Climate and Irrigation Technology Choice

by

Jake Grobe

A Thesis Submitted to the Faculty of the

DEPARTMENT OF AGRICULTURAL AND RESOURCE ECONOMICS

In Partial Fulfillment of the Requirements

For the Degree of

MASTER OF SCIENCE

In the Graduate College

The University of Arizona

2014

STATEMENT BY AUTHOR

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ACKNOWLEDGEMENTS

We thank two anonymous reviewers for comments that greatly improved the manuscript. This work was supported by the National Oceanic and Atmospheric Administration's Climate Program Office through Grant NA07OAR4310382 with the Climate Assessment for the Southwest program at The University of Arizona.

I would like to thank Professor George Frisvold for all of his assistance, as well as Professor Dennis Cory and Professor Satheesh Aradhyula. I would also like to thank my parents for their support and especially Meghan and Finn Maria for their inspiration.

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ABSTRACT

Because studies of irrigation technology adoption often concentrate on small geographic areas with the same climate, few have estimated effects of climate on irrigation technology choice. This study examines the choice of sprinkler versus gravity-flow irrigation across 17 western states. Analysis considers long-term seasonal temperatures and growing season length at two points in time using a special tabulation. An erosion index captures effects of rainfall, field slope, and soil water-holding capacity. Sprinkler adoption increases with reliance on groundwater, water costs, agricultural wages, and erosion. Sprinkler adoption was significantly lower for smaller farms. In colder climates, climate warming may lengthen the growing season, but increase susceptibility to frost during the expanded growth period, which may encourage sprinkler adoption. In warmer areas, there is less scope to adapt to warming by switching from gravity to sprinkler technology. Sprinkler adoption declines monotonically in Spring/Summer temperature and growing-season-adjusted Fall/Winter temperature. A drier climate would reduce sprinkler adoption, while climates with more rainfall and more intense rain events would see greater adoption.

CHAPTER ONE

INTRODUCTION

Improved irrigation efficiency has often been cited as an important way to adapt to climate change (e.g., Burton, 2000; Cavagnaro et al., 2006; Jackson et al., 2009; Joyce et al., 2009; Kurukulasuriya and Rosenthal, 2003; Smit and Skinner, 2002). Compared to gravity irrigation, drip or sprinkler irrigation can achieve better control over the timing and level of water applied to crops. This can better match water applications to plant requirements. Improved irrigation timing can help protect crops from drought stress, frost, or other climate extremes. Drip or sprinkler irrigation can require large capital investments, however. Because these capital costs take years to recover, growers have an incentive to select irrigation methods suited to the climate they face. Irrigators often cite financial constraints as major barriers to investing in improved irrigation efficiency (Frisvold and Deva, 2012).

CHAPTER TWO

IRRIGATION TECHNOLOGY CHOICE AS CLIMATE ADAPTATION

Although researchers have thoroughly studied factors affecting adoption of improved irrigation technology, and the importance of climate in irrigation choice is often acknowledged, relatively few studies have formally focused on the role of climate or included climate variables. Many empirical studies of irrigation technology adoption have concentrated on small geographic areas, such as a single irrigation district or relatively small production region. The geographic scope of such analyses can be too narrow to effectively measure effects of climate over the long term. By their very nature, long-term climate averages change little over time, and localized studies may have insufficient variation in climate to allow for econometric analysis. To measure the effects of long-term climate variables, studies must have large enough geographic scope to have measurable differences in these variables across observations. Small geographic scope can also lead to a high degree of multicollinearity between seasonal climate variables, limiting the number of climate variables that can be assessed (Fleischer et al., 2008).

This study adds to a small list of studies that have focused on the role of climate in adoption of irrigation technology. These include Negri et al. (2005), who examined the effect of climate on the decision whether or not to irrigate; Negri and Brooks (1990), who considered effects of climate variables on choice of irrigation technology among irrigators; Mendelsohn and Dinar (2003), who examined climate effects on the share of irrigated acreage and share of irrigated acreage under different technologies across U.S. counties; and Caswell et al. (2001), who also examined climate effects on the choice of whether to irrigate along with the choice of irrigation method for individual producers. These studies found that climate variables had important impacts on irrigation adoption decisions. In Dinar et al. (1992), temperature and rainfall variables were not significant, but the coefficients of variation for these climate variables were quite low. More recently, Moreno and Sunding (2005) and Schoengold et al. (2006) found the number of frost-free days was important for explaining joint crop-irrigation technology choices.

Here, we consider how climate, farm size, water costs, labor costs, and soil characteristics affect irrigator choice between gravity flow and sprinkler irrigation in 17 western states. To make sure there is enough spatial variation in climate variables, we use data from special cross-tabulations of the Farm and Ranch Irrigation Survey (FRIS) developed by USDA's Economic Research Service (USDA ERS 2004). While the USDA conducts the national FRIS roughly every five years, published tables report state-level aggregate data, focusing on 2 x 2 relationships. Thus, one can consider how irrigation technology choices change by farm size *or* pumping costs *or* other factors, but this data configuration is not amenable to multivariate analysis. ERS's Special Tabulation, however, reports data for the 1998 FRIS and 2008 FRIS, stratifying observations by four farm sales classes for the 17 westernmost contiguous U.S. states. This provides 68 state-farm size pairs with sufficient geographic scope to conduct a western region-wide analysis of the choice of irrigation technology.[1]

The study begins with a discussion of the importance of irrigation to western agriculture. Next, we compare the salient features of sprinkler and gravity flow irrigation technologies and discuss trends in the diffusion of sprinkler technology. We then review the literature on sprinkler irrigation adoption. This literature has examined the role of field and soil characteristics (especially those

[1] One reviewer noted that irrigation technology and crop choice can be joint decisions as modeled by Green et al., (1996), Moreno and Sunding (2005), and Schoengold et al. (2006). Thus, explanatory variables may affect results via their unobserved effects on crop choice. The ERS Special Tabulation, however, does not report irrigation technology choice by crop choice. We consider the scope for using aggregate FRIS data from multiple survey years for analysis of joint crop-technology choices in the Discussion section of this article.

affecting water-holding capacity of soils), costs of water, labor costs, farm size, and climate as important factors influencing adoption of modern irrigation technologies. The next section introduces a regression specification and data sources to examine how these variables contribute to differences in sprinkler adoption across states and across farm sales classes. We then analyze the results of the regression and conclude by discussing the implications of our main findings.

Some main findings follow. Sprinkler adoption rates were significantly lower for farms operating at a smaller scale (measured by sales). An aggregate index of sheet and rill erosion was also a significant predictor of sprinkler adoption. This erosion index embodies variables – rainfall, field slope, and soil water-holding capacity – that have been found to explain sprinkler adoption in farm-level and irrigation district-level studies. Sprinkler adoption increased with water costs and with greater reliance on groundwater. In colder climates, climate warming may lengthen the growing season, but increase susceptibility to frost during the expanded growth period. This may encourage sprinkler adoption for frost protection. In warmer areas, there is less scope to adapt to climate warming by switching from gravity to sprinkler technology. Sprinkler adoption declines monotonically in Spring/Summer temperature and growing-season-adjusted Fall/Winter temperature. The response to the erosion index suggests a drier climate would reduce sprinkler adoption, while climates with more rainfall and more intense rain events would see greater sprinkler adoption.

CHAPTER THREE

WESTERN IRRIGATED AGRICULTURE

Irrigation is enormously important to western agriculture. In the 17 westernmost contiguous states, about 75% of the value of crops grown comes from the 25% of the cropland that is irrigated (Gollehon and Quinby 2000). Improved irrigation technology has been seen as a necessary, if not sufficient, part of relieving pressure on water supplies and quality in the West. Improved technologies such as sprinkler or drip irrigation allow producers better control over water applications and increase the share of applied water that is taken up by plants. Such improved technologies have been seen as means to improve farm yields and incomes (Caswell and Zilberman 1986; Aillery and Gollehon 2003), allow producers to better adapt to drought or climate change (Mendelsohn and Dinar 2003; Schuck et al. 2005), and reduce water pollution from soil erosion and chemical leaching (Caswell et al. 1990, 2001; Dressing, 2003).

The role of improved irrigation technology in water conservation has proven more controversial. Although improved application efficiency means less water is needed to generate a given level of crop yield, improved efficiency does not necessarily reduce demand for water (Caswell and Zilberman 1986; Peterson and Ding 2005). Even when increased farm-level efficiency does reduce demand for water diversions, it may still increase consumptive use of water. Increasing the percentage of diverted water consumed by crops can reduce return flows and aquifer recharge. Thus, improved farm-level efficiency may not necessarily conserve water at the basin level (Huffaker and Whittlesey 2000, 2003; Skaggs 2001; Skaggs and Samani 2005; Ward and Pulido-Velazquez 2008).

CHAPTER FOUR

IRRIGATION TECHNOLOGY

Traditional irrigation systems use gravity to distribute water. Water is conveyed to the field using open ditches or pipes, and then released along the upper end of the field. Furrows control water movement and channel the flow down or across the field. Gravity systems are best suited to soils with higher moisture-holding capacities and relatively flat fields to prevent excessive water runoff.

With sprinkler systems, water is sprayed over the field, usually using aboveground pipes. Sprinkler irrigation systems use pressure to distribute water, which requires energy for pumping. As Negri and Brooks note, "Sprinkler irrigation technologies save water relative to gravity-flow systems by distributing water evenly on the field, reducing percolation below the root zone, and eliminating field runoff" (1990, 214). Sprinkler systems can be used on steeper slopes unsuited to gravity systems and on soils with lower water-holding capacity. Sprinkler irrigation also can have much higher application efficiencies than traditional gravity irrigation (Sloggett 1985). While gravity systems have field application efficiencies that usually range from 40% to 65%, efficiencies from sprinkler systems more typically range from 75% to 85% (Aillery and Gollehon 2003). Sprinkler systems have higher capital costs than gravity systems, however, which may act as a barrier to adoption for farms below some critical size. Sprinkler systems tend to be energy using and laborsaving relative to gravity systems. Thus, their relative profitability will depend on labor and energy costs.

The amount of U.S. acreage irrigated with sprinkler systems increased from 36% to 54% between 1979 and 2008. Acreage devoted to drip irrigation rose from 1% to 7%, while acreage irrigated by gravity systems declined from 63% to 39% over the same period (Table 1). Drip irrigation is most commonly used for vegetables, orchards, vineyards, nuts, and other perennial crops. In the 17 Western States, 81% of acreage under drip irrigation is in California, primarily on citrus and specialty crops. While drip (trickle, low-flow and micro-sprinkler) irrigation accounts for 32% of California's irrigated acreage, it accounts for just 1.6% of irrigated acreage in the remaining 16 states (USDA, NASS 2010). Because of limited adoption of drip systems outside of California, we focus here on the choice between sprinkler and gravity systems.

Table 2 reports acres irrigated with sprinklers (as a proportion of total acres irrigated by sprinkler and gravity methods) for major crops in the West from the most recent (2008) FRIS (USDA, NASS 2010). Table 2 highlights some interesting differences between California and the other 16 Western States. California accounts for a relatively large share of the western United States' specialty crop (vegetable, orchard, vineyard, and nut trees) acreage and a small share of acreage of many field crops (wheat, hay, corn, and barley). The proportion of acres irrigated with sprinklers varies by both crop and region. While sprinkler adoption on field crops tends to be relatively low in California, it tends to be high in the remaining 16 Western States. Studies examining joint irrigation technology-crop choices have focused on a single irrigation district in California (e.g. Green, et al. 1996; Moreno and Sunding, 2005; Schoengold, et al., 2006). Table 2, however, suggests that these joint technology-crop choices appear quite different outside of California and suggests some caution is warranted in extrapolating behavior outside of California. An interesting area of future research would be to apply the joint crop-technology framework to a wider geographical area.

CHAPTER FIVE

IRRIGATION TECHNOLOGY CHOICE: THE LITERATURE

Caswell and Zilberman (1986) introduced a theoretical model of irrigation technology choice that characterized modern irrigation systems (sprinkler and drip systems) as land quality augmenting. Modern systems, they argued, enhanced the water-holding capacity of soils. Thus, improved irrigation technologies would be relatively more profitable to adopt on land with poorer water-holding capacity. Subsequent empirical literature supports Caswell and Zilberman's theoretical specification. This suggests soil and field characteristics matter for choice of irrigation technology, and that growers are more likely to adopt modern irrigation technologies for soils with lower water-holding capacity (Dinar and Yaron, 1990; Dinar et al., 1992; Green and Sunding, 1997; Mendelsohn and Dinar, 2003; Negri and Brooks, 1990; Schuck and Green, 2001). Sprinkler adoption rates are generally higher on fields with steeper slopes, which also reduce water-holding capacity.

Economic theory and previous empirical findings suggest there are systematic relationships between scale of operation and irrigation technology choice. Leib et al. (2002) found significant positive relationships between farm size and adoption of scientific irrigation scheduling methods (use of crop evapotranspiration data and soil moisture testing) among Washington farmers. In a study of New Mexico irrigators, Skaggs and Samani (2005) reported a "lack of interest in making improvements to current irrigation systems or methods on the smallest farms (p. 43)." Comparing irrigation districts in Alberta, Canada Bjornlund et al. (2009) found evidence of greater adoption of information-intensive irrigation management in areas with larger farms. Frisvold and Deva (2012) found that smaller farms (measured by sales) in the U.S. West were, “less likely to investigate irrigation improvements, use management-intensive methods for irrigation scheduling, or participate in cost-share programs to encourage adoption of improved irrigation practices (p. 569).”

Sprinkler systems require fixed capital investments, so average fixed costs fall with the scale of operation. One might expect, then, that adoption rates would increase with scale. Evidence of the impact of farm size on sprinkler adoption is mixed, however. Skaggs (2001) and Schuck et al. (2005) found evidence of a positive relationship between farm size and adoption by New Mexico and Colorado irrigators, but Negri and Brooks (1990) reported the opposite result in a large sample of western groundwater-using farms from the 1984 FRIS. Green et al. (1996), Green and Sunding (1997), and Dinar et al. (1992) observed positive relationships between sprinkler adoption and farm field size.

The different ways that researchers measure scale of operation complicates comparisons of studies considering farm size and irrigation technology adoption. Some measure scale in terms of sales volume. In addition to area scale, this may be also capturing the effects of growing high-value specialty crops. Thus, cropping decisions may drive technology choices. Analyses that focus on total farm area may be, in contrast, capturing the effects of low-value, land extensive crops (e.g. irrigated pasture). As a reviewer has noted, there is also a distinction between farm scale and field scale. Technological factors may account for economies of scale at the field level. Scale of farm operation (that includes multiple fields) may affect adoption via relationships between farm operation scale and risk aversion or access to credit.

A number of studies have examined the role of water cost on sprinkler adoption. Caswell and Zilberman (1985), Negri and Brooks (1990), and Dinar et al. (1992) found a positive relationship between water costs and sprinkler adoption. Green et al. (1996) reported that water price had a negative but statistically insignificant effect, whereas Green and Sunding (1997) found water price had a positive effect on sprinkler adoption in citrus production, but not in vineyards.

Empirical findings for the relationship between water source and technology choice have also been mixed. According to Negri and Brooks (1990), greater reliance on surface water decreased the probability of sprinkler adoption. Moreno and Sunding (2005) found such a negative relationship to be statistically significant. Caswell Zilberman (1985), Dinar et al. (1992), and Green et al. (1996) found a negative, but statistically insignificant relationship between reliance on surface water and sprinkler adoption. Mendelsohn and Dinar (2003), in contrast, found a significant, positive relationship between reliance on surface water and sprinkler adoption.

The number of studies on the effects of climate variables is limited, because smaller-scale studies at, for example, the irrigation district level may not exhibit sufficient cross-sectional variation in climate. Studies covering wider geographic areas, however, have found climate to have important effects on irrigation technology choice. Both Negri and Brooks (1990) and Mendelsohn and Dinar (2003) found higher rates of sprinkler adoption in areas with greater rainfall. Dinar et al. (1992) did not find a significant rainfall effect, but this analysis was confined to the San Joaquin Valley of California, which has less variation in rainfall than the other two studies. Negri and Brooks argued that sprinkler adoption would be greater in areas with greater rainfall. This is because growers in high-rainfall areas face a greater risk of crop damage from unexpected rainfall following flood irrigation; here sprinklers provide growers with greater control over applications. In contrast, in hot, arid regions, evaporation losses are large with sprinkler technology. Evaporation losses in sprinkler systems can reach levels close to 50%

under the hot, arid conditions found in Arizona or Southern California (McLean et al. 2000). Negri and Hanchar (1989) state, "Farmers in hot or windy regions are more likely to adopt gravity since a large fraction of water applied with sprinkler systems evaporates under these climate conditions (p. 9)." Based on farm-level analysis of California, Oregon, and Washington irrigators, Olen et al. (2012) argue that above a critical temperature threshold, high evaporative losses from sprinklers negate water application efficiency advantages of sprinklers, making them less attractive relative to gravity or drip systems. Mendelsohn and Dinar also pointed out the problem of large evaporation losses and noted "sprinkler systems are more frequently adopted in cooler locations with a lot more rainfall" (2003, 338).

Negri and Brooks (1990) reported that sprinkler adoption was lower in areas with more frost-free days and a longer growing season (measured in growing degree-days) and greater in areas with more frost. They argued that sprinklers are better suited for irrigation for frost protection, whereas longer growing seasons are associated with warmer climates, where sprinkler evaporation losses are greater. Olen et al. (2012) cite several studies reporting the frost protection advantages of sprinkler irrigation over other systems. Mendelsohn and Dinar (2003) also pointed out that sprinkler adoption rates were inversely related to temperature. Dinar et al. (1992) again found no significant effect, but as before, this may be because of the low variance of weather and climate variables in their sample.

Finally, because sprinkler systems tend to be labor saving, some studies have considered impacts of labor costs on sprinkler adoption. Negri and Brooks (1990) found that higher farm labor wages were associated with greater adoption of sprinkler irrigation systems. Mendelsohn and Dinar (2003) reported greater use of sprinkler systems in counties with higher farm wage rates in January, but lower wage rates in April.

CHAPTER SIX

DATA AND REGRESSION MODEL SPECIFICATIONS

Irrigation data come from special cross-tabulations of both the 1998 and 2008 Farm and Ranch Irrigation Survey (USDA, NASS, 1998) (FRIS) made available by USDA's Economic Research Service (USDA ERS 2004, 2008). Although the regular FRIS report does not report detailed data by farm sales class, the ERS special cross-tabs report data for each of the 17 westernmost contiguous states by four farm sales classes:

- Small farms, with sales less than $100,000;
- Medium farms, with sales from $100,000 to $249,999;
- Large farms, with sales from $250,000 to $499,999; and
- Very large farms, with sales of $500,000 or greater.

The 17 states in the database are North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Texas, Montana, Wyoming, Colorado, New Mexico, Idaho, Utah, Arizona, Nevada, Washington, Oregon, and California.

Let the proportion of acres irrigated with sprinkler systems (as a share of acreage under sprinkler plus gravity irrigation) by irrigators in sales class i and state j be PS_{ij} while the proportion of acres irrigated with gravity systems be PG_{ij}. Drip and subsurface irrigation acreage were not included, as data were not reported for many states and farm sales classes because of insufficient observations.

Following previous work on irrigation adoption using proportions data (Caswell and Zilberman 1985; Mendelsohn and Dinar 2003; Schaible et al. 1991), the regression equation explaining adoption is specified as a logistic function:

$$ln(PS_{ij}/(PG_{ij})) = \alpha_0 + \alpha_1\text{Small} + \alpha_2\text{Medium} + \alpha_3\text{Large} + \boldsymbol{\beta}'\boldsymbol{X}_{ij} + u_{ij} \quad (1)$$

where

Small = 1 for small farms, = 0 otherwise;

Medium = 1 for medium farms, = 0 otherwise;

Large = 1 for large farms, = 0 otherwise;

$\boldsymbol{X}_{ij}$ = a vector of other explanatory variables (discussed below); and

u_{ij} = a stochastic error term.

A regression intercept α_0 is included; so, one farm class dummy (for very large farms) is omitted. Coefficients for the other sales-class variables represent differences from the very large farm class. Operations may be in the larger sales classes if they have more acreage, grow higher-value crops, or both. The sales class variables may therefore capture some combination of acreage and crop value effects.

The variable *Water Costs* is measured as water cost per acre-foot applied (in $ per acre; one acre equals 0.404686 hectares) to pump water by farm size and state, for 1998 and 2008 FRIS irrigated farms. Irrigators use pumps to bring well water to the surface; re-lift or boost water within irrigation systems; discharge water from ponds, lakes, reservoirs, and rivers; or discharge water from tailwater pits. Pumping costs increase with well depth and energy prices. Water costs are a weighted average of surface water delivery costs and groundwater pumping costs, calculated as the percentage of water applications from surface sources multiplied by the prices of surface water and added to the percentage of water applications from groundwater multiplied by the cost of pumping water. This water cost is then logged.

The variable *Surface Water* is the share of surface water to total irrigation water applied by farm size and state, for 1998 and 2008 FRIS irrigated farms. Irrigators' relative reliance may affect sprinkler adoption in at least two ways. First, as discussed above, marginal costs of surface water are usually lower than costs for groundwater. Previous research suggests that sprinkler adoption increases with water costs. Second, surface water diversions naturally complement gravity flow systems.

We also include two climate variables: *LNTEMP5-9*, *LNTEMP10-3*. *LNTEMP5-9* is (the log of) the average of monthly 40-year mean temperatures in degrees Fahrenheit of cropland in a state from May through September. *LNTEMP10-3* is (the log of) the average of monthly 40-year mean temperatures of cropland from October through March, adjusted for growing season. Winter months with average temperatures below 32 degrees F (0 degrees C) are not included in the *LNTEMP10-3.* Sprinkler irrigation is often used to protect crops from frost (Negri and Brooks, 1990; Skaggs, 2001; Dressing, 2003; Moreno and Sunding, 2005; Olen et al., 2012). *LNTEMP10-3* is intended to measure such frost risk. Temperatures in months of freezing temperatures represent the off-season and are not likely to affect this decision. Above freezing, but low Fall/ Winter temperatures suggest areas where frost risk is greater, and sprinkler adoption is higher. One would thus expect an inverse relationship between *LNTEMP10-3* and frost protecting uses of sprinkler irrigation.

The climate variables come from Teigen and Singer (1988), who weighted average weather station measurements by harvested cropland. The climate variables thus give more weight to temperature readings where crops are grown. For example, readings from Death Valley or high in the Rocky Mountains with no agricultural production would receive no weight. In contrast, readings from major agricultural production areas would receive great weight.

The variable *LNEROSION* measures average annual sheet and rill erosion on cultivated cropland in each state, measured in tons of soil per acre per year. Data come from the 1997 Natural Resources Inventory of the USDA's Natural Resources Conservation Service (USDA NRCS 2000). Sheet and rill erosion is caused by water. *LNEROSION* is derived from the universal soil loss equation (USLE) (Wischmeier and Smith 1978; IWR-MSU 2002). It is included because it comprises several variables that past studies have found affect irrigation technology choice.

LNEROSION = ln (RKLSCP), where *R* is a rainfall factor, *K* is a soil erodibility factor, *L* is a slope length factor, *S* is a slope steepness factor, *C* is a cover and management factor, and *P* is a conservation practice factor. *R* is a factor measuring erosivity of soil from rainfall runoff. It increases with the total amount and peak intensity of rainfall. The USLE's *R* factor is highly correlated with measures of precipitation (with $R^2 \sim 0.86$–0.91) (Yu and Rosewell, 1996; de Santos Loureio and Azevedo Coutinho, 2001; Diodato, 2004). The USLE measure of erosion has been found to be more sensitive to changes in the *R* factor than to other environmental variables (Nearing, 2001).

The factor *K* assigns values to different types of soil based on susceptibility to erosion and rate of runoff. *K* is thus related to the water-holding capacity of soils. Sprinkler irrigation technology enhances the water-holding capacity, and previous studies have found higher adoption rates on soils with low water-holding capacity. For example, clay soils have *K* values ranging from about 0.05 to 0.15, because they resist detachment. Loam soils tend to have moderate *K* values, and sandy soils have higher *K* values. Both Negri and Brooks (1990) and Mendelsohn and Dinar (2003) reported that farming on sandy soils encouraged sprinkler adoption, while farming on clay soils discouraged sprinkler adoption, relative to farming on loam soils. These results also suggest that sprinkler adoption would increase in *LNEROSION*, via the relationship with *K*.

Land with steeper slopes has also been associated with greater adoption of sprinkler irrigation relative to gravity irrigation. Mendelsohn and Dinar (2003), however, argued that slope length should be positively associated with gravity irrigation, because it implies flatter fields. They found empirical evidence to support this argument. Slope length appears to be the only variable that increases *LNEROSION* and has been associated with less sprinkler irrigation use. All the other components of the USLE appear to both increase *LNEROSION* and contribute to greater sprinkler adoption. Thus slope length may have a confounding effect. However, computed values for *LNEROSION* are not very sensitive to slope length, particularly on flat landscapes (IWR-MSU 2002). In sum, the individual factor components that increase *LNEROSION* all appear to be positively associated with greater sprinkler adoption except for slope length, *L*. Slope length, however, exerts relatively minor influence on *LNEROSION*. Overall, then, one might expect a positive association between *LNEROSION* and sprinkler adoption.

Several studies suggest gravity systems are more labor intensive than sprinkler systems (Maddigan, et al., 1982; Bernardo et al., 1987; Negri and Hanchar, 1989; Negri and Brooks, 1990; Sauer, et al., 2010). Sprinkler systems may thus represent a laborsaving change from gravity systems. The variable used *LNWAGE* was the log of hired farm labor wages. Annual wage rates are reported by multistate region rather than state in the USDA's Quick Stats database (http://quickstats.nass.usda.gov/).

Descriptive statistics for the variables are presented in Table 3. Adoption rates for sprinkler irrigation range across state–farm size pairs from 2% to 95%. There are also wide ranges between minimum and maximum values for most of the explanatory variables used in the regression analysis. Growing season adjusted Fall/Winter temperatures range from 39 to 57 degrees F (4 to 14 degrees C), while Spring/Summer temperatures range from around 61 to 83 degrees F (16 to 28 degrees C). The number of months with average temperatures below 32 degrees F (0 degrees C) ranges from zero (which is the mode) to five months, with a median of two months.

CHAPTER 7

SPRINKLER SYSTEM ADOPTION: REGRESSION RESULTS

The regression equation was estimated using ordinary least squares (Table 4). With the log proportions transformation of the dependent variable, we failed to reject the null hypothesis of homoscedasticity. The coefficients for small, medium, and large farms were negative and statistically significant, indicating that these operations had a lower percentage of acreage under sprinkler systems than did very large farms. The coefficient for small farms was the most negative.

While the regression is linear in $ln(PS_{ij}/(PG_{ij}))$ it is non-linear in PS_{ij}, the proportion of irrigated acres irrigated by sprinklers. The predicted value of PS_{ij} = $E[PS_{ij}]$ is

$$E[PS_{ij}] = \{1 + \exp [-(\mathbf{X}'_{ij}\, \boldsymbol{\beta} + \sigma^2 /2)]\}^{-1} \tag{2}$$

where $\boldsymbol{\beta}$ is the vector of regression coefficients, $\mathbf{X}_{ij}$ is a vector of regressors and σ^2 is the variance of the regression equation. The non-linear structure of this logistic function, implies three things: (a) the marginal effect of a change in a variable X_1 depends on values of the other variables; (b) the marginal effect declines as the baseline proportion of adoption moves away from 0.5; and (c) the marginal effect of explanatory variables on sprinkler adoption approaches zero as the underlying proportion of sprinkler adoption approaches one. One can examine how the proportion of acres irrigated by sprinklers changes for changes in continuous variables for different farm sales classes.

In the regression, water costs had a positive and significant effect on sprinkler adoption (Table 4). This result is consistent with earlier findings suggesting that sprinkler irrigation increases with water costs (Caswell and Zilberman, 1985; Negri and Brooks, 1990; Dinar et al.

1992; Green et al., 1996; Moreno and Sunding, 2005). The farm sales class variables effectively shift up the adoption curve. Irrigators face a wide range in reflecting differences in well depths and relative reliance on surface and groundwater.

The proportion of acres under sprinkler systems decreased with greater reliance on surface water. Reliance on surface water appears to have a negative effect on sprinkler adoption beyond differences in water costs. Irrigating with surface water entails lower pumping costs than pumping groundwater from wells. Yet, this cost difference is already reflected in the *Water Cost* variable. Negri and Brooks (1990) note that marginal costs for water from surface sources can be quite low. Surface water supplies in the West are often quantity-rationed rather than price-rationed. In many western surface water projects, average costs can deviate substantially from marginal costs. Indeed, in many cases, irrigators are charged per acre of irrigated land, rather than per acre-foot of water applied. In these cases, the marginal cost of water (per acre-foot) is zero. The fact that sprinkler irrigation adoption rates increase with reliance on groundwater in the regression may also reflect the lower *marginal* cost of surface water. Moreno and Sunding (2005) also note that costs of surface water are less variable than costs of groundwater, which can fluctuate based on changes in the water table and volatile energy costs. Thus, irrigators relying on groundwater may face both higher and more variable marginal costs of water. Both factors may encourage adoption of more water-efficient technologies.

Turning to the temperature variables, there is a significant negative relationship between May-September temperatures and sprinkler adoption. We experimented with quadratic and log quadratic specifications of this temperature variable. In no case was the quadratic term significant, suggesting that sprinkler adoption is monotonically decreasing in May-September temperatures. Using the same procedure, it was also found that sprinkler adoption was monotonically decreasing in growing-season-adjusted Winter/Fall temperatures (*LNTEMP10-3*).

The proportion of acres using sprinkler irrigation is evaluated at the regressor sample means for different ranges of May-September temperatures. At the lower range of observed data (about 61 degrees F), sprinkler adoption is relatively high. As May-September temperatures increase, the expected proportion of sprinkler acres declines. Adoption rates for smaller scale operations is everywhere lower than for larger operations. At the limit of observed data (about 83 degrees F), the sprinklers are expected to be used on about 30% of acres on the largest operations and on less than 20% of acreage irrigated by the smallest. A similar pattern holds for growing-season-adjusted Fall/Winter temperatures. As temperatures reach the upper end of observed data, sprinkler adoption rates among acres irrigated by the smallest operations falls to about 20% of irrigated acreage.

These results suggest that, in areas with warmer climates, there may be limited scope to adapt to climate warming via adoption of sprinkler irrigation systems. In cooler climates, the relationship between climate warming and sprinkler adoption is more complex. The variable *LNTEMP10-3* does not include fall and winter months with average temperatures below 32 degrees. This is because one would not expect changes in off-season temperatures to affect irrigation decisions for the growing season. However, climate warming may convert and off-season month to a relatively cold growing-season month. If it does so, it is possible that this effect will *lower* the value of *LNTEMP10-3* and encourage sprinkler adoption. This is a mathematical explanation, but not an agronomic one. In agronomic terms, warming in cold climates increases the number of months where plant growth is possible, but simultaneously may increase frost risk in this expanded growth window. Whether climate warming has a positive effect on sprinkler adoption in colder states, however, will depend on a complex combination of changes in the length of growing season, Fall/Winter temperatures and Spring/Summer temperatures. Our results do suggest, however, that in warmer western states (Arizona, California, New Mexico, Oklahoma, Oregon and Texas), climate warming would discourage sprinkler adoption.

These results regarding temperature apply only to the choice of sprinkler irrigation relative to gravity irrigation (i.e., changes at the intensive margin). They say nothing about whether sprinkler adoption may encourage more land to be brought under irrigated cultivation. Caswell and Zilberman (1986) discuss conditions where introduction of sprinklers would increase total acreage under irrigation. Caswell et al. (2001) found evidence of warmer temperatures increasing sprinkler irrigation adoption, relative to dryland production. There is also the possibility that some irrigators may switch to drip irrigation in response to warmer temperatures (e.g., Mendelsohn and Dinar, 2003; Olen et al., 2012). Other climate adaptations include switching the mix of crops grown and deficit irrigation (Moreno and Sunding, 2005; Schoengold, et al., 2006; Frisvold and Konyar, 2012b; Olen et al., 2012).

The coefficient on average annual sheet and rill erosion is positive and significant, indicating that in areas with high erosion, sprinkler irrigation systems are more likely to be adopted. Because sheet and rill erosion is more likely on areas with greater rainfall, steeper slopes, and poorer water-holding capacity, it is likely this variable is picking up the effects of combinations of these factors. The results here are consistent with previous research suggesting sprinkler adoption will be greater in areas with greater precipitation where it can supplement rainfall (Negri and Brooks, 1990; Mendelsohn and Dinar, 2003) and on lower quality soils (Caswell and Zilberman, 1985; Negri and Brooks, 1990; Mendelsohn and Dinar, 2003). Figure 4 illustrates how the proportion of acres irrigated with sprinklers increases with a state's index of sheet and rill erosion. In arid regions such as Arizona, California, and Nevada, there is less scope for sheet and rill erosion because there is less rainfall. In these states, the index is near its lowest level among observations (0.2–0.7). In this range, the proportion of acreage irrigated with sprinklers would be expected to be in the 20%-30% ranges among the smallest scale operators.

Finally, because sprinkler systems tend to be laborsaving, we would expect that higher wages would encourage sprinkler adoption. Negri and Brooks (1990), using annual wage rates, find a positive relationship. The regression coefficient for wages is positive and significant in our analysis (Table 3).

CHAPTER EIGHT

POLICY IMPLICATIONS AND CONCLUSIONS

This study illustrates how special tabulations of the USDA Farm and Ranch Irrigation Survey (FRIS) can be used for multivariate regression analysis. A simple model that divides irrigators into state–farm size pairs explains 80% of the variation in the extent of adoption of sprinkler irrigation relative to gravity irrigation across 17 western states. The proportion of acres irrigated with sprinkler irrigation was greatest for the largest operations and lowest among the smallest (in terms of sales). Adoption of sprinkler irrigation was also positively influenced by the extent of sheet and rill erosion, which captures effects of greater rainfall, steeper slopes, and soils with less water-holding capacity. Sprinkler adoption increased with water costs, reliance on groundwater and farm wages.

Several commentators have suggested adoption of improved irrigation will be important for agricultural adaptation to climate change (e.g., Burton 2000; Cavagnaro et al. 2006; Jackson et al. 2009; Joyce et al. 2009; Kurukulasuriya and Rosenthal 2003; Smit and Skinner 2002). A number of studies have raised questions about whether smaller-scale agricultural operators will have the financial or technical capacity to adequately adapt to climate change (Joyce et al. 2001; Wolfe et al.. 2008; Walthall et al., 2012; McLeman et al., 2008). Our findings suggest smaller scale producers in the western United States adopt more efficient sprinkler irrigation systems to a significantly lower extent than their larger-scale counterparts.

The lower rates of sprinkler adoption among smaller-scale producers raise the question of whether policy interventions are warranted to encourage greater adoption by these producers. The Environmental Quality Incentives Program (EQIP) provides cost share payments to U.S.

farmers, subsidizing adoption of a variety of conservation practices and investments. Sprinkler adoption is the third most common EQIP-subsidized practice, with growers receiving more than $400 million in payments from 1997 to 2010 (Wallander et al., 2013). Farmers with lower sales have participated less in EQIP and other water- or energy conservation programs, however (Nickerson and Hand, 2009; Frisvold and Deva, 2012). The 2002 and 2008 Farm Bills included provisions to increase use of EQIP among beginning, socially disadvantaged, or limited resource farmers (Nickerson and Hand, 2009). These groups include farmers with relatively lower sales (our definition of small-scale operations). Schaible (2004) raises the point that there may be an efficiency-equity trade-off in targeting smaller scale irrigators for greater conservation program participation. He points out that larger scale operators account for the bulk of irrigated acreage and irrigation water use. Targeting larger-scale producers may thus lead to greater overall improvements in irrigation technology and water conservation.

This study's results suggest that even among larger scale operations, adoption of sprinkler irrigation may not be a preferred adaptation to climate warming. Sprinkler adoption declined monotonically in Spring/Summer temperature and growing-season-adjusted Fall/Winter temperature. In colder states, complex interactions of changing growing season length and frost risk may encourage sprinkler adoption. For warmer climates, however, warmer temperatures discourage sprinkler adoption. Adoption of sprinkler irrigation was also positively related to an index of sheet and rill erosion, which may proxy for effects of greater rainfall, steeper slopes, and soils with less water-holding capacity. Values for the erosion index have been found to be more sensitive to changes in rainfall amounts and intensity than changes in other environmental variables (Nearing, 2001). Projections of future rainfall for the western United States remain highly variable. Nearing (2001) projected that the rainfall component of the erosivity index would increase in some parts of the West under climate change, but decrease in other parts.

The Third National Climate Assessment of the U.S. Global Change Research Program projects a decrease in spring and winter precipitation in the Southwest, which would reduce the erosion index (Walsh and Wuebbles, 2013), which our regression results suggest would discourage sprinkler adoption. However, the Assessment also projects an increase in the frequency and intensity of extreme precipitation events (Walsh and Wuebbles, 2013), which would have the opposite effect. In sum, our results suggest sprinkler irrigation is more likely to be a potential climate adaptation in areas that are relatively cold and where extreme precipitation events increase. Sprinkler adoption is less likely in warmer climates and under drier climate change scenarios. An implication for climate adaptation policy is that for hot, arid parts of the U.S. West, other adaptation strategies – such as deficit irrigation, adoption of drip irrigation, and use of advanced water management practices (such as soil- or plant-moisture sensing devices, commercial irrigation scheduling services, or computer-based crop-growth simulation models) – may be more important to pursue.

Regression results suggest that sprinkler adoption is lower where water costs are low and where reliance on surface water is greater. One policy option to encourage greater sprinkler adoption may be incentive pricing for surface water. Many irrigation districts do not charge irrigators the marginal cost of surface water, but apply quantity rationing, price water for district infrastructure cost-recovery, or follow other allocation schemes that do not reflect the true scarcity of water. Movements to marginal cost pricing, perhaps under tiered pricing schemes may act to encourage adoption of more efficient irrigation technologies such as sprinklers and drip systems.

Major policy proposals to mitigate climate change usually involve some form of carbon tax or cap-and-trade scheme for emission permits. Both policies would increase the cost of fossil fuels. Such policies can greatly increase costs of groundwater pumping and the relative profitability of growing different crops (Frisvold and Konyar, 2012a). Carbon taxes or cap-and-trade policies could have complex implications for irrigation technology. While our results suggest that irrigators shift away from gravity systems under higher water costs, sprinkler systems tend to be energy intensive. More research is needed in the area of the role of energy costs, irrigation technology choice, crop choice, and water demand.

The FRIS collects the most detailed, comprehensive data on irrigation practices and water use at the national and state level in the United States. Yet, the survey data is seldom used for statistical analysis of irrigator behavior. This is because USDA reports data as tables of state-level aggregates, providing far too few observations for multivariate analysis. To protect respondent confidentiality, access to farm-level FRIS data is restricted. For this reason, rigorous research using FRIS data has been limited to a few studies conducted by USDA economists (and collaborators) (e.g. Negri and Brooks, 1990). A notable exception to this rule is a recent, interesting study by Olen et al. (2012) that analyzed farm-level FRIS data for >1,000 irrigators in California, Oregon, and Washington. This study has sufficient geographic scope to assess effects of climate and irrigator behavior in detail.

One goal of this article is to illustrate that data such as the Special Tabulation of the FRIS provided by USDA's Economic Research Service is a valuable type intermediate data product for researchers without access to farm-level FRIS data. If USDA made more such special tabulations available, then researchers would actually use FRIS data for more than simple descriptions of general irrigation trends and patterns. Another possibility for using publicly available FRIS data could be to assess joint crop-irrigation technology choices in a framework similar to Moreno and Sunding (2005), Schoengold et al. (2006), and Olen et al. (2012), albeit for more aggregate data. The FRIS does report irrigation technology choice, acreage, and water use by crop and state for multiple years. It is possible to exploit the time-series cross-section nature of the data to evaluate a wide geographic area with a sufficient sample size. The geographic scope of the FRIS means it is a valuable source of detailed data to assess climate-irrigation relationships. More and better use of this data would significantly increase our understanding of such relationships.

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Table 1. Shares of irrigated acreage in the United States by method of irrigation

Year	Agency Report	Gravity	Sprinkler	Drip and subsurface
1979	NASS	63%	36%	1%
1995	USGS	52%	40%	3%
1998	NASS	50%	45%	5%
2000	USGS	48%	46%	7%
2003	NASS	43%	51%	6%
2005	USGS	44%	50%	7%
2008	NASS	39%	54%	7%

Sources: USDA NASS (1998, 2004, 2010); Aillery and Gollehon (2003); Solley et al. (1998); Hutson et al. (2004); Kenny et al. (2009)

Table 2. Crop specialization and adoption of sprinkler irrigation by crop: California and the rest of the west

Crops	Percentage of Regional Irrigated Acreage		Percentage of Region's Acreage Irrigated with Sprinklers	
	California	Other 16 Western States	California	Other 16 Western States
Alfalfa	19%	81%	12%	53%
Vegetables	36%	64%	54%	54%
Orchards	43%	57%	14%	26%
Cotton	22%	78%	9%	38%
Wheat	11%	89%	7%	66%
Hay	9%	91%	10%	14%
Potatoes	6%	94%	95%	96%
Corn	3%	97%	1%	72%
Barley	6%	94%	23%	67%

Source: USDA NASS (2010)

Table 3. Descriptive statistics for variables used in irrigation choice regression

Variable name	Variable description	Mean	Minimum	Maximum
PS_{ij}	Acreage irrigated with sprinkler systems as a proportion of the sum of area to irrigate with sprinkler and gravity systems	1.21	0.02	18.01
$Ln\ (PS_{ij} / PG_{ij})$	Ln of the proportion acres irrigated with sprinklers over the proportion of acres irrigated with gravity methods	-0.38	-3.95	2.89
D2008	Dummy variable	0.5	0.0	1
Small	Farms with sales less than $100,000	0.25	0.0	1
Medium	Farms with sales from $100,000 to $249,999	0.25	0.0	1
Large	Farms with sales from $250,000 to $499,999	0.25	0.0	1
LNWater Costs	Average water cost per acre foot applied	$3.01	$1.32	$4.34
Surface Water	Proportion of surface water to total irrigation water from all sources	0.58	0.0	0.99
LNTEMP5-9	Ln of average of long-run monthly temperatures from May to September	4.21	4.11	4.41
LNTEMP10-3	Ln of growing season adjusted average of long-run month temperatures from October to March	3.78	3.66	4.04
LNEROSION	Average annual sheet and rill erosion on nonfederal land	0.48	-1.61	1.55
LNWAGE	Hired farm labor wages	0.07	0.008	0.15

Table 4. Factors affecting the adoption of sprinkler irrigation.

Dependent variable: $ln\ [(PS_{ij}/PG_{ij})]$ where PS_{ij} is the proportion of acreage irrigated with sprinkler systems and PG_{ij} as a proportion of acreage irrigated with gravity systems.

Adjusted R-squared: 0.70. Number of observations: 136.

Variable	Parameter coefficient	Standard error	P value
Intercept	22.168	3.237	3.01E-10
D2008	-0.179	0.102	8.69E-11
Small	-0.451	0.143	0.0019
Medium	-0.328	0.138	0.0189
Large	-0.256	0.138	0.0671
PCSW	-1.459	0.296	2.48E-06
LNTEMP5-9	-3.697	1.128	0.0014
LNTEMP10-3	-1.888	0.831	0.0247
LNEROSION	0.534	0.071	7.63E-12
LnP	0.372	0.139	0.0086
LNWAGE	3.381	1.223	0.0066

*The null hypothesis of homoscedasticity could not be rejected