and three hours, and in all cases at least two water managers were interviewed for each module (either employees or members of the board of the directors). Refer to Appendix C for a complete list of questions from the water manager interviews.

Figure 4.1 Map of irrigation module offices surveyed, Mexicali Valley (Google Earth 2012)

Of the 22 irrigation module offices, we visited 15 offices, shown in figure 4.1. The total number of hectares in the sample summed to 21,751, which is 10.5% of the total hectares cultivated in the irrigation district. The selection of irrigation module offices was based upon many factors. First, we had better contacts in some offices and we were able to complete larger numbers of surveys in offices with supportive management. Second, we did not visit modules 10, 11, and 12 due to significant earthquake damage that left a large percentage of farmers out of production at the time the surveys were completed. And third, the irrigation modules only possess lists of farmers who own land and no lists exist of active farmers who are *leasing* in a given module. Thus, it was not possible to achieve a random sampling of all active farmers. Therefore, we conducted a random sampling of farmers who entered the 15 offices we surveyed. Farmers enter the irrigation module offices to pay outstanding bills, request a crop permit, or deal with other irrigation-related business. Farmers do not need to enter the offices to request water as those requests can typically be conducted by cell phone or Nextel radio. The majority of farmers agreed and only about 10% of farmers declined. About 25% of the sample was a purposive sample: we selected a range of large- and small-scale farmers to better answer our question of "which innovations have farmers adopted in response to water supply variability." Farmer surveys lasted on average from 10 minutes to 25 minutes. Refer to table 4.1 for a list of total numbers of surveys included in the econometric analysis by primary module.[10]

Table 4.1 Total number of surveys by primary module

Primary Module	Number
1	12
2	5
3	25
4	14
5	1
6	9
8	19
9a	9
14	21
15	8
16	1
17	3
18	3
19	2
21	23
22	13

[10] Please note that although the table is listed by primary module, many farmers have land in more than one module. Surveys are listed by where the farmer cultivates the largest percentage of land, not where the surveys were administered. Only in cases where it was unknown in which module the farmer had the largest percentage of land (about 10% of surveys) was the location of the interview used, assuming that farmers are likely to spend more time in their primary module.

The surveys were anonymous, following the guidelines of the University of Arizona Institutional Review Board (IRB), who granted us approval for conducting Human Subjects Research, after completing a lengthy training and application process. This anonymity allowed farmers additional freedom to express any grievances or proprietary information with the guarantee of privacy. Likewise, to protect privacy, we did not include any questions directly inquiring about income and debt levels. Despite these precautions, we occasionally encountered farmers who offered guarded answers to questions. In cases where the irrigation module staff and board of directors personally introduced us to farmers, this introduction appeared to increase the level of trust among the researchers and farmers. Thus, the data collection process itself served as an exercise in building relationships.

The first goal of the farmer survey was centered on answering two central questions, 1) Classify and rank the biggest impacts on profitability from agricultural production in the past five years; and 2) How have farmers responded to water supply variability in the past five years. The idea was influenced by the findings of Patrick *et al*. (1985), who found that selection of risk management strategies is influenced by which risks farmers are managing for. Specifically, we wanted to gauge where “lack of water” ranked in comparison to other impacts on farm profitability. The latter question was intended to discover if innovations exist that have not been reported in the academic literature. The second principal objective of the surveys was to quantify the perceived level of water shortages and delivery delays so that the data could be used to analyze how water supply variability influences decision making.

The farmer surveys began with a series of general questions on demographics, crops grown, water resources and technology, and various proxies for wealth (refer to Appendix A for the complete survey questions). Next, the surveys contained questions quantifying total irrigations, delivery shortfall s, and frequency and extent of irrigation delivery delays. The next section covered other sources of income, governmental support, and organizational aspects. Then, farmers were asked the two questions on impacts to agricultural profitability and response to water supply variability. Finally, the last questions related to other uses of water (such as fishing and hunting) to assess if farmers might be benefitting from environmental uses of water beyond irrigation and from direct household use.

The time period covered in the study was the October 2010 – October 2011 agricultural production year for questions related to agricultural practices. However, farmers answered based upon current situation for questions such as those regarding age, education, crops grown and hectares of each crop, cattle, and members of household. It is worth explaining that the survey included two separate questions: 1) How many hectares of land do you own? and, 2) of the hectares owned, how many are currently under cultivation? In designing the survey question, we hypothesized that total hectares owned (which includes hectares cultivated and hectares fallowed) would be larger than hectares owned (and currently under cultivation). However, in the sample, both values are correlated at 0.9986 (at 0.0001 confidence), so effectively, farmers in Mexicali Valley cultivate 100% of their property in a given year.

Percent of income from agricultural production was also reported for the current situation. For percent of income from agriculture, the survey used during the pretest asked farmers to estimate the percent as a continuous variable. However, farmers found it challenging to calculate even the approximate percentage, especially given the difficulty in calculating percentage for years when agricultural net returns are negative. Thus, the question was changed to a categorical variable, asking whether agricultural represented more than half, half, or less than half of household income.

When looking at crop diversification, it is important to assess a broad enough timeframe to capture changes in perennials such as alfalfa, which have a life span of approximately four years in the Mexicali Valley. The calculation of change in crop portfolio diversity was based upon the number of crops grown ten years ago and the number of crops grown in the October 2010 – October 2011 agricultural production year. However, in rare cases that a farmer voluntarily mentioned the crops currently in production (in spring 2012), we included those as well for measuring change in crop diversity. We asked farmers how many years they have been growing each crop in their current portfolio; this demonstrated whether the crops have been in production for less than 10 years and also enabled us to quantify a “crop experience” variable.

The crop experience variable was calculated as the sum of the two crops with the largest share of hectares (in cases where the farmer had only one crop in the portfolio, we included only the number of years growing that one crop). When asking farmers all other crops grown in the past 10 years, and which year they stopped growing those crops, the farmers were surprisingly effective at remembering. In many cases, farmers could list all crops grown for the past 40 years and the year they stopped growing those crops. In hindsight, seeing that 45% of farmers in the sample have only one crop in their crop portfolio, and 47% have two or three crops in their crop portfolio, it is logical that farmers will have strong recall regarding other crops grown in the past. Although this does not guarantee accuracy, the strong recall does greatly improve accuracy.

The delivery shortfall and delivery delay variables were calculated for the October 2010 – October 2011 agricultural production year. In the literature, water supply variability is often measured simply as variance from the mean, and one of our contributions to the literature is the division of this variable into two separate components, delivery shortfall s and water delivery delays. In this research, we define these as follows: ***delivery shortfall*** is the number of irrigation deliveries arriving with lower volume of water than requested, as a percent of total irrigations, and ***delivery delay*** is the maximum number of days late for all irrigation deliveries. Quantification of shortages and delivery delays as separate variables is fairly uncommon in the literature, outside of controlled irrigation experiments. We hypothesized that the inclusion of both components would enrich our contributions to the literature on water supply variability and adaptation responses.

For delivery shortfalls, we chose to count the number of irrigation deliveries, including any irrigation deliveries in which farmers believed that insufficient water was delivered. Quantifying *all* shortages (for instance, whether 30%, 50%, or 80% of the water was delivered) provides additional information, compared to *only* counting a full missed irrigation (that is, where 0% was delivered), which has been the practice in some of the common pool resources literature. We also opted to quantify the number of irrigations with delivery shortfalls instead of measuring the magnitude of the under-delivery. The motivation was two-fold. First, farmers make decisions based upon perceptions, so their perception of the shortage is likely to be more important than the quantity in terms of decision making; and second, due to a lack of equipment for measuring exact volumes of water at the parcel level.

The delivery shortfall survey question consists of four columns. The first column controls for farmers who have parcels in multiple irrigation modules, as we expect that delivery shortfalls may vary on a per module basis. The module-based information on delivery shortfalls also serves to calculate module-level descriptive statistics presented in chapter 5. The second column reports the sum of the total number of irrigation deliveries, by hectares and by crops. The third column shows the number of irrigation deliveries in which farmers believed that less water was delivered than the volume that they ordered. The final value of interest was an aggregate percentage by farmer. For example (refer to table 4.2), if a farmer irrigated a total of 200 times in the October 2010-October 2011 crop production year, and 40 irrigation deliveries were shortages, the value used in the regression is (60/300) *100 = **20%**. Shortages can also result in water stress to the crop, which could lead to lower yields and may significantly impact profitability. For the purpose of comparison, the fourth column in the survey shows the number of irrigations in which the plant suffered crop water stress (for example, 10%).

Table 4.2 Example of the calculation of the delivery shortfall variables

Irrigation Module Number	**How many times did you request irrigation water (for each crop)?**	**Number of times that less water than requested was delivered**	**Number of times that the crop suffered from water stress due to delivery shortfall**
21	10 hectares of alfalfa **x** 9 irrigations = 90 35 hectares of wheat **x** 6 irrigations = 210 Total irrigations = 300	Total irrigations with shortfalls **x** # hectares = 60 Percentage of irrigations with shortfalls = (60/300) *100 = **20%**	Total irrigations with shortfalls *and* water stress **x** # hectares = 30 Percentage of irrigations with shortfalls *and* water stress = (30/300) *100= **10%**

Given constraints on farmer and researcher time, in cases where farmers had multiple crops or land in multiple modules, we requested that the farmer list only the top three crops and modules. This still provides an accurate assessment of the most important crops, which is expected to have a proportionately strong impact on decision making. Before conducting the survey pretest, it was unclear whether farmers would have difficulties recalling accurately the number of delivery shortfalls or delivery delays from the previous year. Farmers, in fact, answered with such speed and confidence, that it seems clear that they remember quite well. Given their 100% reliance on irrigation, the lack of precipitation, the extreme desert heat, and the fact that water is a crucial input, farmers were highly in tuned to the quantity and timing of their irrigation deliveries.

Given that water supply variability consists of both volume and timing components, we next asked questions related to timing and delivery delays. To better understand the irrigation delivery system, it helps to understand that farmers must contact the irrigation module to schedule an irrigation delivery and an irrigation module employee (the *canalero*) is responsible for opening the canal gate within three days from when the delivery is requested. The *canalero* is also responsible for reporting the number of hours the gate is open and for estimating the quantity applied based upon the amount of time lapsed. In the survey, we asked the maximum number of days that the farmers had to wait for irrigation water to be delivered last year, beyond the 72 hours they normally have to wait from the time they request their water. From this point forward, whenever we refer to the variable **delivery delay** we are referring to this variable that represents maximum days irrigation water was delayed last year. The maximum number of days the delivery was delayed is intended to capture the extent of delays, a shock to the farming system. The maximum delay for deliveries from October 2010-October 2011 is by definition specific to that time period, and is likely to be higher than in other years because of the impact of the earthquake on delivery infrastructure. Again, the selection of this region as a post-earthquake case study was intentional, to assess how farmers respond to shocks to their irrigation water supplies.

Then, we followed up by asking the frequency with which delays in irrigation water deliveries resulted in crop water stress, ranked on a 3-point scale (frequently late, occasionally late, and almost never or never late). It is worth recalling that we also asked a question with respect to delivery shortfall and crop water stress. Although the irrigation water survey questions are divided into delivery delays and shortages, it helps to point out that a delayed irrigation eventually can become a shortage when a delay is sufficient to result in a full missed irrigation. Thus we would expect there to be some overlap in cases where number of days delayed is high.

A few survey questions, instead of focusing on the previous agricultural year, focused on the past five years. The questions regarding principal impacts to profitability and responses to water supply variability were focused on the past five years. It is worth clarifying that when asking farmers the response question, we used two different versions. If farmers reported in prior questions that delivery shortfalls or delivery delays had been problematic, we asked how they had responded to a lack of water in the past. In cases where farmers indicated that they had little to no problems with water supplies, we asked more broadly how farmers have responded to water supply insecurity and how at the irrigation district level, management has been managing water resources more conservatively. The question on responses to water supply variability was first left open-ended, to observe which innovations farmers have encountered. Then, farmers were prompted with a list of 15 possible adaptive responses.

The issue of missing survey values was minimal. Refer to table 5.3 for the mean and median values used to fill the missing values. Only one survey had the farmer's age missing, and we filled with the median. One survey of a 72-year-old farmer was missing level of educational attainment. Since the majority of farmers in that age bracket did not have access to education when they were young, we filled with the mean education level for that age bracket (the age group older than 70 years old), which was primary education. One farmer survey was missing number of cattle and we filled with the median. Three surveys were missing number of members of the household, and we filled with the median. One farmer survey was missing the average age of farm machinery, and we filled with the median. Finally, three farmer surveys were missing the years of crop experience (growing each crop in their crop portfolio). Thus, assuming that the typical farmer in the Mexicali Valley becomes active in agriculture at age 18, we subtracted 18 from the current age of the farmer and filled that for all crops grown (none of these three farmers had a college education). The following chapter presents the descriptive statistics and econometric models.

Chapter Five - Summary of Variables and Descriptive Statistics

In this chapter, we show the summary of variables, descriptive statistics, and expected signs. All descriptive statistics are from the 168 survey observations. The first section of descriptive statistics presents general information on the sample to give an overview of the characteristics of the irrigation modules and farmers surveyed. Then, specific variables included in the regression models are presented. (Only the most relevant descriptive statistics are presented and the full set of descriptive statistics is provided in Appendix B.) The next section highlights the descriptive statistics related to water supply reliability at the farm and irrigation module levels. Then, the results on the most significant influences on farm profitability and common responses to water supply variability are presented. The top impacts and farmer responses are themselves a result; a better understanding of actual risk management strategies and responses to shocks can support formulation of future research in arid regions that rely on irrigation. Next, the descriptive statistics of the dependent variables are presented. The three dependent variables described in this section represent a crop diversification model, parcel-level cement lining of irrigation canals model, and geographic diversification model. The purpose of all three models is to assess the characteristics of farmers who select these risk management strategies. Do strategies differ dependent upon wealth and assets? Are strategies selected based upon extent of unexpected reductions in water resources? Although income diversification is also a risk management strategy discussed in this paper, we analyze the role of off-farm income as an explanatory variable that can reduce variance in net income and not as a separate model. The model specifications, econometric methods, and results are presented in chapter six.

5.1 Aggregate statistics at the irrigation module level

There are virtually no clear trends that differentiated the farmer sample at the irrigation modules level with respect to many of the general survey questions. For instance, there is a range in the percentage of farmers in each module who had invested in cement lining of parcel-level canals (from 0 to 67%), with no obvious pattern among the modules. However, one notable difference among the modules is that Module 9a ranked first place in terms of average number of hectares per farmer, quantity of machinery, number of employees, hectares of alfalfa, and quantity of equipment purchased through the governmental program that funds 50% of equipment purchases. Thus, it appears that there is something unique that characterizes Module 9a. These differences may indicate higher levels of resources and wealth, though Module 9a also has the highest number of hectares on average of wheat, and wheat has lower investment costs compared to other common crops, so perhaps some other intangible factor characterizes this group. Another difference among modules is percent of land dedicated to high value crops, mainly vegetable production for export: Module 2 has the highest percentage of high value crops (19% of hectares in the sample) and the remaining modules have between 0 and 7% of hectares dedicated to high value crop production. Given the investment required for vegetable production and high standards for quality in export markets, a larger percentage of vegetable production distinguishes these modules to a certain degree. Table 5.1 presents the descriptive statistics by module on number of hectares.

Table 5.1 Mean and total hectares by module, from survey results

Primary module	# of farmers per module	Mean hectares (total) per module	Mean hectares (owned) per module	Mean hectares (leased) per module	Sum of hectares for farmers surveyed in that module
3	25	45	20	25	1,113
6	9	46	27	19	415
4	14	49	29	20	682
1	12	61	24	37	733
5	1	70	10	60	70
16	1	70	70	0	70
17	3	75	19	56	225
21	23	83	27	56	1,913
15	8	94	42	52	751
18	3	103	98	6	309
14	21	104	49	55	2,187
22	13	127	29	97	1,648
8	19	130	77	53	2,465
2	5	348	272	76	1,742
19	2	363	53	311	726
9a	9	516	139	377	4,643

5.2 Descriptive statistics for the dependent variables

The purpose of our crop diversification model is to see if crop diversification is employed by farmers as a tool for risk management, given the debate in the literature on whether farmers are diversifying for risk management and scope economies, or specializing due to economies of scale. If we are able to determine whether farmers are already diversifying crops, this would give us insights into the feasibility of introducing a new crop that consumes less water, which would have implications for regional water supply reliability. Looking in greater detail at the change in diversity allows for assessment of which factors are associated with an increase or decrease in the number of crops in the crop portfolio.

The dependent variable is equal to the change in crop diversity over the past 10 years. The variable was calculated as follows:

$$Percent\Delta Crops = \frac{\sum_{i=1}^{n}\left(Crops\_grown\_final\_period\right) - \sum_{j=1}^{m}\left(Crops\_grown\_initial\_period\right)}{\sum_{j=1}^{m}\left(Crops\_grown\_initial\_period\right)}$$

Number of crops in final period, i=1,…n

Number of crops in initial period, j=1,…m

Negative values show that specialization has occurred in the past 10 years; positive values show that diversification occurred in the past 10 years; and a value of 0 means that no change occurred in the total number of crops grown.

In the most recent time period, the total number of crops grown can be viewed graphically in figure 5.1, which shows that 46% of farmers at the time of the survey grew only one crop. However, it is clear that the region is not fully specializing in a single crop, as 33% of farmers grow 2 crops and 21% grow between 3 and 10 crops. Figure 5.2 presents the mean number of crops in the crop portfolio in the initial period and final period by quartile. Small-scale farms are the bottom quartile, where total hectares cultivated is less than 20 hectares. Medium farms have total hectares between 20 and 40. Large farms have total hectares of 40 to 90. And the top quartile, extra-large farms, cultivates more than 90 hectares.

Figure 5.1 Number of crops grown, current

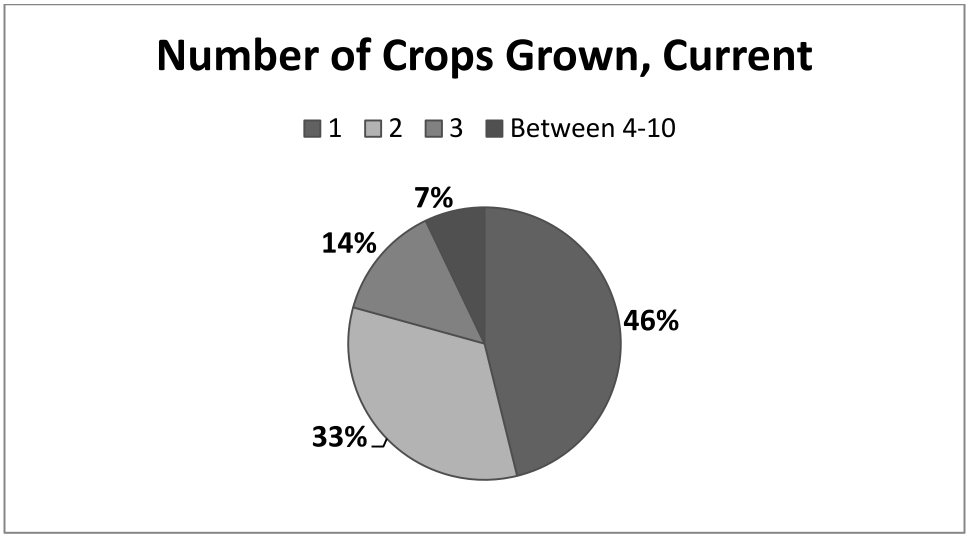
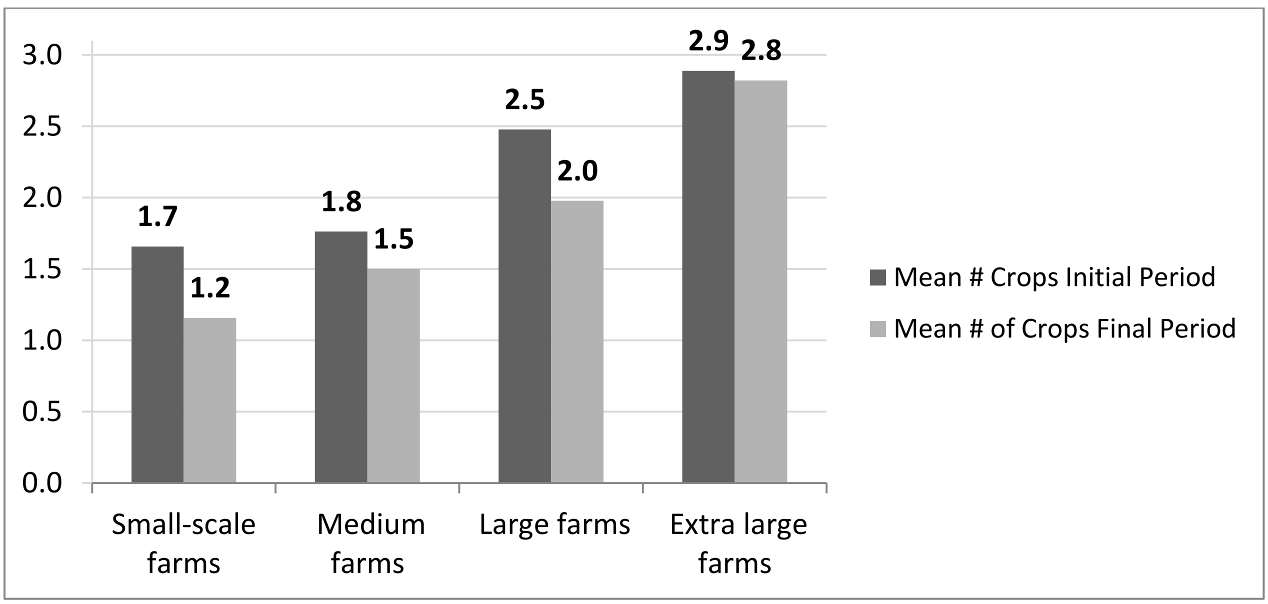
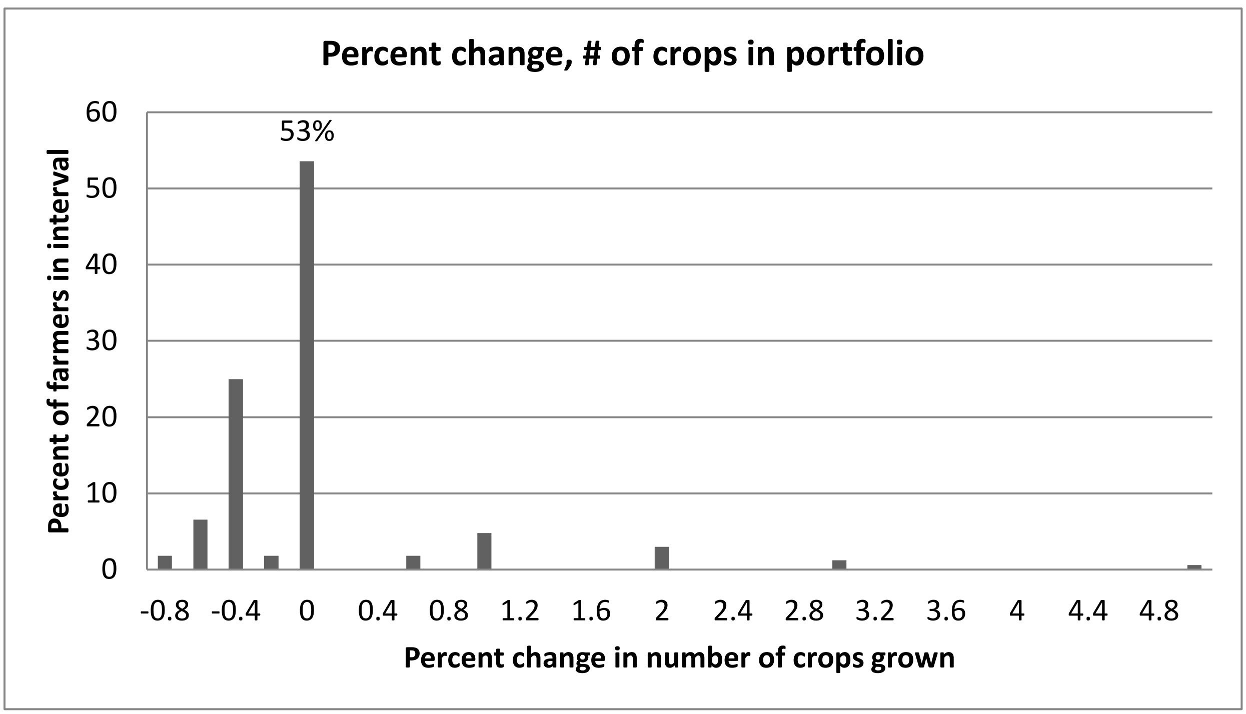


Figure 5.2 Mean number of crops grown by quartile



However, our dependent variable is the change in crop diversity over time, which captures the dynamic aspect. The range of the dependent variable (percent change in diversity of crop portfolio) is -0.75 to 5.10. The change in crop diversity is represented in a histogram in figure 5.3, with percent change on the x-axis and percent of farmers in the interval on the y-axis. Not all farmers changed the number of crops grown: 53% (90 farmers) did not change the number of crops in the crop portfolio over the past 10 years. However, 15 of those 90 farmers changed from one crop to a different crop while maintaining the same total number of crops. Thus, it is important to acknowledge that the crop diversification model is only designed to classify diversification in terms of number of crops grown, missing the more subtle response that is captured by a change in crops. Only 12% of farmers diversified over the time period (represented in the figure as those to the right of zero), so one conclusion could be that, in general, the trend over the past 10 years was towards specialization, since 36% of farmers specialized (represented as those to the left of zero). However, such a conclusion is simplistic, and the multivariate regression enables a closer analysis of which factors are associated with crop diversification.

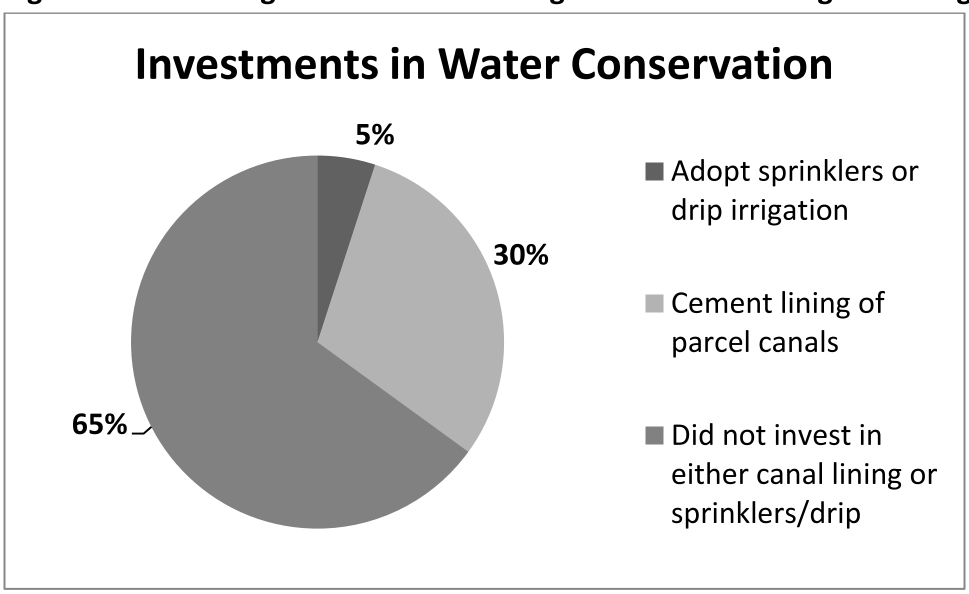
Figure 5.3 Histogram of percent change in number of crops in portfolio



For our second model, the canal lining model, figure 5.4 shows the percent of farmers who have invested in sprinklers/drip irrigation, cement lining of parcel-level irrigation canals, and those who have invested in neither of the options. Of the total sample, 30% (50 farmers) have invested in cement lining of parcel-level irrigation ditches. The question on the survey was presented in a more general format: “Have you changed irrigation technology in response to water supply variability? If so, what type of technology?” We focused on cement lining of canals because it was the most frequent type of "technology." However, there were also two farmers who irrigate with groundwater and who reported having invested in tubing to transport their water from the well to the parcel-level. Because this tubing is the groundwater equivalent to cement lining of canals, and because we expect that the same factors that motivate canal lining also motivate investment in tubing, we included these two farmers among the 30 farmers. (There were an additional 4 farmers who had invested in both cement lining of canals *and* tubing. These farmers are also included in the 30 farmers.)

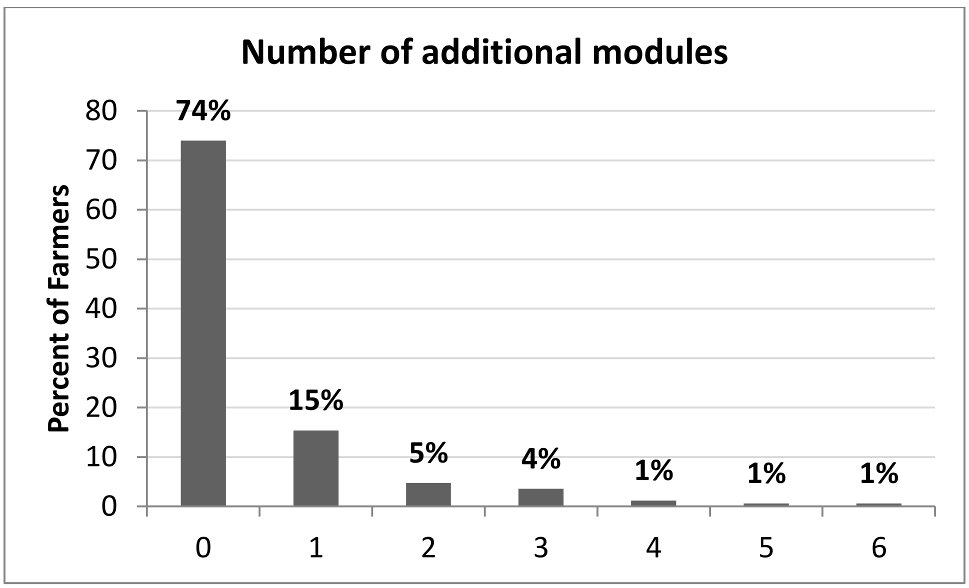
Only 5% of the sample (9 farmers) has invested in drip or sprinkler irrigation systems. No farmers in the sample have invested in cement lining of parcel-level irrigation ditches *and* either drip or sprinkler systems. Nearly all of the 5% who adopted drip or sprinkler irrigation are involved in vegetable production and the total number that comprises the group is too small to analyze as a separate regression model.

Figure 5.4 Percentage of farmers investing in water conserving technology



As is common in the literature, we use cross sectional data to assess the general attributes of farmers who choose to invest. Because having 100% of a farmer's parcel-level irrigation ditches lined with cement is uncommon in this region, we include farmers even if lining occurred on only for a portion of their hectares. Such an approach is appropriate because (given the high cost of investment) the presence of *any* improvement is an indicator. It is true that investments in the cement lining of parcel-level irrigation ditches are also supported by government programs paying 50%, and the irrigation module office provides additional support through allowing use of their machinery. Yet for many government programs in the Mexicali Valley, farmers are required to prepay the investment and seek reimbursement afterwards, further implying that a farmer decision to make irrigation improvements is based upon out-of-pocket costs and not only based upon assistance. Nonetheless, because the governmental support programs do exist, the model may also reveal, to a certain degree who has received these supports. However, even with assistance, the remaining cost to the farmer is still considered substantial. Therefore, the primary objective of the model is the analysis of which farmer attributes are associated with investment in cement lining of parcel level irrigation canals.

Figure 5.5 Geographic diversification dependent variable histogram



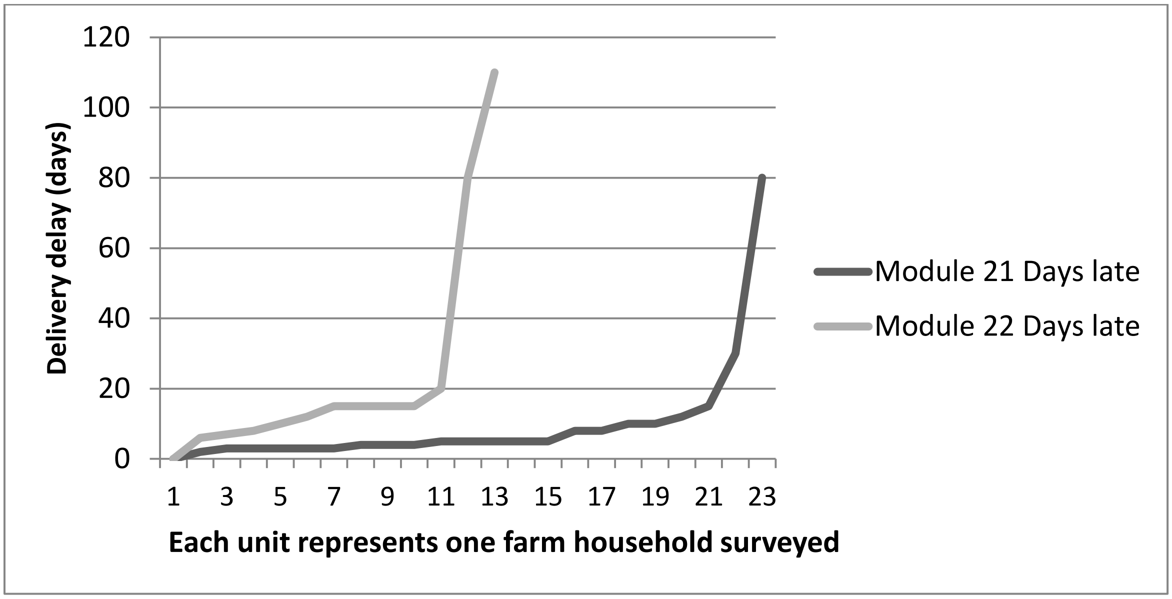
The third risk management strategy we analyze econometrically is geographic diversification. The dependent variable is defined as the number of *additional* modules in which farmers cultivate. Although technically this variable can equal any integer from 0 and 21, in this sample the range is 0 to 6. Refer to figure 5.5, showing that 74% of the sample cultivates in only one module (that is, zero additional modules beyond their primary module). This implies that for many, the benefit of geographic diversification may not outweigh the costs. Yet, 26% of the famers have diversified, with 15% of the sample cultivating in one additional module and the remaining 11% cultivating in between 2 and 6 additional modules.

We initially hypothesized that farmers with greater variability in water supply in their primary irrigation module are more likely to see geographic diversification as a risk management strategy. However, the descriptive statistics revealed that farmers in every single module (except Module 6) have diversified geographically, which means that even farmers whose primary module has virtually no water supply reliability problems have diversified in certain cases. Therefore, we expect that some other factor, in addition to water supply variability in the farmer's primary module, is influencing the decision to geographically diversify. Specifically, we expect that wealth variables may positively influence access to land and the decision to diversify geographically, with hectares leased having a stronger impact than hectares owned.

In this chapter and in previous chapters, various statistics have been presented showing several of the differences among irrigation modules, giving a strong overview of why one might expect that even within a single irrigation district differences may exist. Soil type and quality also vary significantly among the irrigation modules, though one can state in general terms that on average, the soil quality is best in the northern portion of the module and in what was once the floodplain of the Colorado River. The percentage of soils that are poor quality, clay soils increase as one moves south and west towards the city of Mexicali. However, because soil quality changes within each irrigation module and even within each field, it would be nearly impossible to use an accurate measurement of soil quality as a variable in the regression models.

The intuition is that even in occasional cases where a farm lies on the boundary between two modules, there will exist differences in management between the two modules and thus diversification represents an improvement in resilience to shocks as compared to one module. Evidence from surveys supports this hypothesis, revealing that even within a small geographic region the impact of the earthquake varied among farmers (figure 5.12). Likewise, even within a small geographic region delivery delay can vary substantially. Figure 5.6 shows the great variation found in the delivery delay among farmers in the two modules that are considered tailenders, Modules 21 and 22 (defined in chapter 2 as farmers located at the endpoints of the distribution canals). Figure 5.6 demonstrates that geography of parcels may play a role, either through location in reference to the end of the canal or through management.

Figure 5.6 Differences in delivery delays among farmers in irrigation Modules 21 and 22



5.3 Summary of explanatory variables and descriptive statistics

Table 5.2 provides the independent variables used in the three regression models. Explanatory variables were intentionally kept as similar as possible in each of the three models to enable comparison among strategies. The expected signs column in the table is for all three regression models. Variables distinct for a specific model are noted in the detailed descriptions that follow the table. The detailed description following the table of variables also explains the economic intuition behind the expected signs.

Table 5.2 Summary of explanatory regression variables

Variable Name		Description	Expected Sign
Age		Age of farmer at time of survey	**-**
Crop experience		Sum of years growing top two crops	**+**
Hectares owned		Total number of hectares owned	**+/-**
Hectares leased		Total number of hectares leased	**+/-**
Machines		Quantity of agricultural machinery owned	**+/-**
Cattle		Number of cattle owned	**+**
Delivery shortfall (%)		Delivery shortfall as a percent of total irrigations	**+**
Delivery delay (days)		Maximum number of days water delivery was delayed	**+**
Percent alfalfa		Percent of hectares of alfalfa	**+**
Percent high value		Percent of hectares of high value crops[11]	**+/-**
Members household		Total number of people living in household	**+/-**
Family labor		Number of family members working on farm	**+/-**
Binary variables	**D_Secondary**	=1 for at least some secondary education	**+/-**
	D_High School	=1 for at least some high school education	**+**
	D_College	=1 for at least some secondary education	**+**
	D_Other Income	=1 for presence of other income	**+/-**
	D_Module management	=1 for employee or member of board of directors of the irrigation module	**+/-**

Age: Defined as the age of the farmer, this variable is expected to have a negative influence in all three models. This expectation is based upon results from past studies in the literature and because older farmers are closer to retirement and may not be interested in additional investments at that late stage in their careers.

[11] In only three cases, the calculation of high value crops involved a crop other than vegetables – dates, citrus trees, and flowers.

Crop experience: Crop experience is calculated as the sum of years a farmer has been growing the top two crops in the crop portfolio. They are ranked as the top crops dependent upon the number of hectares grown, not the net returns. Crop experience is only included in the parcel-level cement lining of irrigation canals model (abbreviated as the *canal lining* model) and geographic diversification model. It is not included in the crop diversification model because of a potential problem with endogeneity: a recent change in crops grown would register as a low level of crop experience, and it would falsely appear that low crop experience leads to higher crop diversification, whereas it is more likely that recent crop diversification leads to lower crop experience. The variable is expected to have a positive impact on canal lining, because crop experience and in turn information are typically variables associated in the literature with adoption and also because our method of calculating crop experience also represents intensity of production.

Hectares owned, Hectares leased, and Machines: Hectares owned and hectares leased represent the total number of hectares owned and leased and currently under cultivation. They are included as two separate variables, rather than as a sum of total hectares, under the premise that farmers who own a larger portion of land may behave differently than farmers who lease a larger portion of land. The total quantity of agricultural machinery included only the number of self-propelled machines and did not include tractor implements. Machinery, hectares owned, and hectares leased could all be considered proxies of wealth.

- Crop diversification: If crop diversification was undertaken for the purpose of taking advantage of economies of scope, then we might expect these wealth proxies to be positive. If specialization is occurring due to economies of scale, we might expect these same variables to be negative. Therefore, we do not have a clear a priori expectation on the sign.
- Canal lining: Hectares leased is expected to have a negative impact, as farmers are less likely to invest in infrastructure if they do not own the land. Land ownership and quantity of machines, proxies for wealth, are expected to have a positive impact on the decision (and ability to) invest in cement lining of parcel-level irrigation canals.

- Geographic diversification: Hectares leased is expected to have a positive impact on diversification, as a farmer will probably have more flexibility and ability to respond in the short run through land leases. Hectares owned and machines are also expected to have positive impacts, as they imply a higher wealth and greater ability to lease or purchase more land.

Cattle: The expected sign on number of head of cattle is ambiguous. While the sign of the parameter could be negative if cattle-raising is a risk management strategy that reduces variance in net income (are therefore a substitute for other risk management strategies), the sign could be positive if cattle are an indicator of wealth and greater ability to invest in the various risk management strategies. Therefore, there is no clear a priori expectation on sign.

Delivery shortfall and **Delivery delay**: Delivery shortfall represents the percentage of total irrigations where shortfalls occurred (refer to table 4.2 for more information on the calculation). Delivery delay is the maximum days late for irrigation deliveries last year. We expect delivery shortfalls and delivery delay to have a positive effect, as both impacts to irrigation water supplies are thought to increase variance of net income. The surveys also include a variable that captures delivery shortfall *with* plant water stress. Although the percentage of irrigations resulting in plant water stress may be a more accurate representation of profitability and yields, the variable that captures delivery shortfalls (regardless of whether water stress was an issue or not) is more appropriate in terms of decision making. The reason is that any delivery shortfall indicates water supply variability and uncertainty, and signals to the farmer that future water supplies may be even less reliable. Thus, the implication is that farmers are more likely to make decisions based upon general variability in supplies, not only based upon loss of yields, which is essentially a worse-case scenario. Therefore, the general delivery shortfall variable is included in all three models.

Percent alfalfa: Because alfalfa is a crop that uses more water than any other crop grown in the Mexicali Valley, the percent of total acreage dedicated to alfalfa is expected to have a positive influence on farmer decision making and the selection of risk management strategies.

Percent high value: As a subset of the population, vegetable producers appear to behave differently than growers of field crops, thus the motivation behind a variable that represents the ratio of hectares dedicated to vegetable crops over total hectares. Moreover, because of strict phytosanitary, packing, processing, and labor requirements, and competition in obtaining contracts for vegetable production, we hypothesize that any value above zero is likely to, in some way, distinguish farmers in this category as a unique segment. However, the expected sign on this variable is ambiguous, as little is known how this group behaves as a segment.

Members household: This variable quantifies the number of people currently living in the home of the farmer surveyed. The expected sign is ambiguous, as it is hard to predict if households with an increasing number of members are a unique demographic and if so, how they may behave differently.

Family labor: Family labor represents the number of family members who work on the farm in a typical year. This variable could either represent a form of social capital or also could indicate a higher level of productivity. Either way, the expected sign is ambiguous.

Education: The education variable was calculated as a discrete variable, with four categories: primary education, secondary education, high school education, or college education. In general we expect that more information, and specifically an increase in human capital, will positively influence the decision to adopt various risk management strategies.

D_Other Income: Other income is a binary variable that indicates the presence of other income, and excludes day wages within agriculture (a small number of cases where a farmer had permanent employment in agricultural management *were* included). Day wages in agriculture is presumed to be temporary and less substantial than other types of non-farm income, though is only 2% of the sample and thus does not represent a large percentage. The expected sign on D_Other income is ambiguous. If other income serves to finance the investment in risk management strategies, then the sign could be positive. However, other income is likely to reduce variance in net household income and could be considered a substitute for selecting crop diversification as a risk management strategy, which could lead to a negative impact on the decision.

D_Module management: As mentioned in chapter 2 in the section on farm resilience, social capital is expected to be an indicator of farm resilience. Our *D_Module management* binary variable is a special case of social capital. The variable is defined as cases where the farmer surveyed is a member of board of directors or employee of irrigation module.

- Crop diversification: One hypothesis is that the expected sign will be negative because those with political and social connections in management of the irrigation module office are likely to have less variability in their water supplies and therefore less incentive to diversify crops.
- Canal lining: Likewise, we expect that the political and social connections will increase water supply reliability and decrease likelihood of investing in cement canals. A second hypothesis is that, because the irrigation module supports farmers through use of their machinery in the cement lining of parcel-level irrigation canals, that D_Module management would have a positive impact on adoption of canal lining.
- Geographic diversification: Similar to the crop diversification model, the expected sign is negative, because employment or being a member of the board of directors of a module could be associated with greater assurance of the correct timing and volume of irrigation deliveries. Also, the variable could be representing a higher loyalty and therefore a lower likelihood to diversify into other geographic regions.

D_Earthquake: Only included in the geographic diversification model, the dummy for earthquake is a self-reported measure of farmer's perception of the impact of the earthquake. The variable was coded where D_Earthquake=1 if the farmer reported that the April 2010 earthquake was among his largest impacts on agricultural profitability in the past five years. The expected sign is positive, as we hypothesize that earthquake damage to canals is associated with a desire to lease additional hectares in a different geographic region.

Table 5.3 presents the descriptive statistics of the principal exogenous variables of interest. It is interesting to note that 37% (62 farmers) own 100% of the land that they cultivate and 8% (14 farmers) lease 100% of the land they cultivate, with the remaining 55% of farmers cultivating a combination of leased and owned land. However, the variables used in the regression are hectares leased and hectares owned (not total land or percentage of hectares leased). Regarding the quantity of machinery per farm household, 90% (152 farmers) own at least one tractor. The remaining 10% rent machinery, share machinery purchased in a collective, or borrow machinery from family members. Machinery is intended as one of several proxies for wealth, and when possible should be considered together with average age of machinery. Machinery is important not only as a proxy for estimating wealth, but also serves for comparison with other agricultural regions, and the Mexicali Valley is known for being one of the most mechanized parts of Mexico (Salinas-Zavala, Lluch-Cota, and Fogel 2006). Initially, we attempted to ask the number of hours on the tractor, which was expected to be a more accurate indication of wealth than average age, but most farmers were unsure of the average number of hours, so we opted for average age of machinery instead.

Table 5.3 Descriptive statistics of principal variables

	Median	Mean	Min	Max
Age (years)	53	53.4	21	79
Total land cultivated (hectares)	40	117	3	1,500
Hectares owned	20	50	0	1,150
Hectares leased	15	67	0	1,000
Hectares leased, % of total land	40%	39%	0%	100%
Machines (number)	2	3.6	0	30
Average age of machinery (years)[12]	20	22	1	60
Cattle (number)	0	68.8	0	10,000
Delivery shortfall (as a ratio over total irrigations)	7%	16%	0%	100%
Delivery delay (days)	4	7.5	0	110
Percent High Value (of hectares)	0%	3%	0%	100%
Percent Alfalfa (of hectares)	0%	11%	0%	100%
Members household (number)	4	3.8	1	10
Family labor (number)	1	1.6	0	12
Employees (number)	2	7.9	0	400

Livestock production is not a common source of income for a majority of farmers from the survey. Regarding cattle, only 17% (28 farmers) owned cattle and an additional 6% (10 farmers) had other livestock that they considered important to their business, including primarily sheep and goats (and to a lesser extent horses and pigs) with the average number of other livestock at

[12] For those farmers who own machinery (average age of machinery >0).

56 head, and a median of 25. High value crop production is also uncommon, with a median of 0%. The number of employees and family labor are also interesting to compare. On average, the number of non-family member employees is higher than the number of family member employees, yet family labor is believed to be more productive than non-family labor. The expectation is that the marginal increase of one family member employee is therefore more significant than the marginal increase in productivity due to a non-family member employee.

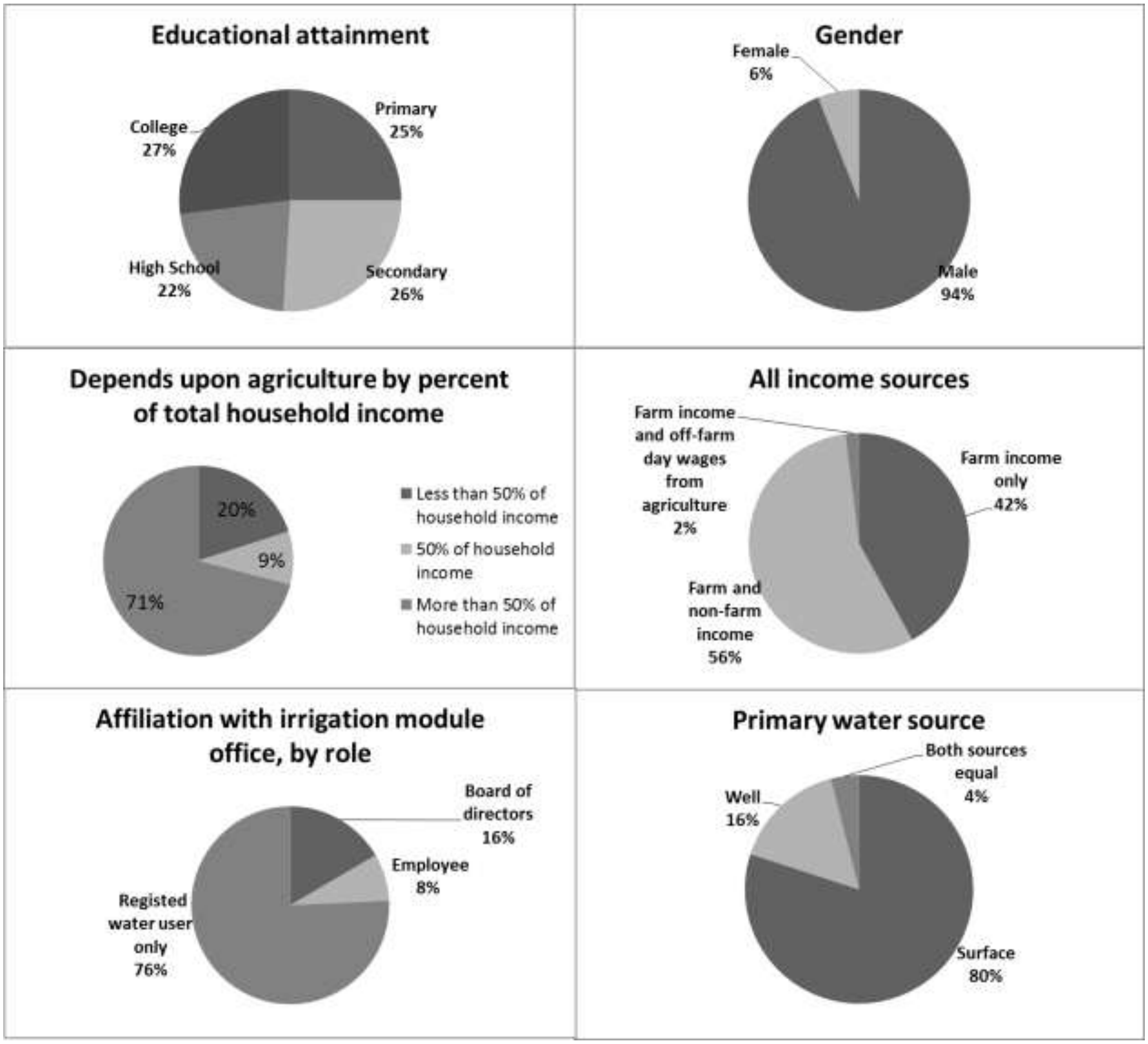
A closer look at the relationship among multiple proxies for wealth is helpful to assess the extent to which they are correlated, as shown in table 5.4. The total land is the sum of land owned and land leased. The total land is highly correlated with other wealth indicators and could lead to issues of multicollinearity, and so the two separate components (land owned and land leased) are each used as explanatory variables in the regressions. Moreover, one would expect that farmers who owned a larger percentage of their total land might behave differently than farmers who lease a large percentage of their land, meaning that the disaggregated variables also have more explanatory value in the models. Indeed, the land owned and land leased variables are only slightly correlated. Most striking to note is that contrary to the expectation, percent high value crops is not correlated with any of the proxies for wealth. The one exception is number of employees, which is consistent with anecdotal evidence that vegetable production is more labor intensive. One final point is that although employees is included in the list of potential proxies for wealth, it is likely that number of employees depends on multiple factors – labor availability in close proximity to the farm, specific crops grown – and therefore this variable was not included in the regression models as it is a weak proxy for wealth.

Table 5.4 Correlation of variables expected to proxy for wealth

Correlation Coefficients							
	Machines	Land owned	Land leased	Total land	Employees	Cattle	Percent high value
Machines	1	0.33	0.60	0.59	0.24	0.43	0.05
Prob > |r|		*<.0001*	*<.0001*	*<.0001*	*0.0015*	*<.0001*	*0.5146*
Land owned		1	0.29	0.75	0.13	0.38	0.08
Prob > |r|			*0.0001*	*<.0001*	*0.097*	*<.0001*	*0.2896*
Land leased			1	0.83	0.29	0.45	0.03
Prob > |r|				*<.0001*	*0.0001*	*<.0001*	*0.714*
Total land				1	0.23	0.54	0.05
Prob > |r|					*0.0028*	*<.0001*	*0.5253*
Employees					1	0.14	0.66
Prob > |r|						*0.0792*	*<.0001*
Cattle						1	-0.02
Prob > |r|							*0.8219*
Percent high value							1

Figure 5.7 represents principal binary and category variables of interest. Education was divided fairly evenly among the four categories. The distribution of gender is much less even, with 94% of farmers interviewed being male. Overall, agriculture appears to be an important source of income for farmers, as 71% depend upon agriculture for more than 50% of their household income. It is interesting to note that even though 56% of farmers have additional sources of non-farm income, 71% still depend on agriculture as their primary source of income. For the social capital variable, D_Module management, representing farmers who are employees or on the board of directors of the module, 24% of the sample fell into this group. And, the water source results are as expected, that farmers depend upon surface water substantially more than groundwater.

Figure 5.7 Descriptive statistics of binary and categorical variables[13]



5.4 Descriptive statistics related to water supply reliability

The initial hypothesis when beginning this research was that groundwater resources will be less variable than surface water resources. A second hypothesis was that farmers with access to both groundwater and surface water resources will experience even less variability in water supplies. Yet access to groundwater resources differs greatly by module, ranging from Module 1 with 97,433 million meters cubic of water from wells (97% of their total water allocation) to eight modules with zero percent of their water allocation as groundwater (refer to table 1.3 in

[13] Only 3 farmers had 0 years of educational attainment and were therefore rolled into the "primary" category.

chapter 1). The depth of wells from the survey range from 11 to 250 meters (there were 16 missing values), and the deeper the well the higher the electricity costs will be for pumping. Though the irrigation modules contribute to electricity costs and maintenance of the federal wells, individual farmers bear the costs for private wells. In the sample, about 25% of farmers had access to a federal well, 7% had access to a private well, and 65% had no access to groundwater. The federal wells are managed by the irrigation modules and the private wells are managed by the individual farmers. Table 5.5 presents the mean values for key water variability indicators, where farmers from the survey are grouped according to their primary water source: surface, ground, or equally reliant upon surface and groundwater.

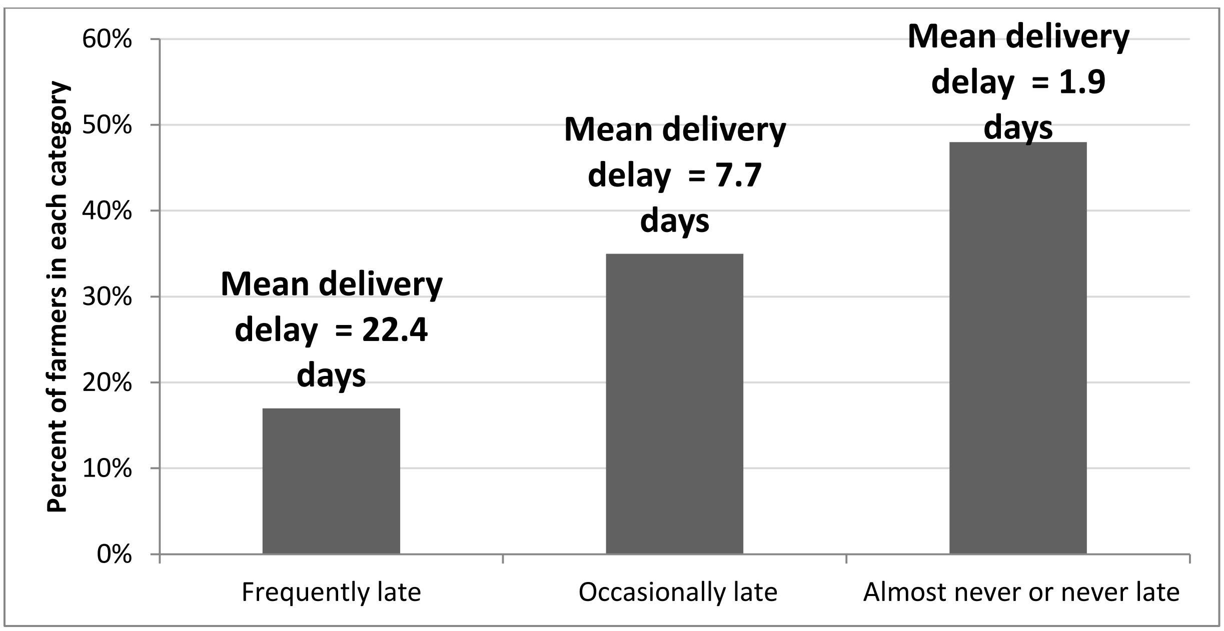
Table 5.5 Water supply variability by primary water source

	Primary water source		
Water Supply Variability	**Surface**	**Ground**	**Equally reliant upon surface and groundwater**
N	131	32	6
Mean delivery shortfalls	18%	11%	12%
Mean delivery shortfalls *resulting in water stress*	12%	7%	9%
Mean delivery delay (maximum days)	7.9	4.4	15.2
Mode frequency of water deliveries resulting in water stress (1=frequently, 2=occasionally, 3=almost never or never)	3	3	2

As expected, farmers depending upon surface water had in nearly all cases higher water supply variability than those depending primarily on ground water. However, farmers who depended equally upon surface and groundwater resources for irrigation had a higher average maximum delivery delay, which is a curious finding. Also, farmers depending upon both water sources had a mode of “occasionally” for frequency of delivery delays resulting in water stress compared to the other two groups, who had a mode of “almost never or never.” Interviews with farmers and irrigation managers also provided evidence that access to groundwater does not guarantee water supply reliability. One logical explanation could be that in the majority of cases several farmers share access to a well, so management can play a role in timely access to irrigation water. Additionally, not all wells are high yielding. Therefore, although it is still possible that groundwater supplies are more reliable than surface water supplies, it is inaccurate to portray groundwater supplies as never being late or always providing the full volume requested.

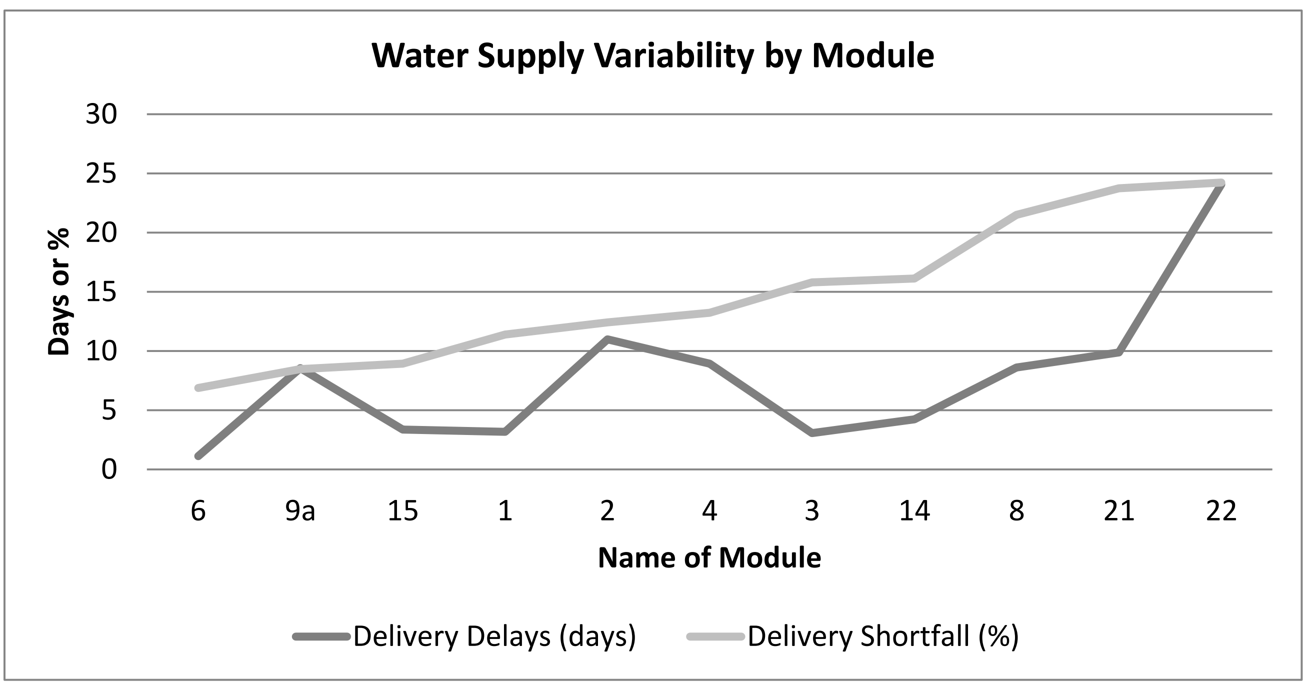
Refer to figure 5.8 for a further look at frequency of delays in water deliveries, this time independent of source. Figure 5.8 was motivated by the question, "Is it possible that the delivery delay (recall that 110 days is the maximum from the sample) was a rare event, occurring just one time? Or do farmers who report a *higher number* for delivery delays also *frequently* receive their irrigation deliveries late?" Yes, the descriptive statistics reveal that farmers who reported a greater frequency of delays had, as a group, a higher maximum delivery delay. This implies that using delivery delay as a variable in the econometric analysis also captures some of the variation from the frequency variable.

Figure 5.8 Frequency of irrigation delivery delays and mean delivery delay by category



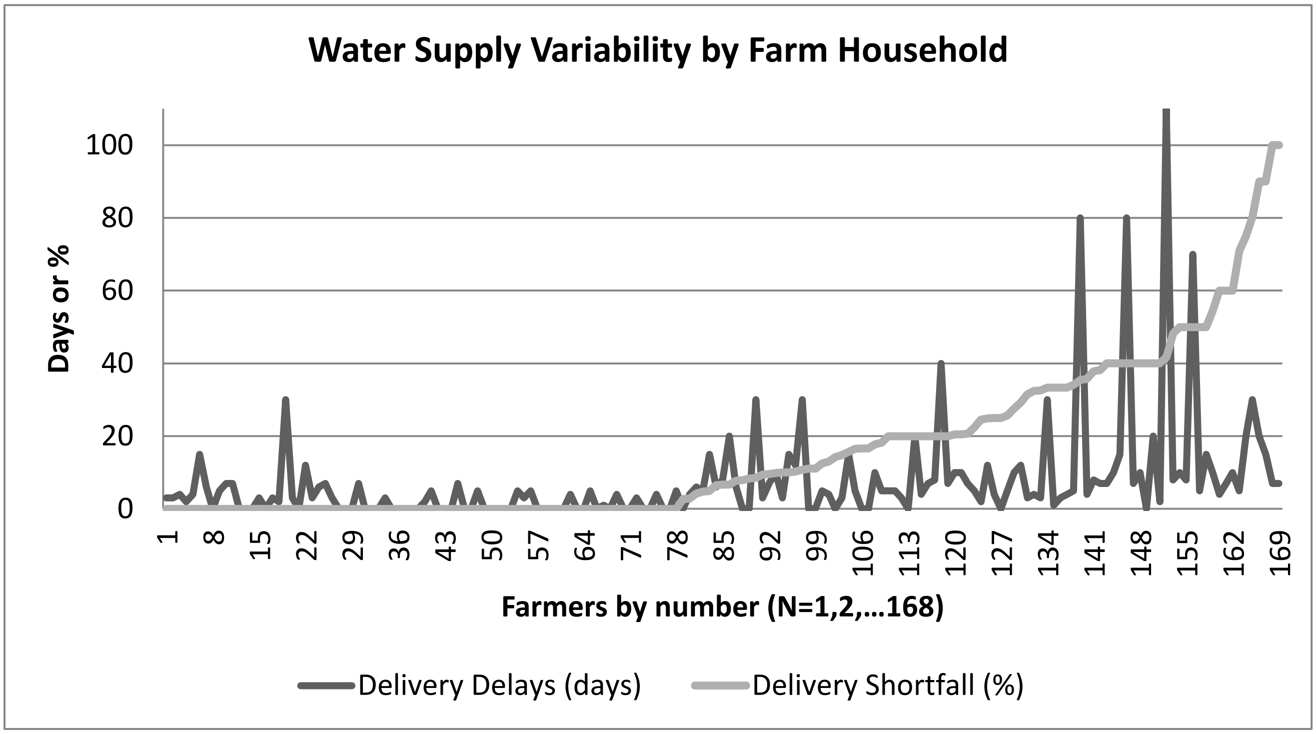
Next, the differences between the delivery shortfall and delay variables are presented at the module and farm levels. The expectation is that differences in water supply variability exist among the irrigation modules, based upon previous findings from the literature that extent of water outages is influenced by proximity to the endpoints of the water distribution canals. In other words, we would expect that tailenders (Modules 21 and 22) are more likely to face problems with water supply variability. Figure 5.9 presents the comparison between mean delivery shortfalls and delivery delays per module (removing modules with not enough data to analyze, or less than 5 farmers representing that module).[14] It is interesting to note that the variables are moderately but not highly correlated; the correlation coefficient at the module-level is 0.64. Therefore, dividing water supply variability into two components based upon volume and timing of irrigation deliveries provides additional information. More noteworthy, however, is to compare the components of water supply variability at the farm scale. Refer to figure 5.10 for a graphical comparison of the additional information gained from separating out water supply variability into two components. The correlation between delivery shortfalls and delivery delays at the individual farmer level is only 0.34. It is clear when comparing figures 5.9 and 5.10 that using aggregated values for water supply variability has a smoothing effect and critical information that may be impacting farmer decision making is lost.

Figure 5.9 Delivery shortfalls versus delivery delays at the module-level



[14] For the delivery shortfall variables, farmers in the survey were specifically asked to differentiate between level of shortfalls in each irrigation module where they had production. Water delivery delay variables are calculated by primary module of the farmer, not based upon module-specific data.

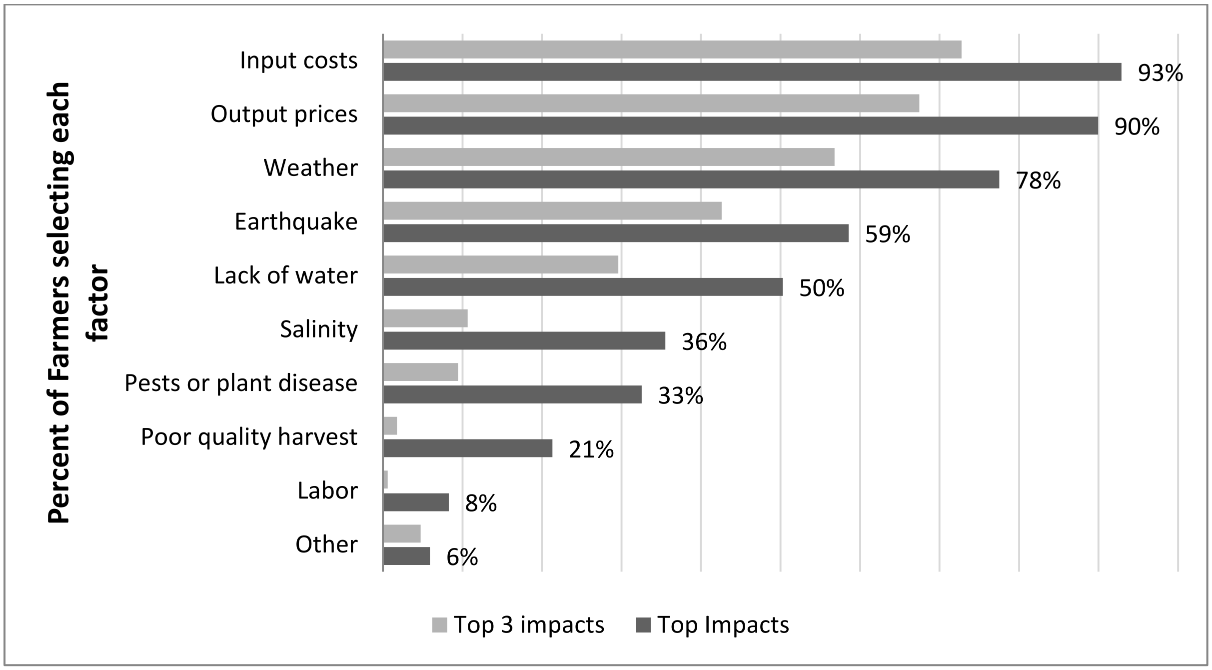
Figure 5.10 Delivery shortfalls versus delivery delays at the farm household level



5.5 Top impacts on farm profitability and common responses to water supply variability, descriptive statistics

This section compares the results on the top impacts on agricultural profitability over the past five years. The benefit of a mixed-methods analysis is the availability of qualitative data that can help explain the regression results. Although the top impacts are not included as variables in the regression models, they provide crucial background information, as farmers are expected to choose risk management strategies based upon which risks they perceive to be highest. The farmers were first asked to select all principal impacts on profitability over the past five years and then to rank them. There was no limit to the number of impacts farmers could select, though the emphasis was placed on only selecting factors that were truly principal impacts. Multiple farmers surveyed expressed difficulties in ranking the impacts, as it was challenging to calculate quickly which impacts (such as the earthquake or low market price) had a bigger financial impact. Therefore, figure 5.11 presents both results – factors *ranking among* *the top 3 impacts* (in light gray) and *all top impacts* (in dark gray). Although the percentage of farmers in each category changes slightly depending upon the method of quantification, the ranking remains nearly the same in both cases.

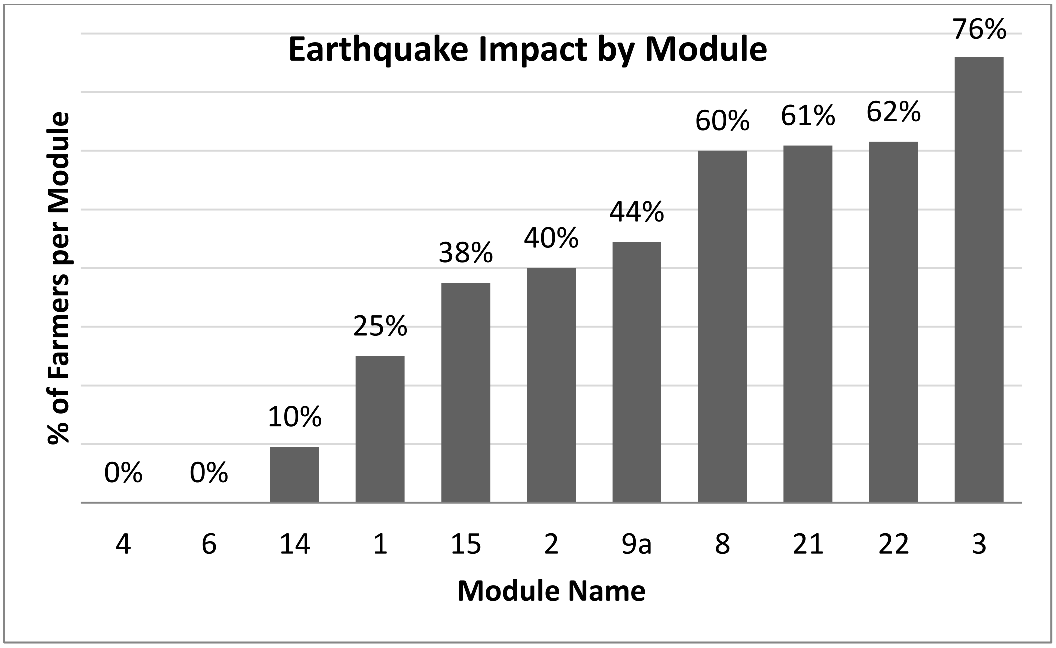
Figure 5.11 Top impacts on agricultural profitability in the past five years



Only 50% of farmers reported that lack of water was among the principal impacts on agricultural profitability and this provides a natural control group, enabling us to assess the response of those who have had recent problems with water compared to those who have not. More specifically, because the irrigation district as a whole is facing uncertainty in future water supplies, it allows us to differentiate between risk management strategies selected for adaptation to *insecure* water supplies and those which are associated with *specific problems* with water supplies.

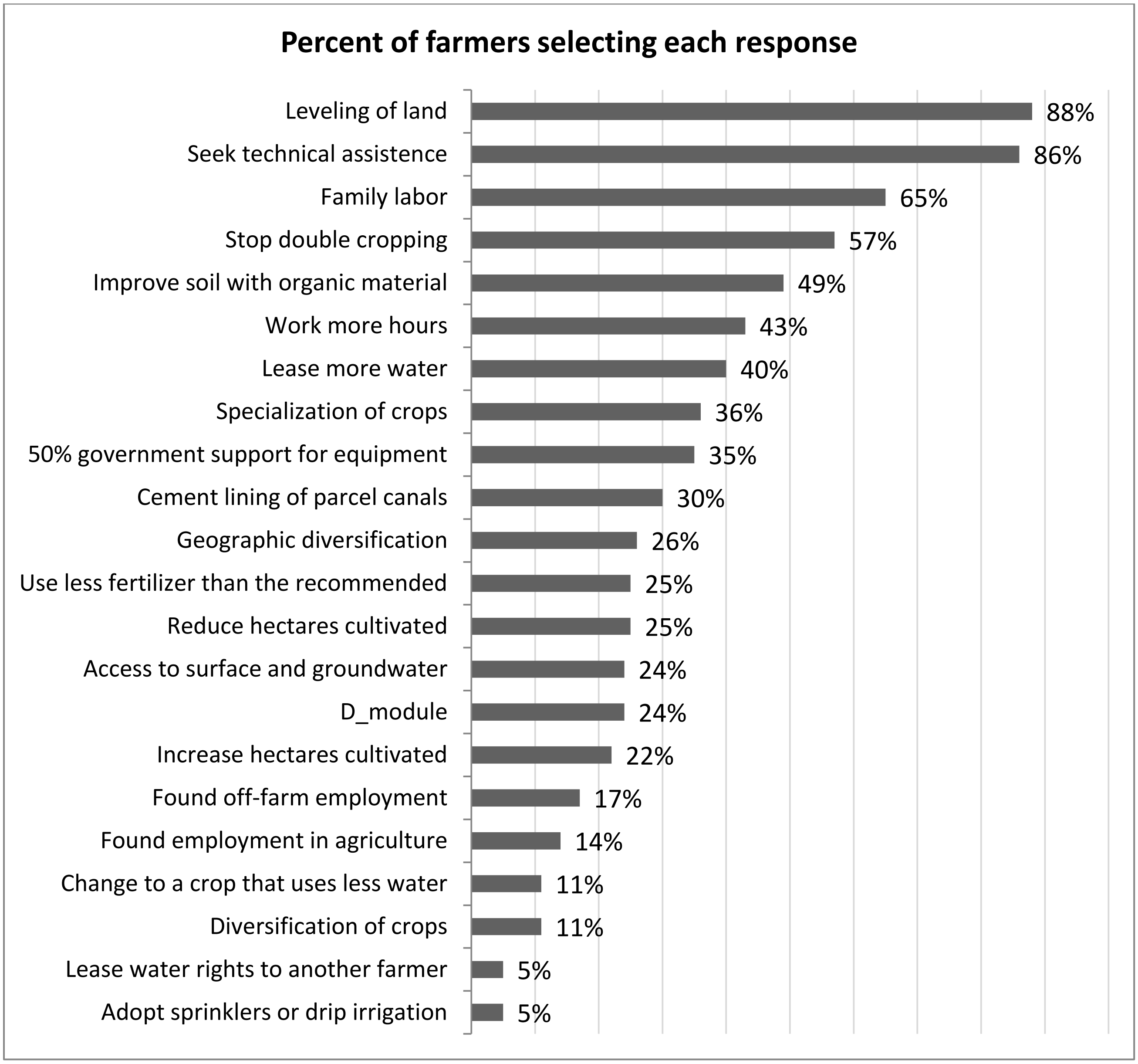
Because risk management literature often emphasizes uncertainty in gross revenues, it is also interesting to see that 93% of farmers ranked rising input costs as the biggest factor impacting profitability. Weather is a general category including weather-based impacts to yields, such as frost, extreme heat, rain, hail, and wind. Water ranks in fifth place. The earthquake itself was a major shock to many farms and water supplies, and 59% of farmers ranked the earthquake as a major impact on agricultural profitability. Aside from the 600 kilometers of canals and drainage ditches destroyed, the earthquake also caused damage to land and equipment. Figure 5.12 shows the differences among irrigation modules and perceived earthquake impact.

Figure 5.12 Percentage of Farmers Ranking Earthquake as a Top Impact



Looking next at the farmer responses to water supply variability and to low profitability in general, figure 5.13 ranks the most common farmer responses by percentage of farmers selecting that response (there was no limit to the number of responses farmers could select). It is worth clarifying that although the survey question was designed to elicit responses to water supply variability, it is challenging for farmers to separate out responses that were only intended to target water-related problems from responses intended to target other issues related to agricultural production. Rather, farmers tend to respond to the cumulative impacts on low profitability for the entire farm system. For instance, 88% of farmers responded to having leveled the majority of their parcels, which improves water use efficiency, which in turn may also be improving profitability. It was not surprising to see this response ranked as the most common response to water supply variability, given that the government supports farmers in leveling their land. Also, farmers mentioned during the surveys that the use of flood irrigation is virtually impossible with unleveled lands. Thus, the surprise is that the percentage was not closer to 100%. In general, the 12% who did not have the majority of lands leveled reported that they have not been able to re-level since the earthquake.

Figure 5.13 Common responses to impacts on agricultural profitability



The list in figure 5.13 includes the wide range of common responses as the whole suite of responses is worth understanding. Although one may assume that in the farmer decision-making process that each risk management strategy is carefully selected, this may not be the case. Rather, some responses may have been imposed by constraints. For instance, a farmer may not decide to stop double cropping because of profit maximization; rather, they stopped double cropping because the irrigation module didn't allow them a permit for the additional crop. Of those farmers who specialized their crop portfolios over the past 10 years, 55% also reported that they have had to stop double cropping due to lack of a permit. The marginal cost of water may also be a factor in decisions regarding double cropping. A survey question asked whether farmers had stopped double cropping in the past five years. A small number of farmers reported that they had never double cropped because the price of water for double cropping was too high. The price of water for the first (the definition of the legal allocation of water) is MXN $9.5/liter and the price of water after that is surpassed is MXN $16/liter. It is worth noting that alfalfa requires more than 117 liters/second/24 hours annually, meaning that farmers also have to pay the higher marginal price or lease water through a transfer to meet the plant-water requirement.

Also, not all responses to water supply variability (and low profitability) increase farm resilience. Seeking technical assistance (a response employed by 86% of farmers surveyed) is likely to increase farm resilience, but irrigating with saline drainage water may be less effective at increasing farm resilience. Irrigating with saline drainage water, a strategy mentioned by 3 farmers in the survey, may not be immediately appear problematic: if large enough volumes of water are available to flush salts, farmers have harvested wheat and sorghum in Mexicali using drainage water for irrigation. However, the large volumes of water needed are not always be available, additional problems can result in areas with poor drainage capacity, and not all crops are salt-tolerant. Thus, saline water can reduce the number of potential crops that can be grown, therefore reducing the ability to diversify crops. Pumping drainage water also uses fuel which increases variable costs and can reduce agricultural net returns.

About half of the farmers reported having added organic material to improve soil quality in the past five years. The act of adding organic material to soil alone says nothing about the soil quality without knowing the frequency of application and the type of organic material applied, it is useful to know that it is a response that farmers are considering as part of their tool set. However, it was more common for farmers to report use of organic material (such as manure) in response to rising input costs rather than in response to water supply variability.

It is noteworthy that 40% of farmers were able to lease additional water permits as a response, as this is considered a highly effective strategy to improve water supply reliability. However, the number is deceptive as it fails to show the number of farmers who wanted to lease additional water but were unable. Mexicali Valley farmers and irrigation managers alike frequently reported anecdotally that they had planned to lease additional water from the water bank but could not. In one meeting with about 30 water managers in March 2012, they reported that the supply available through the water bank was about 33% of the demand this year.

A small number of farmers reported other responses that do not appear in figure 5.13. At times, we can learn as much from outliers and atypical responses as we can from the common responses. For instance, three farmers reported having to decrease the number of hectares devoted to alfalfa due to a lack of water. Two farmers reported having invested in parcel-level drainage ditches to deal with issues of salinity. Six farmers reported leasing out water rights *to* another farmer; one hypothesis is that this is an early sign that a farmer might exit from agricultural production. Two farmers mentioned having invested in green houses, one of which has a personal water storage reservoir in order to have regular flows for his drip irrigation in the greenhouse.[15] Two farmers who depend primarily on groundwater explained that they recently invested in tubing to transport the water from the pump to the field. Only one farmer reported having done a soil analysis to reduce input costs by only applying the necessary fertilizers (in response to our question on what farmers have done to respond to rising input costs).

While the academic risk management literature emphasizes crop diversification, technological innovations and to some extent, geographic diversification, these do not appear as the most common strategies in the Mexicali Valley. Researchers, policy makers, and stakeholders will benefit from understanding the more common responses to low profitability employed by farmers. We assume that farmers are optimizing allocation of resources and therefore, the responses selected are likely to be more economically optimal in their circumstances, except in cases where farmers responses are imposed due to constraints. These

[15] Of the two farmers with greenhouses, one grows flowers and the other grows vegetables.

responses are reflected in other research on agriculture in Mexico, such as Eakin's 2005 study on small-scale farmers and climate risk, where farmers responses includes outmigration, government assistance, seeking off-farm employment, and tapping into resources such as their own labor and seed reserves. Responses will not always be carefully selected risk management strategies, but may be in response to the circumstances and constraints, based upon assets (which can include human capital), or in response to government incentives.

The following chapter presents the econometric regression models, results, and discussion for the three models.

Chapter Six - Econometric Model, Results, and Discussion

6.1 Crop diversification model

The first model, the crop diversification model, was estimated with a linear regression model using ordinary least squares (OLS). The use of OLS tends to be preferred, when possible, due to the desirable and well-established properties of the estimators and the facility of estimation. Further, OLS is appropriate in this case because there is no strong argument for suspecting endogeneity. When using the White test for heteroskedasticity, the chi-square value was 0.03, meaning that heteroskedasticity is a mild problem, though minor enough that OLS is still the preferred method and is used. Also because the issue was minor, we have not corrected for heteroskedasticity in the other two regression models covered in this chapter. We tested for multicollinearity and found that correlation in the explanatory variables is minor as well, and thus is not causing problems in the estimation. The model was estimated using 168 cross-sectional observations. Because of the cross-sectional nature of the data, the results are intended to reveal the general characteristics of farmers who diversify their crop portfolio, rather than implying causality. The results are shown in table 6.1.

The two water supply variables, **delivery shortfall** and **delivery delay**, are of primary interest. Because delivery shortfalls and delivery delays can have impacts on yields, we expect that there may be a positive correlation between the water supply variability and variance in net farm returns. This increased variance in net farm returns was expected to motivate farmers to invest in additional risk management strategies in response to water supply variability. The results present a fascinating finding: while delivery delay is positive and statistically significant, delivery shortfall is not significant. This finding reveals important insights into farmer decision making in response to variability and shows that the *type* of water supply variability matters. Water delivery delays are more likely to be linked to crop diversification than delivery shortfalls. One possibility is that with higher levels of delivery delays, farmers are diversifying into crops that have a higher tolerance to withstand a late irrigation delivery. Another possibility is that crop diversification in response to delivery delays may be for the purpose of expanding crop production into different seasons, with the goal of increasing water supply reliability through changes in seasonal timing of crop production. Or, farmers might not be responding to the magnitude of the delay itself, but instead, the delivery delay variable could be proxying for another unaccounted for attribute of the irrigation module.

Table 6.1 Crop diversification model regression results

Dependent variable=	Change in number of crops over the past 10 years as a %		
Variable	**Parameter Estimate**	**SE**	**Pr > |t|**
Intercept	-1.06**	0.42	0.012
Age	0.0095*	0.0056	0.092
D_Secondary	0.079	0.15	0.61
D_High school	0.24	0.18	0.19
D_College	0.15	0.17	0.38
D_Module management	-0.024	0.13	0.85
Machines	-0.018	0.015	0.23
Cattle	0.000012	0.000081	0.89
Delivery shortfall (%)	-0.0014	0.0028	0.63
Delivery delay (days)	0.012***	0.0043	0.007
Hectares owned	-0.000093	0.00046	0.84
Hectares leased	0.0017***	0.00046	0.0002
D_Other Income	0.16	0.12	0.19
Percent high value	-0.0064+	0.0039	0.10
Members household	0.087**	0.039	0.028
Family labor	-0.039	0.030	0.20
Note: Significant at ***<0.01, **<0.05, *<0.10, +<0.15	**R-square=0.22** **N=168**		

The delivery delay variable also may be representing information. The positive parameter estimate implies that farmers could be basing risk management decisions upon past problems in irrigation deliveries. This result may be related to the definition of delivery delay used – the maximum days late last year – and thus could be revealing a behavior that farmers have that is related to shocks to water supplies. Therefore, beyond risk management, the variable contributes to our understanding of farm resilience. Farmers may reasonably be able to predict a delivery delay of a few days. We could speculate that in certain parts of the district, a delay of up to one month would be unfortunate but not completely unexpected. But for farmers on the upper end of the range – those farmers closest to the maximum from our sample of 110 days late – delays of such magnitudes could not have been predicted and were generally associated with the earthquake. In those cases, the delivery delay variable does represent a shock to the farm system. The higher magnitude of the shock in terms of timing of irrigation deliveries, the more likely the farmer is to have diversified his crop portfolios over the past 10 years. Future studies on risk management, especially those with a focus on resilience, will benefit from including timing variable for irrigation delivery delays, particularly in regions where irrigation depends upon a canal system.

Age is positive and significant, and if age is an additional measurement of information and specifically of expectations, then the result is not surprising. Anecdotal evidence from the farmer surveys revealed comments that the issue in the past was more likely to be flooding than drought. Thus, it is logical that older farmers have greater experience and knowledge regarding the change of water supply reliability over time, and this experience is related to a higher likelihood to diversify crop portfolios.

Hectares leased was the only wealth proxy that is significant. Especially when considering the increasing lease prices for land and water, it is logical that hectares leased represent some aspect of farmer wealth. Additionally, perhaps hectares leased is capturing a set of behaviors unique to the segment of farmers that leases a larger number of hectares. Farm credit tends to go towards the purchase of seeds and inputs, not towards the leasing of land, so the variable might be capturing some aspect of cash flow. Consequently, higher ability to lease land could be associated with higher financial capacity to diversify crops. Next, we test if the delivery delay parameter estimate is larger than the hectares leased parameter. Using a 2-tailed F-test, we find the difference is statistically significant at the 95% level. Therefore, we can say that delivery delay has a bigger impact on crop diversification than hectares leased.

For percent high value, the interpretation of the significance and sign of the parameter estimate is less obvious. Anecdotal evidence showed that farmers involved in vegetable production were more likely to cultivate a larger number of crops, so we had initially expected this parameter estimate to be positive. Yet the estimate is negative and significant at the 10% level. Closer analysis of the descriptive statistics revealed that for farmers growing any high value crops (that is, where percent high value is greater than 0), the mean number of crops in the portfolio in the final period is almost four (3.92 crops). In contrast, the mean number of crops in the portfolio in the final period for those farmers not growing high value crops is close to two (1.7 crops). Therefore, it is true that farmers involved in high value crop production tend to grow a larger number of crops – and these farmers also saw a tendency to *reduce* the number of crops in the crop portfolio during the time period.

In another effort to see if specific crops in the portfolio are related to the decision to diversify or not, we included the percent alfalfa variable in one version of the regression. We had expected that a larger percent of hectares being dedicated to a crop that requires higher volumes of would have a significant impact on the decision to diversify the crop portfolio. However, the parameter estimate was not significant and the variable was removed from the model, and its removal did not lead to a change in sign or significance of any other parameter estimates.

Next, turning to the *members household* and *family labor* variables, it is worth recalling how the survey questions were presented. These two variables were obtained from two separate survey questions, as follows: 1) How many people currently live in your home, including yourself? *and* 2) How many family members work on your farm in a typical year? The interpretation of the significance and sign of parameter estimates for members household is not immediately obvious.[16] At first, one might expect that as the number of members of the household increases that the family labor supply for the farm increases and therefore crop diversification is more likely. However, this explanation is not true, because we control for the number of family members employed on the farm – family labor is negative, though not significant. Therefore, we hypothesize that the members household variable simply proxies some unaccounted for demographic captured by increasing household size.

Moreover, several variables that were expected to be significant are not. Education is considered an information variable and often in adoption models, the number of years of

[16] It is worth noting that these two variables were obtained from two separate survey questions, as follows: 1) How many family members work on your farm in a typical year? and 2) How many people currently live in your home, including yourself?

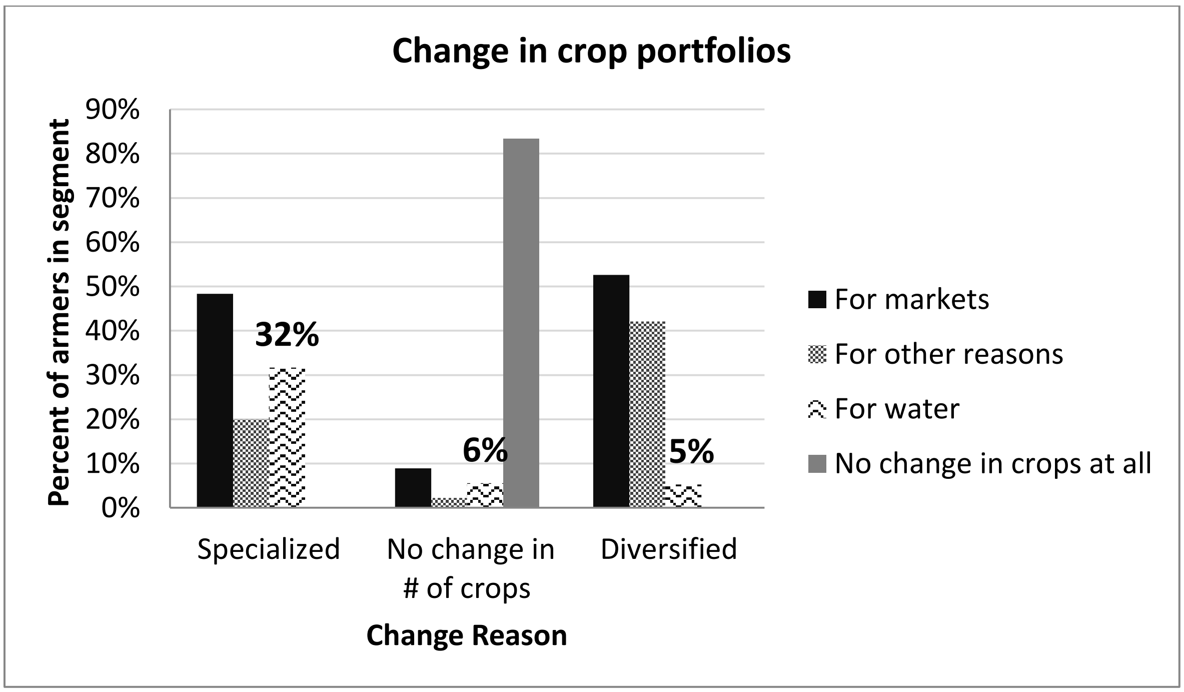
education is positively and significant. The reason for its lack of significance in this model could be due to the measurement of the variable as categorical. A continuous variable rather than a binary variable might have been significant. D_Other Income, machines, and cattle were all expected to be significant, and are not. The lack of significance further highlights the fact that the delivery delay variable is dominating other factors that might normally be significant.

To confirm whether delivery delay had a greater impact than members household or age, we compare using a 2-tailed F-test for each hypothesis. Only in the case of members household was the test significant (weakly at the 89% level). The conclusion is that overall, the delivery delay has a bigger impact on the decision to diversify crops than either hectares leased or members household. This is an interesting result, given the emphasis in past literature on the calculation of the risk aversion coefficient. We are seeing in the crop diversification model that other factors might be important for predicting diversification.

It is useful to recall other factors that can also motivate crop diversification, such as managerial knowledge, crop prices, specialized machinery, and soil type. The benefit of a household survey that presents both quantitative and qualitative questions is that the qualitative answers can further inform the quantitative results. In this case, we asked farmers the reason for any changes in the crop portfolio. The options were either **market-based reasons** (which we defined as problems marketing the crops, low crop prices, or high input prices); **lack of water**; or **other**. Next, we can segment farmers into three categories, which are as follows: 1) Those that specialized over the past 10 years, 2) Those that did not change the total number of crops in the crop portfolio (though in some cases they have changed to a different crop while maintaining the same number of crops), and 3) Those that diversified the crop portfolio over the past 10 years. The most common reason for any changes in the crop portfolio is market-based reasons, as shown in figure 6.1. However, more interesting is that in the segment of farmers who specialized (that is, decreased the number of crops in the crop portfolio over the past 10 years) the percent of farmers whose change reason is "lack of water" is 32%, a notably higher percentage than the other two segment (6 and 5% respectively).

Looking in greater detail at the qualitative data collected during the farmer surveys, we can gain further insights into why the delivery shortfall may not be significant. When asking how farmers responded to past problems with water, 11% reported having switched in the past five years to a crop that consumes less water. The majority of farmers who switched to a crop that consumes less water *did not* change the total number of crops in the crop portfolio. Thus, it is reasonable to hypothesize that farmers experiencing higher levels of delivery shortfalls are more likely to change *type of crop* rather than *number of crops*.

Figure 6.1 Changes in crop portfolio by reason and by segment



6.2 Technology adoption / Cement lining of parcel-level canals models

The two technology adoption models were estimated using a probit model. Probit is the standard model selected when the dependent variable involves binary choice. Similar to the first model, the models analyze 168 cross-sectional units and are intended to show general characteristics of farmers who are more likely to adopt water conserving irrigation technology. The number of farmers adopting sprinkler and drip irrigation is only 5% of the sample and does not allow for a model estimating only that type of technology. Therefore, the first probit regression includes any water conserving technology (canal lining, tubing, sprinklers, *and* drip), and the second model analyzes *only* the 30% of farmers investing in cement lining of parcel-level irrigation ditches. One might expect age and crop experience to be correlated, yet with ρ=0.32, collinearity is not an issue affecting the estimation of the model. Note that we use a dummy for high value crops (D_Highvalue) instead of the percent high value variable used in the prior model. The reasoning behind this decision is that because these adoption models are probit models that analyze the decision to invest or not, and evidence suggests that the behaviors of these farmers are notably different than behaviors of other farmers. Therefore, the presence of any amount of high value crops greater than 0 is more important than the actual percent of high value crops.

The Aldrich-Nelson R-squared (R^2_{AN}) value is presented as one way to measure goodness of fit in a probit regression model, often called a pseudo-R^2. The R^2_{AN} is not a perfect substitute for the R^2 calculated in OLS, though the ease in calculation makes the value an appealing option. Before defining the R^2_{AN}, it is helpful to define the likelihood ratio test statistic, LR=2(I_M-I_0) where I_M is the log likelihood value of the model and I_0 is the log-likelihood for the model where the non-intercept coefficients are restricted to zero. The LR is used to calculate the Aldrich-Nelson R-squared, where R^2_{AN} =LR/(LR + N), where in this model N=1,2,…,168 (Veall and Zimmerman 1994).

For comparison, we also present the log likelihood, percent of correction predictions, and the McKelvey-Zavoina pseudo-R^2. The R^2_{MV} calculation is less common due to the complexity of the calculation, though with the use of SAS's Proc QLIM it is straightforward to obtain this value. The calculation begins with the explained sum of squares (EV) (refer to Veall and Zimmerman 1994 for a more detailed description).

$$EV = \sum_{i=1}^{N} (\hat{Y}_i^* - \overline{Y}^*)^2 ,$$

Where y-hat is the fitted values of the regression and y-bar is as follows:

$$\overline{Y}^* = \frac{1}{N}\sum_{i=1}^{N} Y_i^* = \frac{1}{N}\sum_{i=1}^{N} \hat{Y}_i^*$$

From this, the pseudo-R^2 is calculated as follows:

$$R_{MZ}^2 = \frac{\sum_{i=1}^{N} (\hat{Y}_i^* - \overline{Y}^*)^2}{\sum_{i=1}^{N} (\hat{Y}_I^* - \overline{Y}^*)^2 + V(\varepsilon)}$$

The regression results are presented in table 6.2. The left three columns (not including the variable name) present results from the model which analyzed adoption of any water conserving technology (canal lining, tubing, sprinklers, *and* drip) while the right three columns display results from the model with only the decision to adopt cement lining of irrigation canals. Table 6.3 presents the marginal effects for the two models.

The marginal effects for the continuous variables were calculated by evaluating the marginal effect at the median values for the explanatory variables. The marginal effect of variable *i* is equal to $x'\hat{\beta}$ evaluated at the probability density function for the normal distribution multiplied by $\hat{\beta}_i$, or $ME_i = \varphi(x'\hat{\beta})\hat{\beta}_i$. The marginal effects for the dummy variables were calculated as follows: 1) calculate the fitted value (that is, $x'\hat{\beta}$) for the dummy value=0 and evaluate the cumulative density function (CDF) at that point; 2) calculate the fitted value (that is, $x'\hat{\beta}$) for the dummy value=1 and evaluate the CDF at that point; 3) Take the value obtained in step 2 and subtract from it the value obtained in step 1.

Table 6.2 Water conserving technology adoption model regression results

	Any technology			*Cement lining of canals*		
Parameter	**Estimate**	**SE**	**Pr > ChiSq**	**Estimate**	**SE**	**Pr > ChiSq**
Intercept	-2.48***	0.93	0.0073	-2.14**	0.91	0.019
Age	0.0058	0.014	0.67	0.0054	0.014	0.69
Crop experience	0.016***	0.0059	0.0072	0.014**	0.006	0.012
D_Secondary	0.25	0.38	0.51	0.22	0.37	0.55
D_High_school	0.91**	0.43	0.035	0.69*	0.42	0.10
D_College	0.70*	0.40	0.083	0.53	0.39	0.17
D_Module management	0.64**	0.28	0.022	0.71***	0.27	0.0078
Machines	-0.045	0.038	0.24	-0.015	0.037	0.68
Cattle	0.00007	0.0011	0.95	0.00081	0.005	0.88
Delivery shortfall (%)	0.015**	0.0062	0.013	0.015**	0.0062	0.013
Delivery delay (days)	-0.036**	0.012	0.0022	-0.048**	0.018	0.0083
Hectares owned	0.0055*	0.0032	0.086	-0.0021+	0.0014	0.13
Hectares leased	0.0012	0.0012	0.31	0.00093	0.0011	0.40
Percent alfalfa	0.019***	0.0068	0.0046	0.022***	0.0066	0.0008
D_highvalue	2.57***	0.71	0.00030	-0.36	0.61	0.56
D_Other Income	0.35	0.28	0.21	0.33	0.27	0.23
Note: Significant at ***<0.01, **<0.05, *<0.10, +<0.15 **n=168**	Log likelihood= -74.3587 $R^2_{(AN)}$= 0.29 $R^2_{(MZ)}$= 0.70 Correct prediction= 76.8%			Log likelihood= -76.07 $R^2_{(AN)}$= 0.24 $R^2_{(MZ)}$= 0.54 Correct prediction= 79.2%		

The standard errors of the marginal effects are calculated using the delta method. The partial derivative of the marginal effects are taken for each parameter including the intercept (j=1,2…16) and inserted into a matrix we call G. That is, we take the partial derivative of each marginal effect I (where $ME_i = \varphi(x'\hat{\beta})\hat{\beta}_i$) with respect to each parameter, resulting in a 16x16 matrix G. The general equation for the partial derivative of the i^{th} marginal effect with respect to the j^{th} parameter is as follows:

$$\frac{\delta ME_i}{\delta \beta_j} = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}(\beta_0+\beta_1 x_1+\ldots+\beta_{16}x_{16})^2} \beta_i \cdot -(\beta_0 + \beta_1 x_1 + \cdots + \beta_{16} x_{16}) \cdot x_j$$

The covariance matrix for the parameters is obtained from SAS's Proc QLIM and that matrix is named V($\hat{\beta}$). The next step is to calculate the variance of the marginal effects by multiplying the following matrices: V(ME) = G V($\hat{\beta}$) G'. The square root of the diagonal of this matrix is the standard errors of each of the marginal effects, presented in table 6.3.

Table 6.3 Marginal effects and standard errors for canal lining model

	Cement lining of canals		
Variable Name	**Marginal Effect**	**SE of ME**	***p-value***
Age	0.0022	0.0020	0.27
Crop experience	0.0057***	0.0014	0.0000
D_Secondary	0.040	0.047	0.40
D_High_school	0.16***	0.046	0.0005
D_College	0.12***	0.040	0.0043
D_Module management	0.17***	0.060	0.0051
Machines	-0.0061	0.0058	0.30
Cattle	0.00032	0.0008	0.69
Delivery shortfall (%)	0.0061***	0.0012	0.0000
Delivery delay (days)	-0.019***	0.0044	0.0000
Hectares owned	-0.00084***	0.0003	0.0007
Hectares leased	0.00037**	0.0002	0.044
Percent alfalfa	0.0088***	0.0018	0.0000
D_highvalue	-0.043	0.10	0.68
D_Other Income	0.040	0.056	0.48
Note: Significant at ***<0.01, **<0.05, *<0.10, +<0.15			

In table 6.2 one can observe that the sign and level of significance of parameters in both models are quite similar. The striking exception is the dummy for high value crops, which is only significant in the model that includes all technology. Drip and sprinkler systems are highly linked to vegetable production, as 89% of farmers with those irrigation systems cultivate at least some acreage in high value crops. Compare that to those who only have invested in cement lining of parcel-level irrigation ditches, just 4% cultivate at least some acreage in high value crops, and only 2% of the sample who has no improved irrigation technology have any high value crop production. This is no surprise, as it was common to hear during the surveys that only farmers with vegetable production can afford sprinklers or drip irrigation.

Hectares owned, a proxy for wealth, is significant and positive in the first model while it is negative in the canal lining model. Hectares owned was expected to be positive in both models. However, in the second model the negative parameter was an unexpected result, as we had predicted that land ownership would be positively associated with canal lining, giving that it is a long-term investment in infrastructure. The remaining discussion focuses entirely on the second model, cement lining of canals. Moreover, the discussion is focused on the marginal effects, as the value is a more accurate representation of the marginal change associated with each variable.

Crop experience is positive and significant in explaining canal lining, and this likely represents aspects of information, learning, *and* intensity of production. High school and college education also could be representing information, and are significant and positive factors in adoption. These results are intuitive and consistent with results from past studies indicating that information is a significant factor in the adoption of risk management strategies.

And similar to the crop diversification, the water supply variability variables are useful predictors for adoptions. However, a key difference is seen. Whereas the delivery delay was significant and positive in the crop diversification model, we see nearly the opposite with cement lining of canals. Delivery shortfall is now significant and positive, while the delivery delay is significant and negative. This result points to the possibility that farmers may select crop diversification in response to irrigation delivery *delays*, and water conserving technology adoption for irrigation delivery *shortfalls.* The canal lining result is particularly intuitive, as one would expect that farmers will invest in water conservation in response to delivery shortfall. As hypothesized, farmers will want to increase output per unit input under delivery shortfall. Although these results are logical, it is uncommon to see the use of both irrigation delivery delays and volume variables in an assessment of risk management strategies.

Another interesting result is that hectares leased has a positive relation with canal lining. One possible a priori expectation was that the sign might be negative (or insignificant), as there is no incentive to invest in infrastructure for leased lands. Therefore, hectares leased is likely proxying for wealth. The positive sign is logical as it represents a farm household's financial ability to invest in canal lining. Machines owned, another proxy for wealth, is insignificant. The fact that hectares leased is the only wealth proxy which is significant and positive (with a similar result in the crop diversification model as well) may be revealing that that hectares leased is a more appropriate proxy for ability to invest. As discussed in the crop diversification model, the variable may also be capturing a characteristic related to positive cash flow.

The expected sign of the social capital variable, D_Module management, had been ambiguous prior to running the regression. The positive and significant parameter estimate indicate that the second hypothesis was correct: having an elected position on the board of directors or being an employee of the irrigation module is associated with easier access to government programs and irrigation module machinery for constructing the canals. Independent of delivery delays and shortfalls, a farmer may be interested in cement lining of parcel-level canals for a variety of reasons. The lining of canals can increase the flow rate, which in turn can allow the farmer to complete the irrigation run faster. This not only improves irrigation efficiency but can also lead to lower costs, especially if the farmer is payer an irrigator an hourly wage. The lining of canals also saves in labor costs because dirt canals must be manually reconstructed after irrigation in areas where the canal walls collapse. In general, lined canals are considered desirable regardless of level of reliability in irrigation deliveries.

The Percent alfalfa variable is also highly significant and positive, confirming our hypothesis that cultivating more hectares of a crop that uses large volumes of water is associated with a higher likelihood of investing in cement lining of canals. However, it is worth noting that the marginal effect of both delivery shortfall and percent alfalfa varies across the sample. When all 168 individual farm household marginal effects for the delivery shortfall and percent alfalfa variables are plotted in figures 6.2 and 6.3, they demonstrate that examining the effect at the extremes yields different interpretations.

Figure 6.2 Individual marginal effects for delivery shortfall

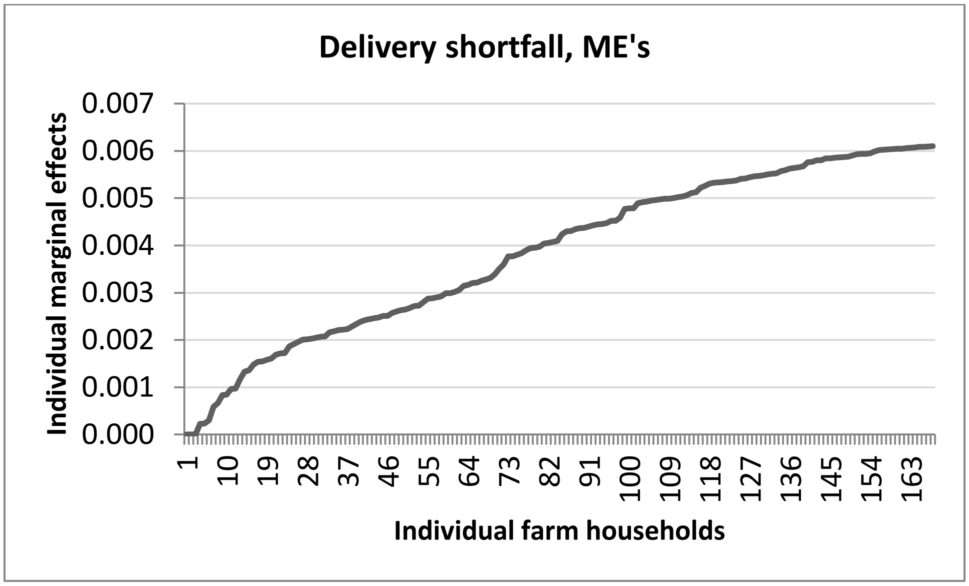
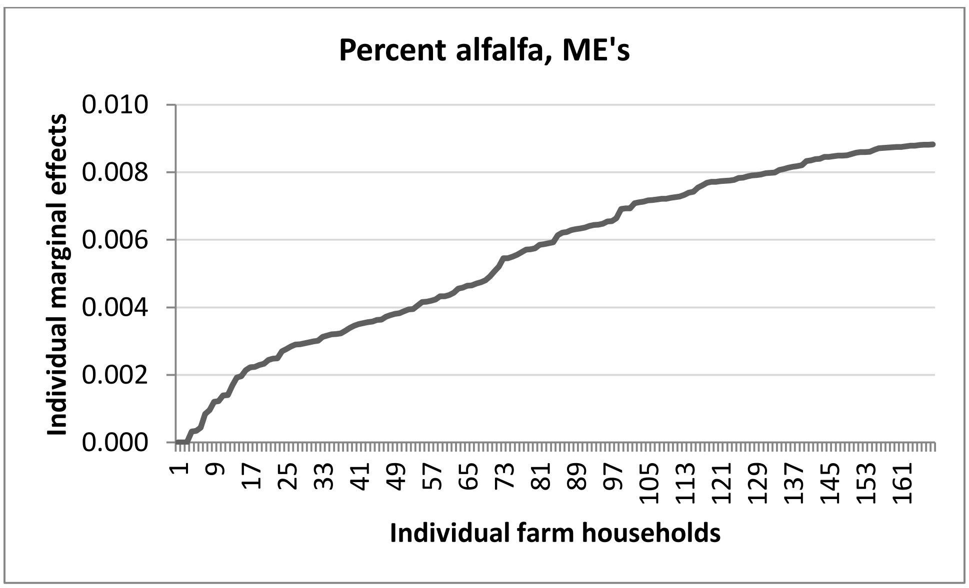


Figure 6.3 Individual marginal effects for percent alfalfa



Surprisingly, the dummy for other income is not significant, as one would have expected that additional income sources would provide greater amounts of resources to invest in agriculture. The sign was not negative, precluding the possibility that off-farm income is associated with the process of beginning to exit from agricultural production, and farmers would be less likely to invest in agriculture. It is possible that using a continuous variable would have been significant, and that the use of the binary variable did not provide enough variation.

Given the role of government assistance in canal lining, we expected that the Sonoran government might be providing difference types of assistance than the Baja California government. Therefore, a state dummy was added to our initial regression model, where D_Sonora=1 for modules 1, 2, and 3. However, the variable was highly insignificant and did not affect any other parameters in the model, so the variable was not included in the final regression.

Other variables were tested in different versions of the cement lining of parcel-level canals model but did not come up as significant. For instance, we tested a couple of variables to account for average age of tractors, including a dummy for average age equaling 4 years old or newer, and also a ratio of number of tractors to average age.[17] In addition, a dummy variable for farmers who listed earthquake as a major impact on agricultural profitability in the past five years was included. However, these parameter estimates were not significant and did not affect the significance or sign of any other variables in the modules, and thus were removed.

In summary, the results demonstrate that information, wealth, and past experience all play a role in investment in cement lining of parcel-level canals. Crop experience (and intensity), high school and college education, delivery shortfall, the dummy for module management, hectares leased, and the percent of alfalfa grown have a positive impact on adoption. Also, the evidence from the crop diversification and canal lining models shows that the type of water supply variability – delivery delays or shortfalls – has different outcomes in terms of adoption of risk management strategies.

[17] We were unable to include the average age of tractors itself as a variable. For farmers who own tractors, the average age is inversely proportionate to value of tractors and thus (indirectly) inversely related to wealth. Yet farmers who have no tractors will have zero listed as the average age. This would lead to a convoluted parameter estimate, since a decreasing average age (approaching 1) is related to higher value of assets but an average age of zero is a low value of assets.

6.3 Geographical Diversification Model

Table 6.4 Geographic diversification model Poisson regression results

Dependent variable=	**# of irrigation modules in which farmers are cultivating *beyond* their primary module**		
Parameter	**Estimate**	**SE**	**Pr > ChiSq**
Intercept	-0.99	0.90	0.27
Age	0.0040	0.013	0.76
Crop experience	-0.0029	0.0080	0.72
D_Secondary	-0.59+	0.406	0.15
D_High school	-0.63	0.46	0.18
D_College	0.049	0.39	0.90
D_Module management	-1.17***	0.41	0.0043
Machines	0.11***	0.022	<.0001
Cattle	-0.00050***	0.00010	<.0001
Hectares owned	0.0032***	0.0010	0.0021
Hectares leased	0.0029***	0.00060	<.0001
# of crops in crop portfolio	-0.21	0.15	0.16
Delivery shortfall (%)	-0.0049	0.0069	0.48
Delivery delay (days)	0.0022	0.011	0.84
D_Earthquake	-0.33	0.27	0.22
Note: Significant at ***<0.01, **<0.05, *<0.10, +<0.15	**N= 168**	**Log-likelihood=** -86.59 **Full Log-likelihood** = -117.43	

The geographic diversification model was estimated using a Poisson regression, which involves maximum likelihood estimation with a Poisson distribution. Again, the number of observations is equal to 168 cross sectional units. Poisson regressions are also referred to as count models and are the standard type of regression model to use when the dependent variable is a non-negative integer, staring with zero, where y_i=0,1,2….(Greene 2012, 803). The dependent variable is the number of additional modules in which the farmers cultivate land, beyond their primary module, where y = 0, 1,..6. The goal for this regression is to provide insights into which factors are motivating geographic diversification, with less emphasis on the magnitude of those factors. Thus, we highlight the significance and sign and not the marginal effects.

A common test in Poisson models is the likelihood ratio test of over-dispersion. This test is to confirm that the equidispersion condition for using the Poisson model holds true, where equidispersion means that the conditional mean and variance are equal. The test is conducted through the calculation of the log-likelihood of the Poisson and negative binomial models. The negative binomial model is selected because it is a model that can handle conditional mean and variance that are unequal. The test is $LR=2*(\ln L_{NB}-\ln L_{Poisson})$~chi-square. For our models, we obtain LR=2(-86.59- -86.59)=0. Thus we can conclude that the negative binomial model is not a statistical improvement over the Poisson model and we proceed with the Poisson.

The results are presented in table 6.4. Given the focus in this thesis research on farm response to shocks, with an emphasis on farmer response to the April 2010 earthquake, we expected that the earthquake dummy would be significant. A farmer who cannot cultivate due to destroyed canals will likely seek land for lease in other areas. Yet, D_Earthquake is not significant. Perhaps the biggest reason is that desire and ability are two different aspects: a farmer may desire to lease additional hectares in a different irrigation module but may not have the financial ability. Rather, the earthquake may have resulted in additional expenses which reduce the ability to lease additional hectares– having to level the land again, repair cracked walls in the house, and the expenses associated with any earthquake-related losses in crop yields. Therefore, considering the confounding potential for the parameter to have either a positive impact or a negative impact, then it is no longer surprising that D_Earthquake is insignificant.

As expected, number of hectares leased is highly significant and positive. Farmers who lease a larger number of hectares are likely to have greater flexibility in the short-run to vary the location of the parcels which they lease. The number of machines and number of hectares owned are also positive and significant, serving as proxies for wealth. As proxies for wealth, they likely increase the *capacity* that a farmer has to invest in geographic diversification. The number of cattle is significant and negative. One possible reason is that cattle are costly to transport, thus disincentivizing geographic diversification; another possibility is that the geographic diversification and diversification of agricultural income to include cattle are substitute risk management strategies.

Also as expected, D_Module management is negative and significant. Such an outcome is intuitively gratifying on multiple levels. One might expect that farmers would have, in general, higher reliability in irrigation deliveries with greater involvement in the management of the irrigation module office. Also, there may be greater loyalty given higher levels of involvement in the irrigation module, leading to a greater likelihood that the farmer has land only in their primary module. In addition, farmers who are active in the module may spend more time at the irrigation module office and find it lower cost to cultivate in the same region where they spend more time.

One small change in the variables in the geographic diversification model is the use of the "# of crops in the crop portfolio" as a variable instead of the percent high value variable. The reason was two-fold. First, the inclusion of the variable was motivated by the 2003 study by Wilson and Thompson that found number of crops in the portfolio to be a positive influence on diversification. Second, we ran the regression with the percent high value variable and found it to be insignificant, and its removal did not change the sign or significance of any other variables. Thus, it was appropriate to include "# of crops in the crop portfolio" as a variable with more explanatory power. Yet unlike the previous study, in this model the sign is negative. The reason may simply be that the Wilson and Thompson study had number of months in a year as the dependent variable, not number of additional modules in the irrigation district.

Delivery shortfall and delivery delay are not significant and there are several potential reasons why this might be the case. First and foremost, the signs are confounded by the fact that farmers whose primary module has minimal problems with water supply variability will see an increase in variability through geographic diversification, while farmers with a primary module with high levels of water supply variability will see a decrease. The lack of significance of the delivery shortfall and delivery delay variables serves to highlight the mixed results that can arise from geographic diversification as a risk management strategy where substantial constraints exist on the land available.

Several irrigation managers mentioned that since the Easter earthquake destroyed canals in April 2010, and because the canals in Modules 10, 11 and 12 are still not fully reconstructed, many of those farmers are renting land in other modules. The government has been paying farmers who have been unable to cultivate since the earthquake a value of MXN $7,500/hectare for their water rights that would otherwise go unused. The cost of renting land and water rights ranges across the district from around MXN $3,000-$5,000 per hectare for less desirable land to $12,000-$15,000 per hectare for the best quality soils. Thus, it is plausible that farmers receiving the MXN $7,500 could offer more than the MXN $3,000-$5,000 that farmers were receiving in the past for renting their land, driving up land prices. The land shortage itself is also probably leading to the increase land prices. Indeed, several farmers who ranked "rising input costs" as a top impact on agricultural profitability in the past five years cited that rising rental costs of land was a large factor. Also, it is plausible that given high levels of competition for scarce resources, a farmer might have to settle for a lower quality soil or a less reliable irrigation module when renting land. A dummy variable for farmers who listed earthquake as a major impact on agricultural profitability in the past five years was included in one version of the regression model as a variable. The expected sign was positive, as we expected that earthquake might have been a motivation for leasing more hectares in another module. However, the parameter was not significant and did not affect the significance or sign of any other variables in the modules, and thus was removed.

The geographic diversification regression could provide greater insights if panel data were available, which would allow researchers to analyze whether geographic diversification on average resulted in higher or lower water supply variability from one time period to another. Nonetheless, these cross-sectional results are valuable for providing greater insights into the complexity of geographic diversification in a region with incredibly strong constraints on land resources. In addition, they reaffirm the hypothesis that the existence of an active market for land leases is a large factor in geographic diversification. The also show that wealth may have a positive influence on diversification and that D_Module management has a negative impact on geographic diversification.

Chapter Seven - Conclusions, Implications, and Future Work

7.1 General discussion and conclusions

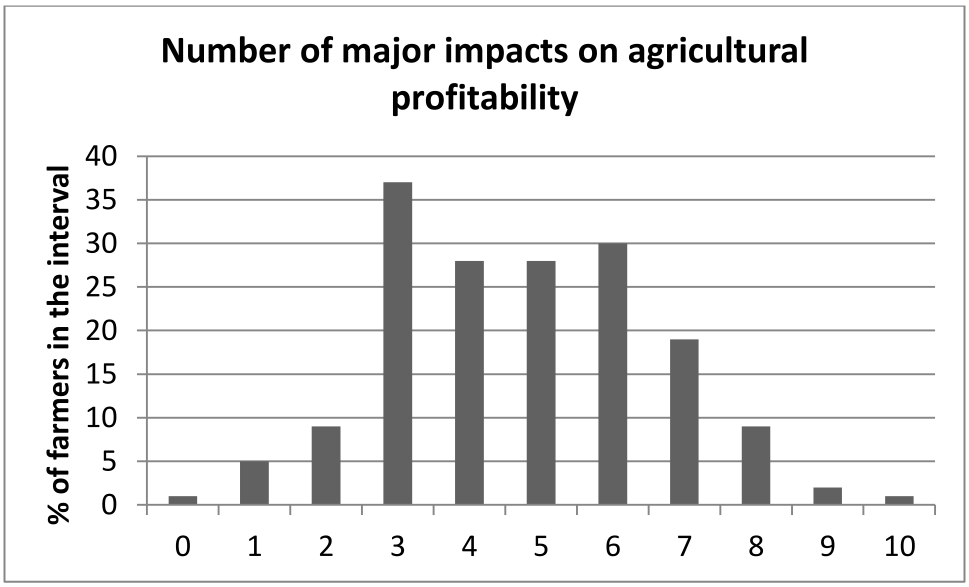
Many categories of conclusions have resulted from this 2-year research project. Our general understanding of risk management and the farmer decision-making process has increased. For instance, qualitative results revealed that within a small geographic region, the type of shocks and stresses that impact farm profitability is heterogeneous. Because farmers will make different decisions on risk management strategies dependent upon which risks these farmers are managing for, controlling for past impacts on profitability is important. Noteworthy is the role of uncertainty in irrigation water supply with respect to timing and volume delivered. Anecdotal evidence as well as quantitative data on delivery delays and shortfalls indicates that unreliable irrigation has a direct impact on yields and consequently on profitability. This contribution is significant in the literature on risk management as uncertainty in irrigation deliveries is rarely documented in a quantitative form focusing on *actual past events at the farm level* and the extent of both *delays and shortfalls in irrigation deliveries*. This research also contributes to the climate change and adaptation literature, where it is often predicted that water available for irrigation may have to decrease in the future and much speculation exists on how farmers would respond. In the Mexicali Valley we have a case study where uncertainty already exists in water available for irrigation, and we can observe how farmers are adapting currently.

An additional contribution related to uncertainty is in reference to rising input costs. The assumption often seen in expected utility models in the risk management literature is that input costs are known at the time cropping decisions are made. Yet our study shows reveals two trends. First, farmers report that input costs have been the single biggest negative impact on agricultural profitability in the Mexicali Valley in the past five years. Second, farmers mentioned in comments during interviews that input costs were rising each month *after* crops were planted, meaning that input costs cannot be assumed to be known when decisions are made at the beginning of a crop production cycle. Stakeholders interested in designing programs to support farmers will benefit from understanding that increasing costs are a key concern of farmers in the Mexicali Valley.

Also, evidence from the surveys shows that the full suite of farmer responses to water supply variability is much wider than the traditional risk management strategies often presented in the literature. It is useful to understand our targeted strategies (crop diversification and cement lining of canals) in the context of the full range of strategies from which farmers are selecting. Understanding which responses are typical at the farm level allows policy makers to use this information to design better incentives. These incentives can lead to higher levels of adoption for strategies that reduce agricultural water use, leading to higher levels of regional water supply reliability. As an example, farmers are clearly interested in technical assistance, with 86% of farmers having sought technical assistance in the past five years. However, many farmers reported that the technical assistance comes from the same company that finances their wheat or cotton input costs. Thus, it is reasonable to think that farmers may be interested in a wider range of options or greater frequency of technical assistance. If the government or another organization were interested in promoting adoption of water conserving technologies, farmers may respond positively to incentives that increased their access to technical assistance.

Next, we focus on our combined risk management and farm resilience framework which can serve as a model for future research. Recall that risk management focuses on the *strategies* of farmers and that farm resilience emphasizes the *ability* of a farm household to recover from shocks and stresses. Thus, under a risk management framework, the biggest impacts on agricultural profitability are expected to influence which risk management strategies are chosen. Under a farm resilience framework, negative impacts on agricultural profitability will impact the financial situation of the farm household and may decrease the ability of a farm household to recover from a shock. The primary data collection process used in this research, based upon farm household surveys and past responses to water supply variability, is a useful method for looking at the combined roles of risk management and farm resilience. By focusing on actual events from the recent past, we gain greater insights into future farm resilience and how farmers are likely to respond to future impacts on their water supply. Also, we expect that a farmer's capacity to respond decreases after each major negative impact on profitability, as the farmer is likely to tap into financial reserves after each event. The farmers in our sample ranged from experiencing zero impacts on profitability in the past five years to experiencing 10 impacts, as shown in the histogram presented in figure 7.1. Understanding the number of events impacting farm profitability contributes to our understanding of farm resilience in the Mexicali Valley.

Figure 7.1 Number of major impacts on agricultural profitability



In addition, it was mentioned in section 2.6 of chapter 2 that the presence of certain responses may be a good indication of farm resilience. We can find several examples of critical responses from the survey data. One example is with the leveling of land – because leveling of land is considered necessary for flood irrigation, the 12% of farmers who do not have the majority of their land leveled may have a lower level of farm resilience. That is, inability to re-level their lands after the earthquake implies a lack of ability to respond to a shock. Also, a quarter of farmers in the survey responded that to reduce input costs and in response to low profitability, they had applied less fertilizer than the recommended amount in the past five years. Yet these farmers are likely to have lower yields and lower profitability. Although using only slightly less fertilizer than required will not necessarily lead to lower profitability, there does exist a threshold, beyond which the low fertilizer application can lead to significant losses in yields. Therefore, using less fertilizer than recommended is another example of a critical response that can give information about farm resilience and vulnerability. In contrast, diversification of crops is likely to increase farm resilience, and the presence of a diversified crop portfolio could be an indication that a farm is more resilient, all else equal.

An additional contribution to our understanding of farm resilience is in regards to household wellbeing. At the start of this research, the author hypothesized about methods for quantifying a wellbeing threshold to measure farm resilience – or rather, to measure a lack thereof. Crossing over this wellbeing threshold, if farm households were unable to respond to a shock, will lead to low levels of household wellbeing. An inability to respond to a shock runs the risk of propelling a household into what Banerjee and Duflo (2011) call the poverty trap zone. However, field research made it clear that it would not be possible to quantify a region-wide wellbeing threshold. Qualitative interviews with five farmers in the Mexicali Valley who had gone out of business revealed that it was rarely one single event or moment that sends a farm below this theoretical threshold. Rather, for one farmer it was a mixture of an injury, water shortage, and old age; for another farmer, it was a mixture of debt and rising input costs. Thus, although the five surveys are not statistically significant, they provide insights into the wide range of circumstances that can lead to exiting agriculture, implying that it is unrealistic to think that a single, quantifiable threshold might exist.

One of the principal research questions presented in the beginning of this thesis was whether water conserving risk management strategies such as crop diversification is economically feasible. Great debate surrounds the question of whether the trend is towards greater specialization or diversification with respect to the number of crops in an agricultural portfolio. If farmers in the Mexicali Valley were all trending towards greater specialization, we could infer that crop diversification may not be feasible in this region. Yet, our results show that diversification *is* occurring among farmers in the Mexicali Valley, based upon the fact that a notable percentage of farmers have diversified crop portfolios in the past ten years. The explanatory power of the crop diversification regression model is not high, given that it is not possible to include as variables the whole range of market-based reasons for diversifying crop portfolios. The value of the crop diversification model is in the key variables that are significant and contribute to our understanding of decision-making processes. In particular, crop diversification is positively related to delivery delay and hectares leased. The implication for regional water supply reliability is that introduction of a crop that consumes less water should be considered if water supplies are further constrained. Technical assistance related to economic and agronomic aspects of producing alternative crops would be useful if this strategy is pursued.

Crop diversification, as defined by a change in the *number of crops* in the crop portfolio, is not the only way to assess whether farmers are changing the specific crops which they cultivate. Farmers might be changing their crop mixes without changing the number of crops in the portfolio. The percent of farmers in the entire sample who reported switching to a crop that has a lower consumptive use of water in response to water supply variability in the past five years is 11%. Yet, only three farmers surveyed chose to diversify their crop portfolio *and also* switched to a crop that has a lower consumptive use of water. This implies that the two responses are different strategies. Further, there is a third strategy: 9% of farmers did not diversify and did not switch to another crop that consumes less water, but *did* change the crops they grow over the past 10 years. Therefore, only looking at crop diversification – that is, the number of crops grown – paints an incomplete picture. When assessing a wider range of strategies related to which crops farmers are growing in the Mexicali Valley, we observe an even greater variety in the crops grown by farmers each year.

Cement lining of parcel-level irrigation canals was also found to be economically feasible at the farm level under certain circumstances. Adoption was positively related to many variables including crop experience, delivery shortfall, high school and college education, percent of hectares dedicated to alfalfa, and social capital (D_Module management, as measured by involvement in the irrigation module). The fact that delivery shortfall was positively related to adoption is consistent with other studies which conclude that investing in irrigation technology is a form of self-insurance. Canal lining was negatively related to delivery delay, which could mean that the common response to delivery delay is crop diversification, not canal lining. Adoption of pressurized irrigation systems such as drip irrigation and sprinkler systems is concluded to be less cost effective for the average farmer given the extremely low rates of adoption, and is associated primarily with vegetable production. Overall, the cement lining of parcel-level canals had a stronger explanatory power than the other two models, with correct predictions at 80% and a large number of marginal effects significant.

Geographic diversification, although not expected to reduce consumptive use of water at the farm level, was explored as an alternate risk management strategy to address water supply variability. Results from the regression are inconclusive. Given the cross-sectional nature of the data, it was not clear whether on average geographic diversification increases or decreases farm-level water supply variability. Geographic diversification is positively related to the number of hectares leased, as expected, and also to the quantity of agricultural machinery owned and hectares owned (proxies for wealth). In contrast, farmers who are more active in the management of their primary irrigation module are less likely to have diversified geographically. The main contribution of this model to the literature is the identification of a few key variables that are significant and should be considered when assessing geographic diversification as a risk management strategy. Future work on geographic diversification should include panel data, allowing for a dynamic analysis.

Next, this research provided conclusions on the nature of water supply variability. Dividing water supply variability into two different components – delivery shortfall and delivery delays – was found to be important. That is, an increase in delivery shortfall was associated with a different risk management strategy than an increase in delivery delays. The delivery shortfall variable was related to higher rates of adoption of cement lining of parcel-level canals. This result was not a surprise, as one would expect that when facing constraints on the volume of water available, farmers might seek strategies to increase crop output per same unit of input of water. Delivery delay was related to greater likelihood to diversify crop portfolios. This could be linked to a desire to take advantage of seasonal differences in crop planting and harvesting or to the addition of crops which are more tolerant of delays.

The use of delivery delay (measured as the maximum days late water was delivered last year) and delivery shortfall (as a percentage of total irrigations) is simply one way to measure the multiple components of water supply variability. The high levels of significance of both variables lead us to believe that other variables that quantify water supply variability might also work. Future work might experiment with *average* days late of irrigation deliveries, water supply variability over time, or other measurements of variability in irrigation supplies. It is important to note that the variable for delivery shortfalls resulting in plant water stress was not significant in prediction risk management strategies analyzed in the three econometric models. The lack of significance points to the fact that farmers are making decisions based upon any level of delivery shortfall, not just those resulting in water stress.

It is also intriguing to note that, regardless of various wealth proxies, farmers found ways to afford investment in the face of sufficient problems. That is, in the crop diversification model, delivery delay dominated the effect of nearly every other variable in terms of magnitude and significance. In the cement lining of canals model, delivery shortfall and percent alfalfa had the largest impact on adoption. These findings suggest that water supply variability may be more important in explaining on-farm irrigation management choices than information, education, and wealth variables.

7.2 Policy implications

The key water conserving investments of interest in this study were crop diversification with the potential to add a crop with a lower consumptive use of water to the crop portfolios and cement-lining of parcel-level canals. The survey data shows that both options are currently being adopted in the Mexicali Valley, implying that they are feasible options for responding to water supply variability. These investments can benefit the farmers by serving as a form of self-insurance and can benefit other regional water users by reducing consumptive use in crop irrigation and making water potentially available for other needs.

Farmers with more *delivery shortfalls* would be good candidates for programs that support cement lining of parcel-level canals or other water conserving technology as they are likely to have a higher willingness-to-pay. Also, 5% of farmers in the sample have adopted drip irrigation indicating that it is feasible for certain farmers in the region. For comparison, the Wellton-Mohawk Irrigation and Drainage District of Yuma County, Arizona (also in the lower Colorado River) has drip irrigation in only 64 of 62,744 irrigable acres, or less than 1% of acreage (Bureau of Reclamation 2010). Thus, although drip (and sprinkler) irrigation were not adopted in a large enough percentage of the Mexicali Valley sample to analyze empirically, these irrigation methods are tools that can be considered for increasing water use efficiency in the Mexicali Valley.

Farmers with a higher level of *delivery delays* would be good targets to participate in programs that promote crop diversification into new crops with a lower consumptive use of water. Likewise, these farmers may also be interested in the adoption of crops that tolerate a longer interval of time between irrigation deliveries.

Collaboration is oft-cited as an effective adaptation strategy in several bodies on literature, including farm resilience, climate change, common pool resources, and communities and natural disasters. Therefore, greater collaboration may be an effective tool within and among communities in the Mexicali Valley. Specifically, collaboration among farmers and conservation groups is an opportunity to build relationships and improve management of water resources. Farmers might not be interested in collaboration under ordinary circumstances due to the costs of travel time and time spent in meetings. Yet input costs are a key concern of nearly all farmers, as indicated in their survey responses. Given the rising costs of inputs, farmers are likely to be more interested in collaboration with other water users if the collaboration includes some form of cost-sharing regarding the inputs cost. This provides an opportunity for local conservation groups to build relationships with farmers. Mutual benefits could include cost-sharing and higher profitability for farmers, and improved management of water resources which could benefit water-dependent ecosystems. Collaboration among farmers and conservation groups based upon incentives and cost-sharing has the potential to be a longer-lasting solution if the agricultural community perceives that it will receive economic benefits from the arrangement.

One example of a cost-sharing arrangement comes from anecdotal evidence from the surveys: farmers are not always clear on which fertilizers or other types of soil amendments are necessary for their soil type, and are potentially wasting money on less than optimal inputs. For instance, using a soil amendment that is meant to counteract salinity can actually exacerbate the problem if the true issue is with sodicity of soils.[18] Thus, better technical assistance and support for farmers to obtain soil tests could decrease costs for farmers. Conservation organizations could use this as an opportunity to build relationships with farmers, providing profit-enhancing technical assistance to farmers.

A further incentive for collaboration among farmers and conservation groups comes from the fact that farmers may also be benefiting from the ecosystem services provided by water-dependent ecosystems. In the survey, we asked farmers the following question:

> In the last 10 years, international attention has been focused on the loss of biodiversity in the Colorado River Delta, which depends upon water for its survival. If you knew that half of water users in your module would support in some way, would you also help with one of these options?
>
> 1) Contributing some water (200m^3/hectare) each year for the environment
> 2) Working 20 hours each year as a volunteer planting trees in the region
> 3) Making a monetary donation to a non-profit dedicated to the protection of the environment. If yes, how many pesos each year?
> 4) No interested

The survey question was added after the farmer survey process had already begun, meaning that only 96 farmers (57% of our final sample) answered the question. The question was designed to gauge farmers' attitudes towards the Colorado River Delta. The results are as presented in table 7.1 (where "any of the 3 options" is the small category of farmers who responded that they could not decide which of the first three options to choose, and stated

[18] A 2011 study on the Mexicali Valley used satellite data to assess the impact of salinity and sodicity on wheat yields (Seifert, Ortiz-Monasterio, and Lobell 2011). The authors reported that the impacts salinity on soils had inconclusive results in terms of reduced yields in wheat. Sodicity, in contrast, was associated with decreased yields in at least 32% of the hectares analyzed in the data set.

that any of the first three options appeared good). The responses in table 7.1 show that an overwhelming majority – 94% - are willing to sacrifice water, time or money to benefit ecological restoration in the Colorado River Delta. Also, 79% of the farmers reported living in a rural part of the Mexicali Valley (that is, outside of the cities of Mexicali, BC, and San Luis Rio Colorado, SO). These farmers are likely to be benefitting in some way from ecosystem services – even a benefit as basic as temperature regulation (i.e. shade from trees).

Table 7.1 Responses to question on willingness-to-support ecosystems in the Colorado River Delta

Response	Number	% of respondents
Contribute water	12	13%
Volunteer to work	53	55%
Donate money	21	22%
Any of the 3 options	4	4%
Not interested	6	6%
TOTAL	96	100%

The farmer surveys also included questions on fishing and hunting, as these activities depend upon water available for ecosystems. The percentages were modest. Only 14% reported that they or someone in their family fish in the region in a typical year and 11% reported hunting. Farmers often volunteered reasons for which they did not hunt or fish, with the most common reasons being that they could not obtain a permit and/or that they did not have enough time for these activities. Thus, though the numbers for fishing and hunting are small, it is another example of a benefit farmers may receive from functioning ecosystems.

An additional connection between agriculture and the environment is employment in nature-based tourism. Informal discussions with farmers and conservation organizations in the region revealed that a handful of farmers have been successful in finding employment in tourism related to hunting, fishing, and bird watching. Other forms of regional tourism linked to water-dependent ecosystems include recreation activities, such as those found on the Río Hardy (a tributary of the Colorado River). Thus, farm households may also have opportunities to expand their household income portfolios by adding income from jobs related to water-dependent ecosystems. Although no conflict between farmers and environmental restoration was observed during the field work undertaken for this thesis, fierce competition for scarce water resources always has the *potential* to result in conflict. Proactive measures to ensure that farm households have employment opportunities in nature-based tourism is a form of demonstrating to farmers that sustainable communities and livelihoods are a top concern of conservation groups. Farmers are more likely to show sustained support for ecosystem restoration where restoration outcomes also have livelihood benefits for farm households. In general, we can state that collaboration between farmers and conservation organizations has the potential to result in mutual, incentive-based benefits to both groups, resulting in more effective water allocation.

7.3 Future work

Future work could involve increasing the total number of surveys to expand the analysis to a comparison of two different irrigation districts in the region. Future work could also look at average farm household yields (for major crops grown in that farm household) over time, and compare the relationship between productivity and the selection of risk management strategies. The relationship between crop shares (percentage of agricultural returns resulting from each crop in the crop portfolio) and the ability of farmers to respond to shocks is another interesting future research topic. Other future research could assess the role of water transfers as a risk management strategy and how that is changing with the increasing lease prices. Also, future research could emphasize the role of soil type, soil quality and soil organic matter; although increasing organic material in soil is at times seen as a panacea for increasing farm resilience to water supply variability, little is known about which methods (such as manure, compost, cover crops, or disking the crop residues into the soil) are more effective and to what extent soil organic matter improves resilience to drought.

Future work on farm resilience can focus on panel data, where ideally one would survey farmers to establish a baseline, and then survey the same farmers a second time (several years later) to establish which risk management strategies, in a dynamic framework, are associated with a greater ability to respond and recover from a shock. The dynamic framework would also allow researchers to analyze which farmers have gone out of business from time period 1 to period 2, gaining more information on how shocks and responses are related to farm households exiting from agricultural production completely. For instance, one could test whether farmers who were reducing the application of fertilizers to less than the recommended amount was actually associated with a higher likelihood of going out of business.

References

Anderson, Colin and Stéphane Marc McLachlan. "Exiting, enduring and innovating: Farm household adaptation to global zoonotic disease." *Global Environmental Change* 22(2012):82-93.

Antle, John. M. and Susan M. Capalbo. "Adaptation of Agricultural and Food Systems to Climate Change: An Economic and Policy Perspective." *Applied Economic Perspectives and Policy* 32.3(2010):386-416.

Antle, John M., Jetse J. Stoorvogel, and Roberto O. Valdivia. "Multiple equilibria, soil conservation investments, and the resilience of agricultural systems." *Environmental and Development Economics* 11(2006):477-492.

Banerjee, Abhijit V. and Esther Duflo. *Poor Economics*. New York: Public Affairs, 2011. Print.

Bezabih, Mintewab and Mare Sarr. "Risk Preferences and Environmental Uncertainty: Implications for Crop Diversification Decisions in Ethiopia." Working paper (5 May 2010). Web. 1 June 2012. http://www.virtualelmar.com/wp-content/uploads/2010/04/Diversity_Risk_Preference_Working_Paper.pdf

Bradshaw, Ben, Holly Dolan, and Barry Smit. "Farm-level adaptation to climate variability and change: crop diversification in the Canadian Prairies." *Climate Change* 67(2004):119-141.

Brun, Lukas, Ajmal Abdulsamad, Christopher Geurtsen, and Gary Gereffi. "Agricultural Value Chains in the Mexicali Valley of Mexico." Center of Globalization, Governance and Competitiveness, Duke University (September 2010). Web. 18 April 2011. http://www.cggc.duke.edu/pdfs/Agricultural-Value-Chains-in-the-Mexicali-Valley-of-Mexico_9-15-2010.pdf

Bureau of Reclamation. Crop and Water Data: Wellton-Mohawk Irrigation and Drainage District. *Report of the Bureau of Reclamation on Crop and Water Data*. Yuma County, Arizona, 2010. Print.

Carrillo-Guerrero, Yamilett. "Water conservation, Wetland restoration and Agriculture in the Colorado River Delta, Mexico." Doctoral Dissertation, University of Arizona, Tucson, Arizona (2009). Available from University of Arizona library database.

Chavas, Jean-Paul. "On the microeconomics of diversification under learning." *Journal of Economics* 104.1(2011):25-47.

Chavas, Jean-Paul, and Salvatore Di Falco. “On the role of risk versus economies of scope in farm diversification with an application to Ethiopian farms.” *Journal of Agricultural Economics* 63.1(2012):25-55.

Darnhofer, Ika, John Fairweather & Henrik Moller. “Assessing a farm's sustainability: insights from resilience thinking.” *International Journal of Agricultural Sustainability* 8.3(2010):186-198.

Darnhofer, Ika. “Strategies of Family Farms to Strengthen their Resilience.” Thematic Session D5: Strategies for enhancing system’s resilience. Presented at the 8th International Conference of the European Society for Ecological Economics, June 2009 in Ljubljana (Slovenia).

Dasgupta, Partha. “Economics of Social Capital.” *The Economic Record* 81.255(2005):S2-S21.

Di Falco, Salvatore, Jean-Paul Chavas, and Melinda Smale. “Farmer management of production risk on degraded lands: the role of wheat diversity in the Tigray region, Ethiopia.” *Agricultural Economics* 36(2007):147-156.

Di Falco, Salvatore, and Jean-Paul Chavas. “Rainfall shocks, resilience and the effects of crop biodiversity on agroecosystem productivity.” *Land Economics* 84.1(2008):83-96.

Eakin, Hallie. “Institutional Change, Climate Risk, and Rural Vulnerability: Cases from Central Mexico.” *World Development* 33.11(2005):1923-1938.

Folke, Carl, Steve Carpenter, Brian Walker, Marten Scheffer, Thomas Elmqvist, Lance Gunderson, and C.S. Holling. “Regime shifts, resilience, and biodiversity in ecosystem management.” *Foundations of Ecological Resilience.* Eds. Lance H. Gunderson, Craig R. Allen, and C.S. Holling. Washington: Island Press, 2010. 119-150. Print.

Foudi, Sebastien, and Katrin Erdlenbruch. “The role of irrigation in farmers’ risk management strategies in France.” *European Review of Agricultural Economics* (July 2011):1-19.

Fuchs, Alan, and Hendrik Wolff. “Concept and unintended consequences of weather index insurance: the case of Mexico.” *American Journal of Agricultural Economics* 93.2(2011):505-511.

Glenn, Edward P., Francisco Zamora-Arroyo, Pamela L. Nagler, Mark Briggs, William Shaw & Karl Flessa. “Ecology and conservation biology of the Colorado River Delta, Mexico*.” Journal of Arid Environments* (2001) 49: 5–15.

Gómez Tovar, Laura, Lauren Martin, Manuel Angel Gómez Cruz, and Tad Mutersbaugh. "Certified organic agriculture in Mexico: Market connections and certification practices in large and small producers." *Journal of Rural Studies* 21(2005):461-474.

Greene, William H. *Econometric Analysis: Seventh Edition.* San Francisco: Prentice Hall, 2012. Print.

Gunderson, Lance. Professor, Emory University, Department of Environmental Studies. Personal communication. January 2011.

Hansson, Helena, Richard Ferguson, and Christer Olofsson. "Understanding diversification and specialization of farm businesses." *Agricultural and Food Science* 19(2010):269-283.

Hart Bise Barham, E., John R.C. Robinson, James W. Richardson, and M. Edward Rister. "Mitigating cotton revenue risk through irrigation, insurance, and hedging." *Journal of Agricultural and Applied Economics* 43.4(2011):529-540.

Helmers, Glenn A., Charles F. Yamoah, and Gary E. Varvel. "Separating the impacts of crop diversification and rotations on risk." *Agronomy Journal* 93(2001):1337-1340.

Holling, C.S. "Resilience and Stability of Ecological Systems." (1973) rpt. in *Foundations of Ecological Resilience*. Eds. Lance H. Gunderson, Craig R. Allen, and C.S. Holling. Island Press: Washington, D.C. (2010). 19-49. Print.

Kaine, G.W. and P.R. Tozer. "Stability, resilience and sustainability in pasture-based grazing systems." *Agricultural Systems* 83(2005):27-48.

Koundouri, Phoebe, Céline Nauges, and Vangelis Tzouvelekas. "Technology Adoption under Uncertainty: Theory and Application to Irrigation Technology." *American Journal of Agricultural Economics* 88.3(August 2006): 657-670.

Krueger, Angela, Victoria Salin, Gary Williams, Lorraine Eden, and Alan Gray. "Profitability of geographic diversification strategy." *Journal of Food Distribution Research* 30.1(March 1999):112-123.

Lam, Wai Fung and Elinor Ostrom. "Analyzing the dynamic complexity of development interventions: lessons from an irrigation experiment in Nepal." *Policy Science* 43(2010):1-25.

Lavee, Doron. "The effect of water supply uncertainty on farmers' choice of crop portfolio." Agricultural Water Management 97.11(2010):1847-1854.

Lellouch, M., Hyun, K., Tognetti, S. Ecosystem Changes and Water Policy Choices: Four Scenarios for the Lower Colorado River Basin to 2050. Island Press: Washington, D.C. (2007).

Lien, Gudbrand, and J. Brian Hardaker. "Whole-farm planning under uncertainty: impacts of subsidy scheme and utility function on Norwegian agriculture." *European Review of Agricultural Economics* 28.1(2001):17-36.

Luers, Amy L., David B. Lobell, Leonard S. Sklar, C. Lee Addams, and Pamela A. Matson. "A method for quantifying vulnerability, applied to the agricultural system of the Yaqui Valley, Mexico." *Global Environmental Change* 13(2003):255-267.

Medellín-Azuara, J., L.G. Mendoza-Espinosa, J.R. Lund, J.JU. Harou, and R.E. Howitt. "Virtures of simple hydro-economic optimization: Baja California, Mexico." *Journal of Environmental Management* 90(2009):3470-3478.

Medellín-Azuara, Josué, Jay R. Lund, and Richard E. Howitt."Water Supply Analysis for Restoring the Colorado River Delta, Mexico." *Journal of Water Resources Planning and Management* 133.5(2007):462-471.

Milly, P.C.D., Julio Betancourt, Malin Falkenmark, Robert M. Hirsch, Zbigniew W. Kundzewicz, Dennis P. Lettenmaier, and Ronald J. Stouffer. "Stationarity is dead: Whither water management?" *Science* 319(1 February 2008):573-4.

Moss, Charles B. Risk, *Uncertainty and the Agricultural Firm*. World Scientific Publishing Co.: Singapore (2010). Print.

Mueller, Valerie A., and Daniel E. Osgood. "Long-term impacts of droughts on labour markets in developing countries: evidence from Brazil." *Journal of Development Studies* 45.10(2009):1651-1662.

Ostrom, Elinor. "A General Framework for Analyzing Sustainability of Social Ecological Systems." *Science* 419(2009):419-422.

Ostrom, Elinor, and Roy Gardner. "Coping with asymmetries in the commons: self-governing irrigation systems can work." *The Journal of Economic Perspectives* 7.4(1993):93-112.

Ottman, Michael J. "Suboptimal Irrigation Strategies for Alfalfa in the Lower Colorado Region, 2009." Forage and Grain Report, College of Agricultural and Life Sciences, University of Arizona (2010). Web. 6 September 2011. http://ag.arizona.edu/pubs/crops/az1526/az1526a.pdf

Parsonson-Ensor, Chris and Caroline Saunders. "Resilience of Farming Systems During Periods of Hardship." Agricultural Research Group on Sustainability, Research Report: Number 11/03. May 2011.

Patrick, George R., Paul N. Wilson, Peter J. Barry, William G. Boggess and Douglas L. Young. "Risk perceptions and management responses: producer-generated hypotheses for risk modeling." *Southern Journal of Agricultural Economics* 17.2(December 1985):231-8.

Pérez Vega, Hilario. SAGARPA, Colorado River District Manager for Rural Development, Baja California. Personal Interview. 10 February 2012.

Peterson, Garry, Craig R. Allen, and C.S. Holling. "Ecological Resilience, Biodiversity, and Scale." *Ecosystems* 1(1998): 6-18.

Pfeiffer, Lisa, Alejandro Lopez-Feldman, and J. Edward Taylor. "Is off-farm income reforming the farm? Evidence from Mexico." *Agricultural Economics* 40(2009):125-138.

Pitt, Jennifer and Sean Crowley. *U.S.-Mexico pact on Colorado River water storage praised by EDF*. Mexico City: EDF News Release. 20 December 2010. Web. 24 April 2012. http://www.edf.org/news/us-mexico-pact-colorado-river-water-storage-praised-edf

Plummer, Ryan, and Derek Armitage. "A resilience-based framework for evaluating adaptive co-management: Linking ecology, economics and society in a complex world." *Ecological Economics* 61(2007):62-74.

Reardon, Thomas, Julio Berdegué, Christopher B. Barrett, and Kostas Stamoulis. "Household income diversification into rural nonfarm activities." *Transforming the Rural Nonfarm Economy: Opportunities and Threats in the Developing World* Eds. Steven Haggblade, Peter B.R. Hazell, and Thomas Reardon. The Johns Hopkins University Press: Baltimore, Maryland. (2007). Web. 18 June 2012. http://dyson.cornell.edu/faculty_sites/cbb2/Papers/IFPRIbookchapter2006Final.pdf

Robles Van dyck, Carlos Fernando. CONAGUA, Director of Operations and Conservation Manager for the Irrigation District, Baja California. E-mail. April 2012.

Robles Van dyck, Carlos Fernando. CONAGUA, Director of Operations and Conservation Manager for the Irrigation District, Baja California. Personal Interview. 10 August 2011.

Saldaña-Zorrilla, Sergio O. "Stakeholders' views in reducing rural vulnerability to natural disaster in Southern Mexico: Hazard exposure and coping and adaptive capacity." *Global Environmental Change* 18(2008):583-597.

Salinas-Zavala, C.A., S.E. Lluch-Cota, and I. Fogel. "Historic development of winter-wheat yields in five irrigation districts in the Sonora Desert, Mexico." *Interciencia* 31.4(2006): 254-261.

Schaible, Glenn D., C.S. Kim, and Marcel P. Aillery. "Towards a sustainable future: The dynamic adjustment path of irrigation technology and water management in western U.S. agriculture." Paper for presentation at the Agricultural and Applied Economic Association's AAEA and ACCI Joint Annual Meetings, Milwaukee, WI (26-28 July 2009). Web. 1 June 2012. http://ageconsearch.umn.edu/bitstream/49244/2/C3c_Schaible-Kim-Aillery_2009%20AAEA%20Selected%20Paper_4-28-09.pdf

Secretaria de Agricultura, Ganadería, Desarrollo Rural, Pesca Y Alimentación (SAGARPA). "Mapoteca Digital – Módulos de Riego Valle de Mexicali." Oficina estatal de Información para el desarrollo rural sustentable, Baja California. OEIDRUS-Baja California 2011. Web. 12 December 2011. http://www.oeidrus-bc.gob.mx/oeidrus_bca/mapoteca/ModulosRiego.html

Secretaria de Agricultura, Ganaderia, Desarrollo Rural, Pesca Y Alimentacion (SAGARPA). Oficina estatal de Información para el desarrollo rural sustentable, Baja California. OEIDRUS-Baja California 2010a. Web. 4 April 2012. http://www.oeidrus-bc.gob.mx/oeidrus_bca/

Secretaria de Agricultura, Ganaderia, Desarrollo Rural, Pesca Y Alimentacion (SAGARPA). Oficina estatal de Información para el desarrollo rural sustentable, Sonora. OEIDRUS-Sonora 2010b. Web. 4 April 2012. http://www.oeidrus-sonora.gob.mx/

Secretaria de Fomento Agropecuario (SEFOA). Direccion de infraestructura hidroagricola, Modulos de Riego. SEFOA 2011. Web. 2 May 2010. http://www.sefoa.gob.mx/HIDROAGRICOLA/MODULOS/modulos.htm

Seifert, Christopher, J. Ivan Ortiz-Monasterio, and David B. Lobell. "Satellite-based detection of salinity and sodicity impacts on wheat production in the Mexicali Valley." *Soil Science Society of America Journal* 75.2(2011):699-707.

Seo, S. Niggol. "Is an integrated farm more resilient against climate change? A micro-econometric analysis of portfolio diversification in African agriculture." *Food Policy* 35(2010):32-40.

Sheffi, Yossi. The Resilient Enterprise: Overcoming vulnerability for competitive advantage. The MIT Press: Cambridge, Massachusetts. 2005. Print.

Simelton, Elisabeth, Evan D.G. Fraser, Mette Termansen, Piers M. Forster, and Andrew J. Dougill. "Typologies of crop-drought vulnerability: an empirical analysis of the socio-economic factors that influence the sensitivity and resilience to drought of three major food crops in China (1961-2001)." *Environmental Science and Policy* 12.4(June 2009):438-452.

Smith, MaryLou and Pritchett, James. Agricultural/Urban/Environmental Water Sharing: Innovative Strategies for the Colorado River Basin and the West. Colorado Water Institute Special Report Series No. 22. Colorado State University. Web. 19 April 2012. http://www.cwi.colostate.edu/publications.asp?pubs=sr

Swinton, Scott M., Frank Lupi, G. Philip Robertson, and Stephen K. Hamilton. "Ecosystem Services and Agriculture: Cultivating agricultural ecosystems for diverse benefits." Ecological Economics 64(2007):245-252.

United Nations Economic Commission for Europe. *Measuring Sustainable Development*. New York: United Nations, 2009. Web. 25 April 2012. http://www.unece.org/fileadmin/DAM/stats/publications/Measuring_sustainable_development.pdf

Valvekar, Mayuri, Jean P. Chavas, Brian W. Gould, and Victor E. Cabrera. "Revenue risk management, risk aversion and the use of Livestock Gross Margin for Dairy Cattle Insurance." *Agricultural Systems* 104(2011):671-678.

Van Nieuwerburgh, Stijn, and Laura Veldkamp. "Information acquisition and under-diversification." Working paper 13904, National Bureau of Economic Research (2009). Web. 1 June 2012. http://www.nber.org/papers/w13904.pdf

Veall, Michael R. and Klaus F. Zimmermann. "Evaluating pseudo-R^2's for binary probit models." *Quality & Quantity* 28(1994):151-164.

Williams, Clinton. "Is irrigated agriculture sustainable? The battle to counteract salinity." *Southwest Hydrology* (July/August 2005):22-23.

Wilson, Paul. N., and Gary D. Thompson. "Agribusiness structure for competitive advantage." *Review of Agricultural Economics* 25.1(2003):30-43.

Wilson, Paul N., Gary D. Thompson and Roberta L. Cook. "Mother Nature, Business Strategy, and Fresh Produce." *Choices,* A publication of the Agricultural and Applied Economics Association (1st quarter 1997): 18-525.

Zamora-Arroyo, Francisco, Jennifer Pitt, Steve Cornelius, Edward Glenn, Osvel Hinojosa-Huerta, Marcia Moreno, Jaqueline García, Pamela Nagler, Meredith de la Garza, and Iván Parra. *Conservation Priorities in the Colorado River Delta, Mexico and the United States.* Prepared by the Sonoran Institute, Environmental Defense, University of Arizona, Pronatura Noroeste Dirección de Conservación Sonora, Centro de Investigación en Alimentación y Desarrollo, and World Wildlife Fund—Gulf of California Program. 2005: 103 pp. Print.

Zanzinger, H. "The use of geosynthetics as barrier materials in civil engineering." *Geosynthetics in civil engineering*. Ed. R.W. Sarsby. Washington, DC: CRC Press, 2007. 181-200. Web. 24 April 2012. http://www.beknowledge.com/wp-content/themes/beknowledge/userfiles/45c48Geosynthetics%20in%20civil%20engineering.pdf#page=194

Appendix A. Complete Survey

Survey number:
Date:
Location of interview:

In which modules are your parcels located?
Are you an *ejidatario*?
Where is your house located?
Gender and age:
Educational attainment: primary secondary high school college

Hectares of private property or *ejidal* property		Of these, hectares cultivated this year	
Hectares rented from other water users		Of these, hectares cultivated this year	

Indicate the number of hectares of each crop grown between October 2010 and October 2011.
How many years have you been growing each crop?
Are there any other crops you grow on a regular basis?
Have you changed the crops you grow over the past 10 years?
Which are the crops you have changed and in what year?
Was the reason for the change market-based (low crop prices, high input prices, or other issues related to markets), due to lack of water, or other reason (if so, list reason). Rank the top two reasons.

Have you had employees working for you in the past 12 months?
Number of employees:
Number of family members you have working on your farm in a typical year:
Do you have your own agricultural machinery?
Quantity of machinery owned:
What is the average amount of hours (or years) on your agricultural machinery?
Do you have machinery that is owned in a collective group? Yes No
How many people are in the collective? ________
Quantity of machinery owned by the collective:___________
What is the average amount of hours (or years) on the collective's agricultural machinery?

Do you irrigation with surface water?
Do you irrigate with well water? *If answering yes*:
Is the well private or federal?
How deep is your well? (meters)
What is your irrigation method(s)? (Flood, furrow, sprinkler, drip)
What is your primary source of irrigation water (surface water, groundwater, I use both surface and groundwater roughly equally)

Think about which modules you had the most hectares planted in and what you planted, between October 2010 and October 2011 (*limit answer to 3 top modules and top 3 crops)*	Module #	Approximate number of times you requested irrigation deliveries	Number of times less water arrived than ordered	Number of times lack of water resulted in water stress

Last year, what is the longest number of days you had to wait for irrigation deliveries?
More or less, would you say that your crops suffered due to late arrival of water: 1) Many times, 2) A few times, 3) Never or almost never

Do you have cattle?

How many heads of cattle?

Dairy or meat

Other livestock and quantities (*if considered important for business*)

Number of people currently living in household *(including yourself).*

List any off-farm employment for any member of the household or any other income sources (include city of employment).

Thinking of your household consumption, would you say that you depend on agricultural production for more than half or less than half of household expenses? A. More than half, B. Less than half, C. Half

Are you a member of an organization, collective, cooperative or association?

Optional: What are the names of the organizations?

Do you have a position in the board of directors for the irrigation module?

Do you participate in Procampo?

Approximately, how many hectares are listed as being eligible to receive support through Procampo?

Have you received governmental support in the last five years to purchase farm machinery or equipment?

Optional: What you have purchased?

Do you receive any other type of government support or participate in any other government programs?

1. List the reasons for negative impacts on the profitability of your farm production over the past 5 years, considering both revenues and costs. (*Circle all applicable, a-j*) 2. Note the 3 most important impacts on profitability of farm operations (*1 for the biggest impact*)	**Loss of yields due to:**	**Most severe impacts?**
	a. Extreme heat or frost	1 2 3
	b. Pests or plant disease	1 2 3
	c. Lack of water	1 2 3
	d. Saline water or saline soil	1 2 3
	Other factors leading to low profitability:	
	e. Low market price	1 2 3
	f. Increasing cost of inputs	1 2 3
	g. Poor quality harvest	1 2 3
	h. Labor market shortage or other labor problems	1 2 3
	i. April 2010 Earthquake	1 2 3
	j. Other	1 2 3

Being a farmer in a region where water supplies may be unreliable at times, how have you responded to water shortages? That is, how have you changed your agricultural production and how do you adapt within the household? (*Choose all that apply.*) *Comments*:	1. Change to a different crop that consumes less water (or to a different seed type). *If yes,* type of new crop:
	2. Decrease hectares under cultivation 2a. Choose to not plant a second crop
	3. Seek technical assistance. From who:
	4. Leveling of land (*majority of parcels*)
	5. Change irrigation technology (*examples, such as cement lining of parcel level irrigation ditches, sprinklers, or drip*). What type of technology and in which year:
	6. Improve soil quality with organic matter *Examples, such as hay, wheat, or manure*:
	7. Work more hours or more intensely
	8. Purchase or lease more water
	9. Increase hectares planted
	10. Find work on another farm
	11. Find off-farm work
	12. Reduce the quantity of inputs used (*reducing quantity of fertilizers used to less than the quantity recommended*)
	13. Reduce input costs. If so, how?
	14. Seek support from the government (*or another organization*)
	15. Lease out a portion of your water rights
	16. I have not had problems with unreliable water supplies
	Other:

In a typical year, do you (or another member of your household) fish in this zone?

If yes, what kind of fish?

In what part of the zone?

How many times a year do you fish?

In general, with how many people do you fish?

In a typical year, do you go hunting in this region?

If yes, what do you hunt?

In what part of the zone?

How many times a year do you hunt?

In general, with how many people do you hunt?

Do you currently lease a portion of your water rights to other people? *If answering yes*:

Approximately how many hectares of your rights do you lease out?

In which year did you begin leasing your water rights?

Do you lease…

a. Only your water rights
b. Or do you also rent your land?

Who do you currently lease to?

a. Other farmers? Which type of producer:______________
b. Cities/municipalities
c. Environmental groups
d. Others:

Have you completely exited from agricultural production? If yes, in what year.

Why did you exit from agricultural production?

Are there any questions remaining that you have regarding this survey?

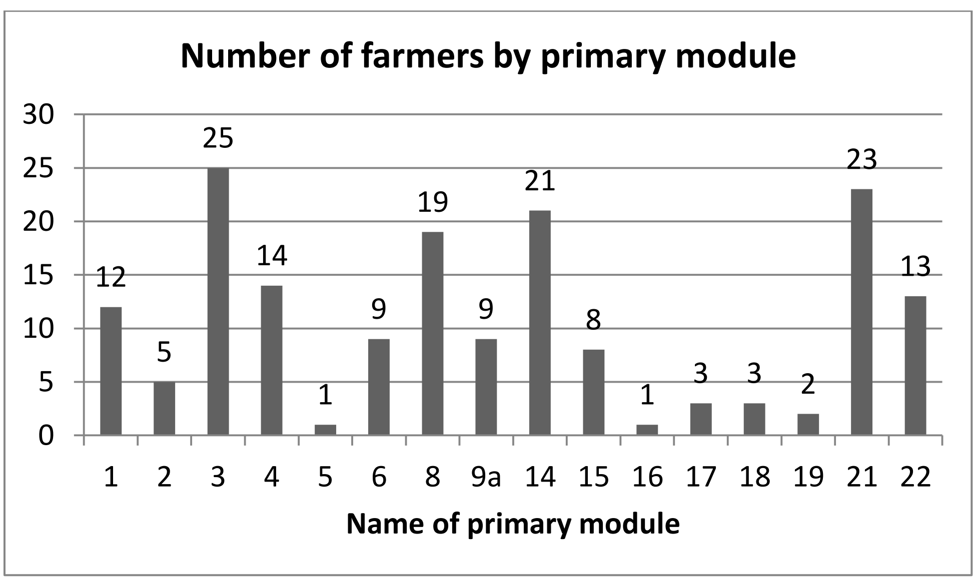
Appendix B. Descriptive statistics for all survey questions

- **All descriptive statistics included in this appendix are for the observations (n=168) included in the econometric regressions. See thesis chapters for additional statistics.**

Location of survey:

Location	Number of surveys
Module 1	10
Module 14	21
Module 15	11
Module 17	2
Module 18	4
Module 2	5
Module 21	22
Module 22	4
Module 3	24
Module 4	16
Module 6	9
Module 8	18
Module 9a	6
Off site	16

Location of farm household by primary module:



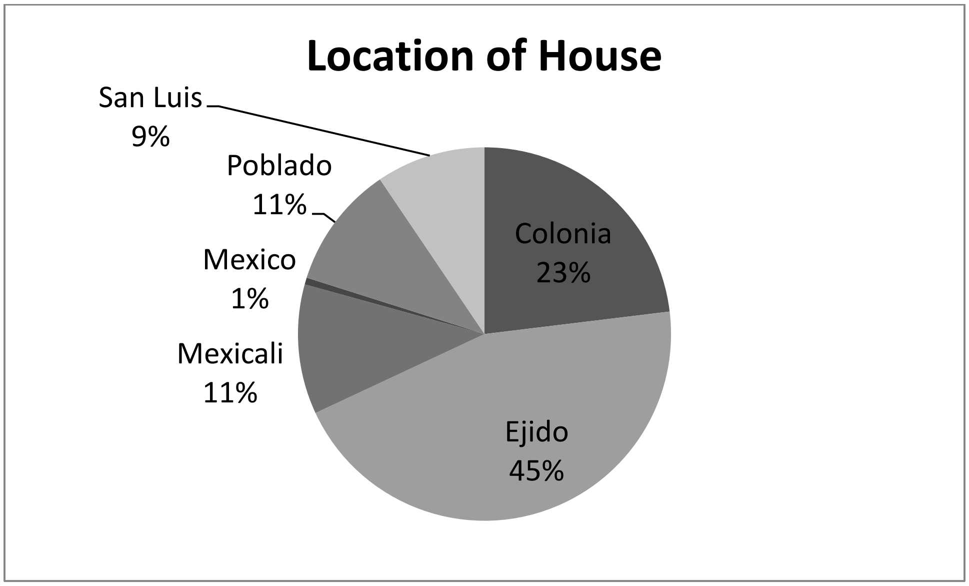
Number of Modules in which farmers cultivate (farmers with >1 module, by farm household and primary module): This table is useful in that it highlights how farmers in primary modules with higher water supply reliability (such as Module 9a) may be worse off when diversifying geographically, whereas farmers whose primary module is on average less reliable (such as Module 21) may be better off from geographic diversification. This is one possible explanation why the delivery shortfall and delivery delay variables are not significant in the Geographic Diversification Model, due to this confounding occurrence.

Primary Module	Total # of modules by farmer	Primary Module	Total # of modules by farmer
1	2	**14**	3
1	2	**14**	2
1	2	**14**	5
2	2	**14**	2
3	3	**14**	4
4	2	**14**	2
4	4	**15**	2
4	2	**16**	2
4	3	**17**	3
5	4	**18**	4
8	4	**19**	2
8	3	**21**	2
8	5	**21**	3
8	2	**21**	2
8	4	**21**	2
9a	2	**21**	2
9a	3	**21**	2
9a	3	**21**	2
9a	6	**22**	2
9a	7	**22**	2
14	2	**22**	2
14	2	**22**	2

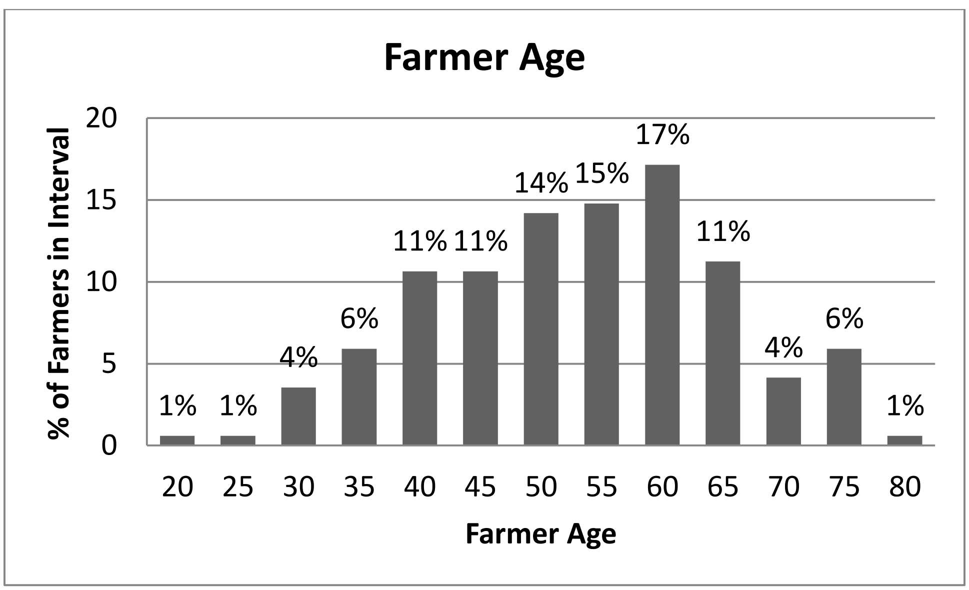
Are you an *ejidatario*? 41% consider themselves *ejidatarios*; 59% do not consider themselves *ejidatarios*

Where is your house located? The options are categorized as c*olonia* (one form of land tenure, around which towns were formed); e*jido* (another form of land tenure, around which towns were formed); the city of Mexicali, BC; the city of San Luis Rio Colorado, Sonora; and *poblado* (which we used to represent primarily the larger towns of Luis B. Sanchez and Guadalupe Victoria, and also in cases where the farmer answered the question by saying "*en el poblado*," or more populated area of the valley). One farmer has his home in the capital city of Mexico.

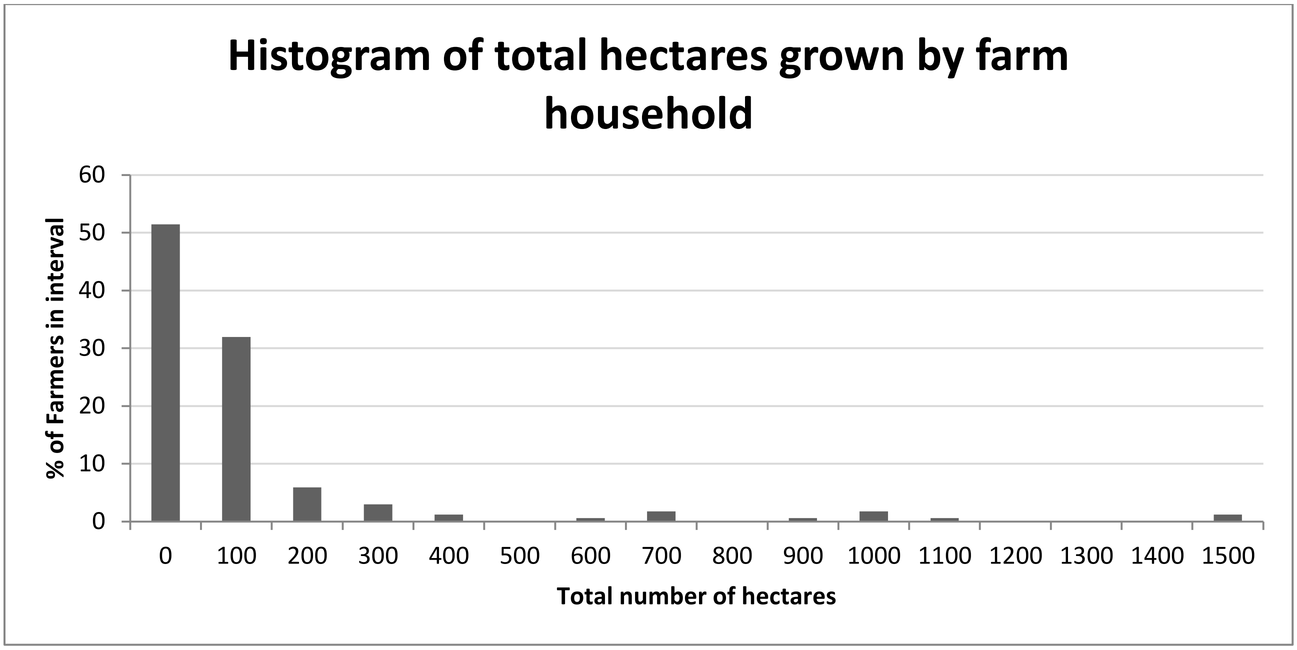
A total of 79% of farmers live in rural areas, outside of the larger cities, implying that they live closer to the land that they cultivate.



Farmer Age, Histogram



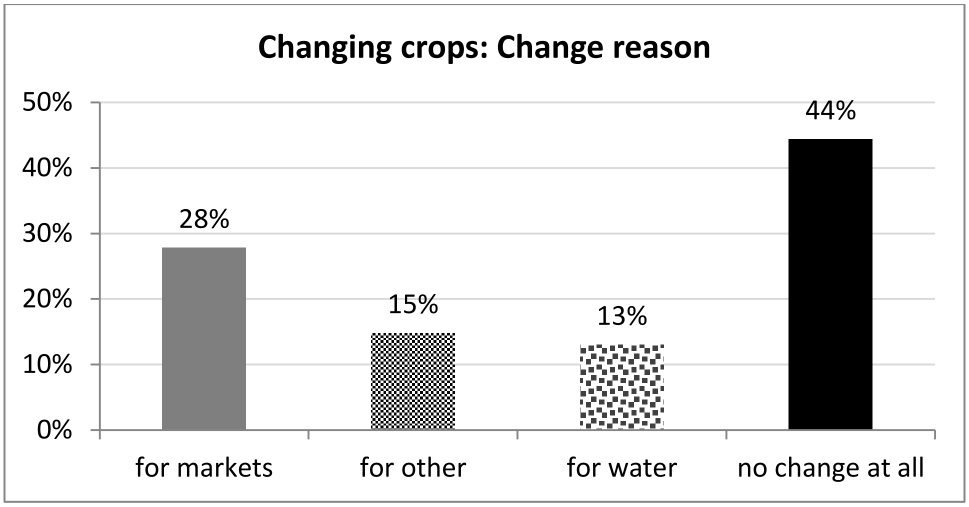
Total hectares (hectares owned + hectares leased) by farmer:



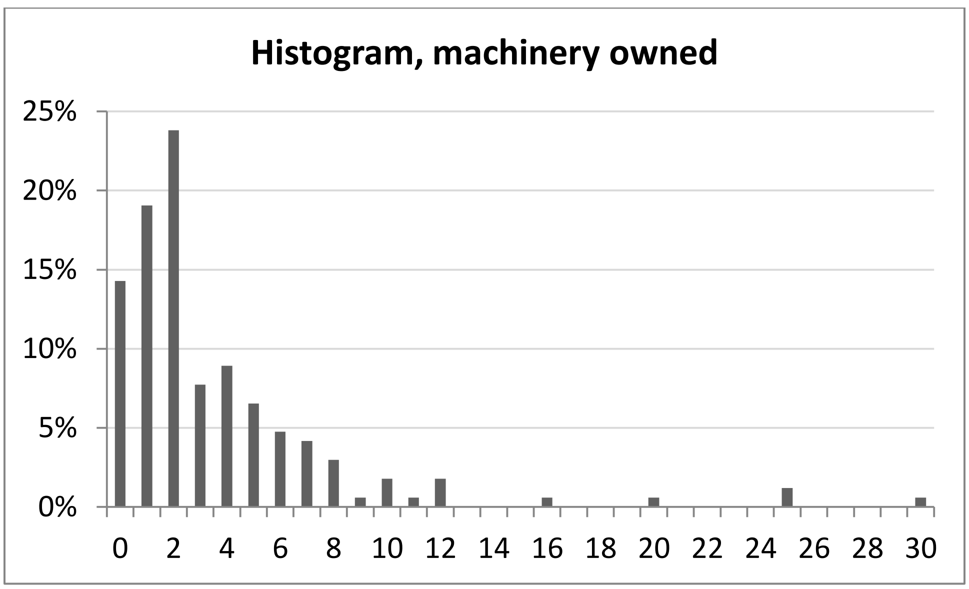
Total crops grown, summed over all farmers in the sample:

Crop	Total # of hectares
Wheat	10,719.75
Alfalfa	4,198
Cotton	3,684
Sorghum	1,293
Sudan	536
Green Onion	250
Ryegrass	242
Other	164
Radish	155
Broccoli	140
Asparagus	100
Cilantro	70
Safflower	58
Celery	50
Citrus	46.5
Oats	20
Parsley	15
Cabbage	10
Sum:	21,751.25

Change reason, for all farmers who switched crops over the past 10 years:

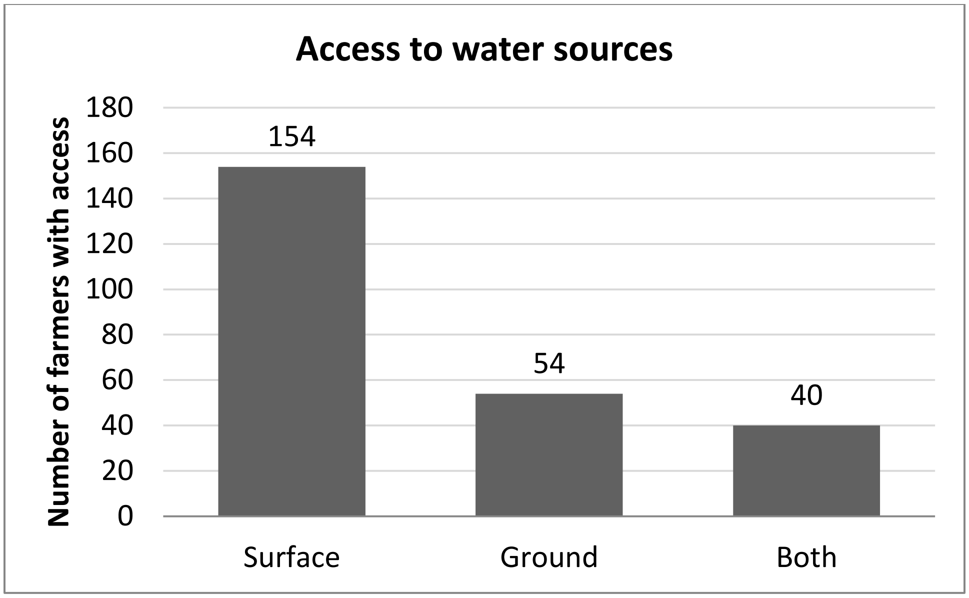


Quantity of agricultural machinery owned by farm household:

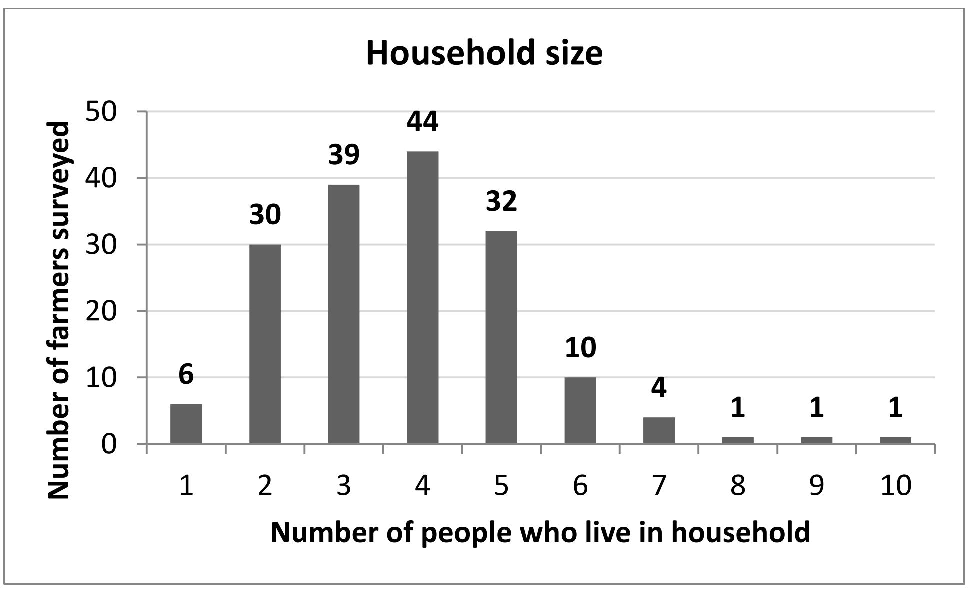


Quantity of agricultural machinery owned in a collective group of farmers: 89% of farmers do not own collective machinery, 11% do own collective machinery. For those who do own machinery, the range is from 1 to 28.

Access to water resources: 154 farmers have access to surface water and 54 farmers have access to groundwater. Therefore, 40 farmers have access to both surface and groundwater.



Number of people living in household, including the farmer interviewed:



Are you a member of an organization, collective, cooperative or association?

- 21% (35 farmers) said yes; the rest said no.

Do you participate in Procampo? If so, how many hectares of land are enrolled to receive support?

- Farmers answered that 11% (19 farmers) had no land enrolled and the remainder of farmers had between 2 and 800 hectares enrolled.

Have you received support from the government to purchase equipment in the past five years?

- We included any type of farm equipment, which were mainly tractors and implements. Of all farmers, 65% had purchased no equipment with government help over the past five years. The remaining 35% purchased between 1 and 6 pieces of equipment.

Appendix C. Protocol for interviews with water managers

The selection criteria to participate in the water manager interviews are that the person must be either an employee of one of the 22 irrigation modules or on the board of directors.

1) What is the total number of hectares in the module with water rights?
2) How many federal wells are in this module? How many private wells?
3) What is the number of registered water users in the irrigation module?
    a. Of the registered water users, what is the number or percent of water users who are considered active? (active means that the farmer still is involved in agricultural production and does not lease out 100% of hectares)
4) What is the percent of water users who are considered *ejidatarios* and the percent who are *colonos*?
5) What are the main crops grown in this module?
6) Are any large agricultural companies or processing plants located in this irrigation module? If so, who and which crops do they target?
7) What is the soil type?
8) Is salinity an issue in this module? If so, how and to what extent?
9) What is the price to lease a hectare of land with water rights? Are water and land leases frequent in this module? Describe the water transfer process in more detail.
10) Is water supply variability a concern for the module?
11) What type of water conservation projects has the module implemented? How many kilometers of canals are now lined with cement?
12) In your opinion, what are the biggest issues that farmers currently face?
13) Did your module experience significant earthquake damage? If so, explain.
14) Which government support programs are most common in this module?
15) Is there a season or time of year where there are more issues with water supply variability?