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Irrigation Technology Choice as Adaptation to Climate Change in the Western United States

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Abstract: Several commentators have suggested adoption of improved irrigation will be important for agricultural adaptation to climate change. This study used data from a special tabulation of the United States Department of Agriculture (USDA) Farm and Ranch Irrigation Survey to examine how climate and other factors influence the choice of sprinkler versus gravity-flow irrigation across 17 western states. 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. Results suggest sprinkler irrigation is a more promising climate adaptation in areas that are relatively cooler and where extreme precipitation events increase. Sprinkler adoption is less likely in warmer climates and under drier climate change scenarios. An implication is that for hot, arid parts of the West, other climate adaptation strategies may be more important to pursue. Consistent with several previous studies, sprinkler adoption was greater among farms that were larger, had higher water costs, and relied more on groundwater. Sprinkler adoption was also greater in states with a higher erosion index that captured effects of rainfall, field slope, and soil water-holding capacity, which also have been found to be important adoption predictors in a number of previous studies.

Keywords: *irrigation, climate change, technology adoption, farm size, sprinkler, gravity-flow*

Improved irrigation efficiency has been cited as an important way to adapt to climate change (Burton 2000; Smit and Skinner 2002; Kurukulasuriya and Rosenthal 2003; Cavagnaro et al. 2006; Jackson et al. 2009; Joyce et al. 2009). 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 weather extremes such as drought stress or frost. Yet, drip or sprinkler irrigation can require large capital costs. Irrigators often cite financial constraints as major barriers to investing in improved irrigation efficiency (Frisvold and Deva 2012).

Irrigation Technology Choice as Climate Adaptation

Researchers have thoroughly studied factors affecting adoption of improved irrigation technology. Yet, relatively few studies have included climate variables in empirical analyses. Studies of irrigation technology adoption have often concentrated on small geographic areas, such as a single irrigation district. The geographic scope of such analyses can be too narrow to measure effects of climate. Long-term climate averages change little over time and localized studies may have insufficient variation in climate to allow for econometric analysis. Put simply, over too narrow a geographic range, potential climate variables do not vary. Narrow geographic scope can also lead to multi-collinearity between climate variables, limiting the number of 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. Negri et al. (2005) examined the effect of climate on the decision whether or not to irrigate. Negri and Brooks (1990) considered effects of climate on choice of irrigation technology among irrigators. Mendelsohn and Dinar (2003) examined climate effects on the share of acres that were

irrigated with gravity, sprinkler, or drip systems across U.S. counties. Caswell et al. (2001) also examined climate effects on the choice of whether to irrigate, along with the choice of irrigation method for individual producers. Frisvold and Deva (2013) examined how climate affects the choice between sprinkler and gravity-flow technologies using farm-size stratified, state-level data. These studies found climate variables had important impacts on irrigation adoption decisions. Dinar et al. (1992) found that temperature and rainfall variables were not significant, but the study was limited to California's San Joaquin Valley and coefficients of variation for 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. Olen et al. (2016), using farm-level data for three West Coast states, found that growers use sprinklers to mitigate risk of crop damage from extreme weather.

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 2016). While the USDA conducts the national FRIS every five years, published tables report state-level aggregate data, focusing on 2 x 2 relationships. This data configuration is not amenable to multivariate analysis. ERS's Special Tabulation, however, reports data for the 1998 and 2008 FRIS, stratifying observations by four farm sales classes for the 17 westernmost contiguous U.S. states. This provides 136 state-farm size pairs with sufficient geographic scope to conduct a regional analysis of irrigation technology adoption.

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 and discuss trends in the diffusion of sprinkler technology. We then review the literature on sprinkler irrigation adoption, which has examined the role of soil characteristics (especially those affecting water-holding capacity of soils), water and 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. We then analyze the results of the regression and conclude by discussing the implications of our main findings.

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).

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 (Negri and Brooks 1990; Negri et al. 2005).

Negri and Brooks (1990, 214) noted, "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." Sprinkler systems can be used on steeper slopes unsuited to gravity systems and on soils with lower water-holding capacity. Sprinkler irrigation can have much higher application efficiencies than traditional gravity irrigation (Sloggett 1985). While gravity

systems have application efficiencies usually ranging from 40-65%, efficiencies from sprinkler systems typically range from 75-85% (Aillery and Gollehon 2003). Beyond critical temperature thresholds, advantages of sprinkler systems may be negated, however, by large evaporation losses (Olen et al. 2016). Evaporation losses from heat can be exacerbated by windy conditions (Negri and Hanchar 1989).

In addition, on-farm application efficiency is not the same as system-wide efficiency. Although more applied water may be taken up by the crop in sprinkler systems, this means that there is less water available as return flows or to aquifers through groundwater recharge. Thus, at a system level, more "efficient" systems can actually increase consumptive use of water (Ward and Pulido-Velazquez 2008). Greater off-farm flows may have benefits of, "diluting agricultural chemicals or septic tank leachate in shallow groundwater, providing groundwater recharge to shallow wells, and providing delayed return flow to the stream thus maintaining in-stream flow after peak runoff periods" (Fernald and Guldan 2006, 79). Yet, in other cases, sprinkler systems can lessen production of contaminated drainage water (Caswell 1991).

Sprinkler systems have higher capital costs than gravity systems. This may act as a barrier to adoption for farms below some critical size. Sprinkler systems tend to be energy-using and labor-saving relative to gravity systems. Thus, their relative profitability will depend on labor and energy costs. The social as well as private benefits of sprinkler versus gravity flow systems will depend on a complex combination of economic, agronomic, and climate factors.

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 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 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).

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. Negri and Brooks (1990, 214) noted, "traditional gravity systems applied to land with high water-holding capacity due to high clay content and level slopes can achieve application efficiencies comparable to sprinkler irrigation. Conversely, lands with porous soils or steep slopes are unsuitable for gravity irrigation because of excessive deep percolation or runoff."

Because modern systems compensate for soils with poor water-holding capacity, improved irrigation technologies would be relatively more profitable on such soils. Subsequent empirical studies supported Caswell and Zilberman's theoretical specification (Dinar and Yaron 1990; Negri and Brooks 1990; Dinar et al. 1992; Green and Sunding 1997; Schuck and Green 2001; Mendelsohn and Dinar 2003).

Economic theory and previous empirical findings suggest there are systematic relationships between operation scale and irrigation methods. 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, 43) reported a "lack of interest in making improvements to current irrigation systems or methods on the smallest farms." 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, 569) found that smaller farms 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."

Sprinkler systems require fixed capital investments, so average fixed costs fall with scale of operation. 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. Frisvold and Deva (2013), in contrast, found a positive relationship between sprinkler adoption and farm size using 1998 FRIS data. Green et al. (1996), Green and Sunding (1997), and Dinar et al. (1992) observed positive relationships between sprinkler adoption and farm field size.

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 areal 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). There is a distinction between farm scale and field scale. Technological factors may account for economies of scale at the field level. Scale of farm operation may affect 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 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 and 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 the irrigation district level (for example) may not exhibit sufficient cross-sectional variation in climate. Studies covering wider geographic areas 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 California's San Joaquin Valley, which has less variation in rainfall than the other two studies. Negri and Brooks (1990) 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, 9) stated, "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." Based on farm-level analysis of California, Oregon, and Washington irrigators, Olen et al. (2016) argue that above a critical temperature threshold, high evaporative losses from sprinklers negate efficiency advantages of sprinklers, making them less attractive relative to gravity or drip systems. Mendelsohn and Dinar (2003, 338) 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."

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. (2016) cited 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. Results have been mixed. Negri and Brooks (1990) found that higher farm labor wages were associated with greater adoption of sprinkler irrigation. Mendelsohn and Dinar (2003) reported greater use of sprinklers in counties with higher farm wage rates in January, but lower wage rates in April. Frisvold and Deva (2013) found no significant relationship between current farm wages and sprinkler adoption, but found growth in wage rates over the previous five years was associated with higher sprinkler adoption rates.

Data and Regression Model Specification

Irrigation data come from special cross-tabulations of the 1998 and 2008 Farm and Ranch Irrigation Survey (FRIS) (USDA, NASS, 1998; 2010) reported by USDA's Economic Research Service (USDA ERS 2016). 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, survey data are 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 study by Olen et al. (2016) 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.

The ERS special cross-tabs report data for the 17 western contiguous states (North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Texas, Montana, Wyoming, Colorado, New Mexico, Idaho, Utah, Arizona, Nevada, Washington, Oregon, and California) 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.

Let the proportion of hectares 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 hectares 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. The proportion of hectares irrigated with sprinklers as a share of hectares irrigated with sprinklers and gravity systems ($PS/(PS + PG)$) has grown for all farm size classes between 1998 and 2008 (Figure 1). 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



Figure 1. Percentage of hectares irrigated with sprinklers. Weighted average from 17 western states by farm sales class (Small: $0 to $99,999 in sales; Medium: $100,000 to $249,999; Large: $250,000 to $499,999; Very Large: $500,000 and greater). Source: USDA, ERS (2016).

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. Table 2 shows descriptive statistics for regression variables.

The variable *ln Water Cost* is measured as (the natural log of) water cost per acre-foot applied. An acre-foot is volume of a sheet of water one acre (0.405 hectare) in area and one foot (30.48 cm) in depth. It equals 1,233.5 m^3 of water. The per-unit-of-volume water cost is a weighted average that combines the costs of pumping surface water and groundwater as well as prices paid for off-farm delivered surface water.

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, 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 include two climate variables. *LNTEMP5-9* is (the log of) monthly 40-year mean temperatures in °F weighted by cropland 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. 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. 2016). *LNTEMP10-3* is intended to measure such frost risk. Winter months with average temperatures below 32 °F (0 °C) are not included in *LNTEMP10-3.* 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. We hypothesize 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 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). According to the NRCS (Potter et al. 2006, 73), "Sheet erosion takes place when the dislodged soil particles are moved by thin sheets of water flowing over the surface. Rill erosion occurs when the surface flow of water establishes paths and the flowing water detaches soil particles from the sides and bottoms of the rills that are formed." *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 that 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 is 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 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

Table 2. Descriptive statistics for variables used in Irrigation Choice Regression.

Variable Name	Variable Description	Mean	Minimum	Maximum
$PS_{ij}/(PS_{ij} + PG_{ij})$	Acreage irrigated with sprinkler systems as a proportion of the sum of area to irrigate with sprinkler and gravity systems	0.53	0.02	0.95
Ln (PS_{ij} / PG_{ij})	Ln of the proportion hectares irrigated with sprinklers over the proportion of hectares irrigated with gravity methods	0.14	-3.95	2.92
Ln Water Costs	Ln of average water cost, $ per acre-foot (AF) applied	$3.01	$1.32	$4.34
	Antilog of ln water costs ($ / AF)	$20.22	$3.76	$77.00
	Antilog of ln water costs ($ / thousand cubic meters)	$16.39	$3.05	$62.42
Surface Water	Proportion of surface water to total irrigation water from all sources	0.578	0.000	0.996
LNTEMP5-9	Ln of average of long-run monthly temperatures from May to September	4.207	4.107	4.413
	Antilog of *LNTEMP5-9* (F)	67.2	60.8	82.5
	Antilog of *LNTEMP5-9* (C)	19.6	16.0	28.1
LNTEMP10-3	Ln of growing season adjusted average of long-run month temperatures from October to March	3.78	3.66	4.04
	Antilog of *LNTEMP10-3* (F)	43.9	38.8	57.0
	Antilog of *LNTEMP10-3* (C)	6.7	3.8	13.9
LNEROSION	Ln of average annual sheet and rill erosion on nonfederal land	0.48	-1.61	1.55
	Antilog of *LNEROSION*	1.61	0.20	4.70
ΔLNWAGE	Continuous growth rate of farm wages	3.01	1.32	4.34

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 suggest that sprinkler adoption would increase in *LNEROSION*, via the relationship with *K*.

Land with steeper slopes has 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 other components of the USLE appear to both increase *LNEROSION* and contribute to greater sprinkler adoption, so slope length may have a confounding effect. Yet, computed values for *LNEROSION* are not very sensitive to slope length, particularly on flat landscapes (IWR-MSU 2002). 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. Following Frisvold and Deval (2013), we estimated the effects of growth rates in farm labor wages on sprinkler system adoption. The variable Δ*LNWAG*E was the log of hired farm labor wages minus the log of wages from five years earlier. This represents the continuous growth rate in hired labor wages from five years before both the 1998 and 2008 FRIS observations. Annual wage rates are reported by multi-state region rather than by state in the USDA's Quick Stats database (http://quickstats.nass.usda.gov/).

Regression Results

The regression equation was estimated using ordinary least squares (Table 3). 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. The coefficients for farm size variables grow increasingly negative as farm size grows smaller. This suggests there is a positive, monotonic relationship between farm size and sprinkler adoption.

Water costs had a positive and significant effect on sprinkler adoption, 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). As noted above, the water cost variable may be measured with error because the measure captures average rather than marginal costs, irrigators are quantity constrained, or both. Our water cost variable may be incorrectly measuring the true water costs irrigators face. This "errors-in-variables" can lead to attenuation bias such that the coefficient estimate is biased downward. The measurement error presents a problem if the *lnWaterCost* variable is correlated with the regression error term. We performed a Hausman-Wu test as follows. First, *lnWaterCost* was regressed on the percentage reliance on surface water, farm size dummies, a year dummy, and fixed effects for USDA production regions (Northern Plains, Southern Plains, Southern Mountain, Northern Mountain, and Pacific Northwest, with California as the default). Next, residuals from this first stage regression were included as an additional variable in the irrigation adoption regression. The null hypothesis that the *lnWaterCost* variable is exogenouse is a test that the residuals are significantly different from zero. We could not reject the null hypothesis that the residuals coefficient is zero ($p = 0.768$). This suggests that *lnWaterCost* is not correlated with the adoption equation error term, biasing the OLS estimates.

The proportion of hectares irrigated with sprinklers decreased with greater reliance on surface water. Reliance on surface water appears to have a negative effect on sprinkler

Table 3. Factors affecting the adoption of sprinkler irrigation. Ordinary least squares* results.

Variable	Parameter Coefficient	Standard Error	P-value (significance level)
Intercept	22.789	3.518	0.000
D2008	0.274	0.113	0.017
Small	-0.667	0.158	0.000
Medium	-0.600	0.153	0.000
Large	-0.342	0.153	0.028
Surface Water	-1.936	0.332	0.000
LNTEMP5-9	-3.591	1.247	0.005
LNTEMP10-3	-2.083	0.917	0.025
LNEROSION	0.760	0.078	0.000
Ln Water Cost	0.448	0.155	0.004
ΔLNWAGE	0.184	1.205	0.879

Dependent variable: *ln* [(*PSij/PGij*)] where *PSij* is the proportion of acreage irrigated with sprinkler systems and *PGij* as a proportion of acreage irrigated with gravity systems.
Adjusted R^2 = 0.754. Number of observations = 136.
*The null hypothesis of homoscedasticity could not be rejected.

adoption beyond differences in water pumping costs (pumping surface water costs less than groundwater). Negri and Brooks (1990) noted 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 hectare of irrigated land, rather than based on the volume of water applied. In these cases, the marginal cost of water (per volume of water) 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) noted 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.

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*).

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 °F (0 °C). 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 an 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 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), warmer temperatures 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. Some irrigators may also switch to drip irrigation in response to warmer temperatures (Mendelsohn and Dinar 2003; Olen et al. 2016). Other climate adaptations include switching the mix of crops grown and deficit irrigation (Moreno and Sunding 2005; Schoengold et al. 2006; Frisvold and Konyar 2012; Olen et al. 2016).

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). The wage growth rate variable was positive as in Frisvold and Deva (2013), but it was not statistically significant. We experimented with current wage levels and lagged levels. These were statistically insignificant as well.

Policy Implications and Conclusions

This study illustrated how special tabulations of the USDA Farm and Ranch Irrigation Survey (FRIS) can be used for multivariate regression analysis of irrigation technology adoption across 17 western states. First, results corroborated findings of a number of previous studies finding that adoption of sprinkler (versus gravity) irrigation increased with farm operation scale, water pumping and purchase costs, and reliance on groundwater. Sprinkler adoption was greater in states with a higher index of sheet and rill erosion, which captures effects of greater rainfall, steeper slopes, and soils with less water-holding capacity. Previous studies have found these individual factors to be important predictors of sprinkler adoption, so the erosion index may serve as a useful summary index of these effects in future research.

Second, the study took advantage of the West-wide scope of the FRIS data to examine the effects of climate on sprinkler adoption. Several commentators have suggested adoption of improved irrigation will be important for agricultural adaptation to climate change (e.g., Burton 2000; Smit and Skinner 2002; Kurukulasuriya and Rosenthal 2003; Cavagnaro et al. 2006; Jackson et al. 2009; Joyce et al. 2009). 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 West, other adaptation strategies – such as deficit irrigation, adoption

of drip irrigation, and use of advanced water management practices (e.g., soil- or plant-moisture sensing devices, commercial irrigation scheduling services, or computer-based crop-growth simulation models) – may be more important to pursue. Adoption of sprinkler irrigation increased with an index of sheet and rill erosion, which increases with precipitation amounts and intensity. 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). 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 cooler and where extreme precipitation events increase.

Third, results suggest smaller scale producers adopt sprinkler systems to a significantly lower extent than larger-scale producers. 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; McLeman et al. 2008; Wolfe et al. 2008; Walthall et al. 2012). 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, (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). Schaible (2004) noted there may be an efficiency-equity trade-off in targeting smaller scale irrigators for greater conservation program participation. Large-scale operations account for the bulk of irrigation water use. Targeting larger-scale producers may thus lead to greater overall improvements in irrigation technology and water conservation.

Fourth, 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.

Finally, a goal of this article is to illustrate that Special Tabulations of the FRIS provided by USDA's Economic Research Service are a valuable data product for researchers without access to farm-level FRIS data. If USDA made more such special tabulations available, then researchers could use FRIS data for more than simple descriptions of general irrigation trends and patterns. 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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