

## **Drought Severity, Crop Diversity, and Irrigation Technology in the Yakima Valley in South-Central Washington State**

**Abstract:** This paper examines the effects of climate change-induced crop water availability scarcity, proxied by drought severity, on agricultural land use. Focusing on the Yakima Valley in South-Central Washington State, we construct a panel of agricultural land use data from 2015 to 2024, and gridded drought and soil moisture data. Drought severity influences cropland adjustments, with moderate-or-worse droughts reducing the irrigated cultivated acreage by less than 1%. We find a shift to lower crop specialization, and intermittent fallowing. We also find that the use of sprinkler irrigation systems decreased for perennial crops. But the use of low volume irrigation systems for perennial crops increased particularly in drier-than-normal soil, as well as the use of surface irrigation systems for annual crops in non-drier-than-normal soil. Our findings provide insight into agricultural settings in arid regions that are increasingly facing climatic and institutional pressures due to the limited natural groundwater storage.

Keywords: Field-level adaptation, cropland adjustment

JEL codes: O13, Q12, Q15, Q54

## **1. Introduction**

Long-term drought exposure has significant and negative impacts on agricultural productivity, including crop failure and damage to pasture and rangelands (Kuwayama et al. 2019; Drugova et al. 2022; Runge et al. 2019; Gupta et al. 2020). Growers respond to drought by shifting cropping patterns away from water-intensive crops to less water-intensive crops (Kuwayama et al. 2019) and adopting water conservation irrigation technology (Boser et al. 2024). With widespread drought conditions in northwest United States and past significant drought-induced economic damage, understanding the effects of changes in crop water availability on agricultural lands are important for future national food security and the livelihood of farmers. There is a sizeable literature on the negative impacts of extreme climatic events on crop yield losses (Fisher et al. 2012; Schlenker et al. 2006, 2007; Lobell et al. 2011; Gammans et al. 2017; Sumner et al. 2026) and how farmers in high-income countries, as well as low- and middle-income countries, respond to extreme climatic events (Asfaw et al. 2018; Wimmer et al. 2024; Miller et al. 2021; Schmitt et al. 2024; Bozzola and Smale 2020; Cui and Zhong 2024).

Despite the extant literature dedicated to understanding the drought effects on agricultural production, yet the effects of climate change-induced crop water availability scarcity on agricultural lands are poorly understood. This paper addresses that gap by focusing on more direct measures of crop water availability, such as the Palmer drought severity index (PDSI) and soil moisture content. Specifically, we ask what is the impact of drought severity on agricultural lands and how the use of various irrigation systems respond to moderate-or-worse droughts.

To estimate the impact of droughts on agricultural land use and the use of irrigation technology, we construct a panel of annual agricultural lands data from 2015 to 2024 in the Yakima Valley in South-Central Washington State, irrigation technology, and gridded drought

and soil moisture data. We follow literature (Cui 2020; Kuwayama et al. 2019; Sumner et al. 2026) and employ a linear panel fixed effects model to estimate the effects of drought severity on agricultural lands. We find that droughts reduce irrigated cultivated acreage; a moderate-or-worse drought reduced the perennial crop shares by less than 1% in the current year. While increasing intermittent fallowing by about 7% in response to moderate-or-worse droughts. Smaller, yet statistically significant, moderate drought is associated with an increase in the share of annual crops. More specifically, the irrigated share of apple, pear, cherry, and alfalfa hay crops decreases in response to moderate-or-worse droughts. In contrast, the irrigated share of corn, grain, and hops crops increases.

Another important contribution of our work is to estimate the effects of moderate-or-worse droughts on various irrigation systems (e.g., sprinkler irrigation, surface irrigation, and low volume irrigation). Results suggest a decrease in the use of sprinkler irrigation systems for perennial crops share in response to moderate-or-worse droughts. In contrast, an increase in the use of low volume irrigation systems for perennial crops in non-drier-than-normal soil. In addition, an increase in the use of surface irrigation systems for annual crops in drier-than-normal soil. These cropland adjustments suggest a possible mismatch between the timing of irrigation decisions and the geophysical attributes of agricultural lands, such as soil moisture content, that support plant growth during drought.

Next, we quantify the risk-reducing potential of drought-induced crop diversification strategies. We find that growers adjust cropland shares to cope with drought-related crop yield shocks, particularly moderate drought exposure levels associated with a shift to lower crop specialization index. But extreme drought exposure levels associated with reduced number of crops grown and a decrease in the crop evenness index, which suggests an increase in spatial scattering, and

perhaps, intermittent fallowing. By understanding the responses of growers to drought exposures and the limited access to water resources, climate-resilient strategies and capacity building efforts can be better targeted.

## **2. Background**

Washington State agriculture produces more than 300 crops annually and is second to California in total agricultural exports (Washington State Department of Agriculture, 2016). The State is also vulnerable to drought conditions that have recently become more frequent and intense in their extent, and have been identified as the most economically damaging weather risk in Washington agriculture (Yoder et al. 2016).

Washington State declares drought based on two main criteria: (1) if total water supply available falls below the threshold 75% of normal (average of the last 30-year period), statewide or in specific geographic areas, and or (2) the water shortage will likely create undue hardship for water users or the environment.<sup>1</sup> There are two main categories of agricultural water users in the Yakima Valley: (1) non-proratable users (those with the most senior rights) and (2) proratable users. Non-proratable users would be served first from the total water supply available in the region and proratable users would equally share the remainder of available supply (U.S. Department of the Interior U.S. Bureau of Reclamation, 2002). For example, the drought in 2015, where 85% of Washington State was declared extreme drought status, resulted in an overall economic loss between \$633 million and \$773 million dollars (Washington State Department of Agriculture, 2016).<sup>2</sup> According to the 2024 Washington Annual Statistical

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<sup>1</sup> A detailed information about the Washington State Drought Declaration and Advisory is available here: <https://ecology.wa.gov/water-shorelines/water-supply/water-availability/statewide-conditions/drought-response>

<sup>2</sup> The final report on 2015 drought and Washington agriculture can be found here: <https://agr.wa.gov/departments/land-and-water/natural-resources/water-quantity/drought-info>

Bulletin, the average cash rent expense per acre in Kittitas, Yakima, and Benton for the past two years, 2023 and 2024, is \$176/acre, \$235/acre, and \$725/acre, respectively. The difference in cash rent expenses per acre in the county-level agricultural statistics potentially reflects the difference in irrigation water costs.

*Study area: Yakima Valley in south-central Washington State*

We focus on the effects of drought severity on agricultural land use in the Yakima Valley, an important agricultural hub in South-Central Washington State (Figure A1). Climate change-induced changes in snowpack accumulation and timing of snowmelt, erratic precipitation patterns, and reduced snow-rainfall fractions have caused a decline in water supply, particularly for agricultural purposes, the largest water user in the Yakima River Basin (Vano et al. 2010; Malek et al. 2018). The availability of irrigation water is dependent on the water reservoirs, and its agricultural economy is vulnerable to shortages in total water supply available. (U.S. Department of the Interior U.S. Bureau of Reclamation, 2002).

Agriculture in the Yakima Valley, which covers approximately 1,000 square miles of Kittitas, Yakima, and Benton counties, accounts for 8.4% of the total sales revenue in the region and much of cropland has access to regulated surface water irrigation (U.S. Department of the Interior U.S. Bureau of Reclamation, 2002). Climate in the Yakima Valley ranges from alpine and Cascade Range in north to arid in lower Yakima Valley in south, with mean annual precipitation levels varying from 140 inches in the northwestern part of the Valley (the Cascades) to less than 10 inches in the lower Valley and the Kennewick area (Morace et al. 1999). The average length of the irrigation season is from April to October. Major crops are apples, cherries, pears, hops, and alfalfa hay. Irrigated cultivated acreage are increasingly exposed to climate

variability and drought (Vano et al. 2010).<sup>3</sup> The main source of irrigation water in the Yakima Valley is surface water diverted from the Yakima River (U.S. Department of the Interior U.S. Bureau of Reclamation, 2002). Drought adaptation includes changes in cropping patterns, deficit irrigation, reduced irrigated acreage, or fallowing/idling land, and on-farm adjustments in the use of irrigation systems.

In 2023 and 2024, the total water supply available for the Yakima Basin watersheds fell short of 75% (average water supply from 1991 – 2020 period) reaching 48% in total and hence was declared as drought. For reference, Figure A2 shows monthly deviations of the historical monthly averages for March, April, May, June, and July. We see that for all years from 2015 to 2024, the deviations for either of the months are negative, except for 2021 when all months from March to July were positive. The larger negative deviations for May, June, and July indicate a significant shortage of water supply during these months of planting season for major crops in the region. The decline in reservoir storage is also seen in the downward trend in irrigated cultivated acreage in the Yakima Valley.<sup>4</sup>

Next, Figure A3 summarizes the crop-specific water supplies across pressurized and gravity irrigation systems. Irrigated field crops (e.g., corn for grain, wheat, dry beans, and other field crops) apply on average 2.15 acre-feet per acre of pressurized irrigation systems, while the use of gravity irrigation systems for field crops is 2 acre-feet per acre. Forage crops (e.g., alfalfa hay and corn for silage) apply on average 1.95 acre-feet per acre of pressurized irrigation systems and 1.75 acre-feet per acre of gravity irrigation systems. Specialty tree crops (e.g., orchards,

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<sup>3</sup> National Oceanic and Atmospheric Administration—National Integrated Drought Information System (NOAA-NIDIS). Washington Drought Information. Available at <https://www.drought.gov/states/washington> (Accessed on 8 April 2026).

<sup>4</sup> Figure A7 shows downward trends in irrigated cultivated acreage for both perennial and annual crops.

vineyards, and nut tree crops) apply on average 2.5 acre-feet per acre of pressurized irrigation systems and 0.5 acre-feet per acre of gravity irrigation systems. Fruits and vegetables apply on average 2 acre-feet per acre of pressurized irrigation systems and 1.75 acre-feet per acre of gravity irrigation systems.

To sum up, the Yakima Valley offers two key advantages. First, field-level data availability on agricultural land use and irrigation systems. This granular field-level data allows us to circumvent issues related to aggregation bias, an inherent issue when analyzing drought exposure effect using the county-year data (Fezzi and Bateman 2015). Second, the lack of groundwater extraction and therefore most growers in the Yakima Valley do not have access to groundwater to supplement surface water irrigation. However, during drought years or when water districts impose curtailments, some farmers can use supplemental groundwater with permits (Vaccaro J.J., and Olsen, T.D. 2007).<sup>5</sup> This unique setting allows us to empirically examine the drought effects of climate change-induced crop water availability scarcity on agricultural lands and irrigation behavior.

### **3. Empirical Model**

Our empirical strategy to identify the effects of drought severity on agricultural lands depends on the panel data of PLS section level and the exogenous temporal and spatial variations in exposure to drought conditions. Our empirical approach leverages annual agricultural land use data from 2015 to 2024, covering 1,640 PLS sections in the Yakima Valley. We assume that growers planting the same crops in the same PLS sections within the same irrigation districts make the same farming decisions.

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<sup>5</sup> The majority of farmers holding groundwater permits are outside of irrigation districts and nonproratable, and most likely grow primarily perennial orchards.

We first consider a parsimonious spatiotemporal fixed effects model including only different drought severity variables, as well as, PLS sections- and year-fixed effects to provide a preliminary understanding about the relationship between drought severity and agricultural land use:

$$y_{it} = \alpha + \sum_{k \in (M,S,E)} f(D_{it}^k; \beta) + \lambda_i + \tau_t + \varepsilon_{it} \quad (1)$$

where the dependent variable,  $y_{it}$ , represents irrigated share of perennial and annual crops, as well as the share of fallow/idled land in PLS section  $i = 1, \dots, 1640$  in year  $t = 2015, \dots, 2024$ ; the panel model includes a PLS section fixed effects  $\lambda_i$  to help control for unobservable time-invariant factors which can affect changes in the irrigated share of cultivated acreage such as soil attributes, irrigation water accessibility and topographic characteristics; and  $\tau_t$  represents the year fixed effects that helps control for unobservable time varying factors that are common to all PLS sections or regions, such as technological progress and factors of production (e.g., input and output prices).

We follow literature and use a flexible functional form,  $f(\cdot)$  to model the nonlinear relationship between drought severity and the irrigated share of cultivated acreage. The term

$\sum_{k \in (M,S,E)} f(D_{it}^k; \beta)$  includes three drought severity variables,  $D_{it}^M$ ,  $D_{it}^S$ , and  $D_{it}^E$ , which are total 5-day weeks under moderate, severe, and extreme drought conditions and will be our climate measure of crop water availability at the PLS section  $i$  in year  $t$ , respectively. Finally, the expression,  $\varepsilon_{it}$ , represent variations in the dependent variables that are not explained by the model. Standard errors are clustered at the PLS region level to account for spatial correlation of PLS sections within regions. There are 16 regions in our sample, comprising between 6 and 236 unique PLS sections. PLS regions also take into account other factors such as population growth

and income per capita in a geographic region that may affect agricultural land use. In the robustness checks, we cluster the standard errors at the irrigation district level and obtain standard errors using bootstrapping with 1000 replications to consider the spatial correlation that captures water-constraint tightness conditions at the growers' end.<sup>6</sup>

The full specification is given by:

$$y_{it} = \alpha + \beta_1 D_{it}^M + \beta_2 D_{it}^S + \beta_3 D_{it}^E + \lambda_i + \tau_t + \varepsilon_{it} \quad (2)$$

Above econometric specification captures the effects of different drought severity on the irrigated agricultural land use relative to near normal conditions.

Specifically, the dependent variable,  $y_{it}$ , represents irrigated share of perennial and annual crops, as well as the share of fallow/idle land at the PLS section  $i$  in year  $t$ . We further disaggregate the share of perennial and annual crops into fourteen major crops grown in the studied region to examine the effects of drought severity on individual crop shares at the PLS section. In this context, the dependent variable,  $y_{it}$ , represents the individual irrigated crop shares at the PLS section  $i$  in year  $t$ .

Following literature, we include control for weather variables,  $\mathbf{X}'_{it}$ . Weather controls include growing degree days and heat degree days, as well as the averages of solar radiation and wind speed. In addition, we also include 30-year moving averages of total precipitation levels,  $\overline{P}_{it}$ , and maximum temperatures,  $\overline{T}_{it}$ , in our main specification.

Our preferred econometric specification is given by:

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<sup>6</sup> There are 23 irrigation districts with 1 and 312 unique PLS sections located in different districts. In addition, 717 unique PLS sections are located outside of any irrigation districts. We re-run the main econometric specification after dropping observations from outside irrigation districts (see Table A7). Quantitatively, the regression results are the same.

$$y_{it} = \alpha + \beta_1 D_{it}^M + \beta_2 D_{it}^S + \beta_3 D_{it}^E + \mathbf{X}'_{it} \gamma + \overline{P}_{it} + \overline{T}_{it} + \lambda_i + \tau_t + \varepsilon_{it} \quad (3)$$

The dependent variable,  $y_{it}$ , represents irrigated share of perennial and annual crops, as well as the share of fallow/idled land at the PLS section  $i$  in year  $t$ .

Next, we create lagged drought severity indices from previous years and consider two time scales: the more recent (average drought severity index between  $t - 3$  to  $t - 1$  years) and the more distant (average drought severity index between  $t - 10$  to  $t - 4$  years). We include six lagged terms of drought severity indices (two different time scale lagged drought severity indices for moderate drought, severe drought, and extreme drought) as additional covariates in the right-hand side of our main specification. Taken together, this econometric specification allows us to consider growers' recent experiences with climate in farming decisions.

### *3.1. Effects of drought severity on various irrigation systems*

The field-level agricultural land use data also provides information about irrigation technologies associated with cropland. We use field-level irrigation system information to group individual irrigation systems into three broad categories: surface irrigation, sprinkler irrigation, and low volume irrigation systems. More specifically, we define a surface irrigation system when irrigated agricultural lands are irrigated by systems such as rill/furrow irrigation, wild flood, wheel line sprinklers followed by rill irrigation, and hand sprinklers followed by rill irrigation. Sprinkler irrigation systems include solid set, wheel line, hand move, big-gun, center pivot, and sprinkler irrigation systems. Low volume irrigation includes drip and micro- or mini- sprinklers. In this context, the dependent variable,  $y_{it}$ , represents the share of surface irrigation, sprinkler irrigation, and low volume irrigation systems for perennial and annual crops at the PLS section  $i$  in year  $t$ . In addition, we include more recent and distant lagged drought terms as previously

defined. This specification allows us to estimate the use of various irrigation systems across crop types in response to moderate-or-worse droughts.

### *3.2. Effects of drought severity on crop diversification strategies*

We are also interested in estimating drought-induced changes in cropping patterns. Following Bozzola and Smale (2020) and Asfaw et al. (2018), we create three measures of crop diversification strategies: (1) crop richness index, (2) evenness index, and (3) specialization index. Richness index represents the count of crops in a particular PLS section in PLS section  $i$  and ranges from 0 to 9. Evenness index represents the Shannon crop index, which is defined as the  $\sum \left( \frac{a_{ji}}{a_i} \right) * \ln \left( \frac{a_{ji}}{a_i} \right)$  where  $a_{ji}$  is the area of PLS section with crop  $j$  and  $a_i$  is the total irrigated area of PLS section. A higher or lower Shannon index suggests an increase or decrease in diversification in PLS section  $i$ . The minimum value of the Shannon crop index is 0 and the maximum value is 1.8 in the studied region. Specialization index represents the Herfindahl-Hirschman crop index (HHI), which is defined as the  $\sum (a_{ji}/a_i)^2$ . HHI values range from 0 to 1. Higher HHI value suggests a shift towards crop specialization and vice versa. Shannon index represents spatial diversity, while Herfindahl-Hirschman index represents concentration-specific diversity. Higher values of the Shannon crop index and lower values of the HHI index indicate higher crop diversity (Aguilar et al. 2015; Chavas et al. 2022).

## **4. Data**

To estimate the impact of different drought severity on agricultural land use in the Yakima Valley in South-Central Washington State, we combine the agricultural land use obtained from the Washington Department of Agriculture from 2015 to 2024 and measure of different drought severity levels obtained from the gridded drought data. In addition, we obtain the gridded soil

moisture content data from 1950 to 2024 to explore the mechanism through which drought may affect irrigation behavior.

#### *4.1. Agricultural land use data*

We obtained field-level agricultural land use data for Yakima Valley from 2015 to 2024 from the Washington State Department of Agriculture. Each field contains information on crop type, acres, and irrigation technology. We overlay the Washington State Public Land Survey (PLS) sections, which is a grid cell that measures 1 mile by 1 mile (~640 acres), on agricultural land use.<sup>7</sup> We then aggregate agricultural acreage at the PLS section level. This allows us to create panel data for our dependent variables, including agricultural land use and irrigation systems, and explanatory variables, such as drought severity levels at the PLS sections from 2015 to 2024. The sample size of the balanced panel data is 16,400, representing a unique 1,640 PLS sections for 10 years from 2015 to 2024. The unit of measurement is a PLS section in all our analyses.

Table A1 presents summary statistics for the share of agricultural land by irrigated and non-irrigated status for fourteen major crop used in the analysis across all PLS sections from 2015 to 2024. Panel A of Table 1 reports on the perennial crops share. Irrigated share of pasture and alfalfa hay are the dominant crops, with 20.1% and 18.7% respectively. The share of irrigated apples, grapes, cherries, and pears is 10.3%, 7.1%, 2.8% and 1.7%, respectively. The remaining irrigated perennial crops, such as blueberry and caneberry, are less than 0.5%. Panel B of Table 1 reports on the annual crops share. The share of irrigated corn crops is 9.6%, followed by hops (6.1%) and grain crops (3.0%). For completeness sake, we also report the non-irrigated crop

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<sup>7</sup> Washington Public Land Survey Sections is available at <https://geo.wa.gov/datasets/wadnr::wa-public-land-survey-sections/about>, accessed in March 2026.

types. The share of alfalfa hay (1.0%) and grain crops (8.4%) are the dominant non-irrigated crops.

To summarize, the total mean irrigated perennial crop shares in the studied region between 2015 and 2024 is 61.0% and the total mean irrigated share of annual crop share is 20.4%.

Table A3 report the annual mean difference in percent for each transition type: (1) irrigated agricultural land ( $t + 1$ ) minus irrigated agricultural land ( $t$ ), (2) non irrigated ( $t + 1$ ) minus non irrigated ( $t$ ), and (3) fallow/idled land ( $t + 1$ ) minus fallow/idled land ( $t$ ). The negative sign indicates that cropland in that category has transitioned to other crop types, while the positive sign indicates that that crop type has gained additional agricultural land in that year. For example, from 2017 onwards, irrigated agricultural land has been negative (row 1 of Table A1). This suggests that irrigated agricultural land either changes to non-irrigated agricultural land or becomes fallow/idle land for that year. During the majority of years during our study period, irrigated agricultural lands transitioned to fallow/idle land, with the percentage of fallow/idle land ranging from 0.05 to 5%.

#### *4.2. Drought data*

We assessed drought using the Palmer Drought Severity Index (PDSI). More specifically, we obtained 5-day weeks PDSI gridded data from the gridMET, a daily surface meteorological dataset with a spatial resolution of approximately 4 km for the years 2005 to 2024 (Abatzoglou 2013).<sup>8</sup> PDSI values are calculated using the temperature and precipitation data, and can range from -4 (extreme drought) to 4 (extreme wet). We follow literature to categorize the drought severity index into four indicators: (1) near normal (PDSI between -1.9 and 1.9), (2) moderate

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<sup>8</sup> Drought data is available at <https://www.climatologylab.org/gridmet.html>, accessed in March 2026.

drought (PDSI between -2.0 and -2.9), (3) severe drought (PDSI between -3.0 and -3.9), and (4) extreme drought (PDSI less than or equal to -4.0).<sup>9</sup> We then summed each category separately to calculate the total number of different drought severity levels in a year.

We also include weather variables such as total annual precipitation levels, and averages of solar radiation and wind speed obtained from the gridMET. Degree days are calculated using the daily minimum and maximum temperatures and then summed over the growing season to estimate the nonlinear effect of temperature on crop yields (Schlenker and Roberts 2009).<sup>10</sup>

Table A2 summarizes the drought and weather data used in the analysis. On average the total number of 5-day weeks associated with moderate, severe, and extreme drought is 11, 9, and 28 weeks, compared to the near-normal of 22 5-day weeks. During the study period, the average number of growing degree days was 1,551 and 3 heat degree days. In addition, the average annual precipitation level is 234.5 mm, the average annual solar radiation level is 185.5 watts per squared-meter, and the wind speed is 3.4 meters per second.

Figure 2 (left panel) plots PDSI values over time along with (a) the irrigated share of perennial crops, (b) irrigated share of annual crops, and (c) the share of fallow/idle land to examine the possible relationship between drought exposure and irrigated agricultural land use.

Similarly, Figure 2 (right panel) plots PDSI values over time along with the irrigated land share associated with (a) surface irrigation, (b) sprinkler irrigation, and (c) low volume irrigation.

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<sup>9</sup> National Weather Service, Climate Prediction Center: Drought Indices – Explanation. Available at [https://www.cpc.ncep.noaa.gov/products/analysis\\_monitoring/cdus/palmer\\_drought/wpdanote.shtml](https://www.cpc.ncep.noaa.gov/products/analysis_monitoring/cdus/palmer_drought/wpdanote.shtml)

<sup>10</sup> Degree days are defined as the sum of degrees above a lower baseline (here 10°C ) and below an upper threshold (here 29°C ) during the growing season (Schlenker et al. 2007).

Sprinkler irrigation systems account for the most irrigated cultivated acreage, followed by surface irrigation and low volume irrigation systems.

Taken together, perennial crop shares are majorly associated with sprinkler and surface irrigation systems, while annual crop shares are associated with sprinkler irrigation systems. During drought periods, the share of fallow/idled land increases, as well as the use of low-volume irrigation systems for perennial crops.

Figure A4 shows sufficient spatial variation in irrigated share of cultivated acreage and different drought severity in the studied region. Perennial crop shares are concentrated more in the northern and central parts of the Valley, whereas annual crop shares are concentrated in the southern part of the Valley. In addition, the southern part of the valley has experienced relatively more extreme drought levels. This shows enough temporal and spatial variations in drought severity and agricultural lands to empirically estimate the effects of drought on agricultural lands.

## **5. Empirical Results**

This section demonstrates the relationship between the share of irrigated agricultural land use and drought severity as well as the relationship between proportion of irrigation systems for irrigated cultivated crops and drought severity. First, we present a simple correlation between the share of irrigated agricultural land use and different drought severity exposure levels. Secondly, we present our main empirical results, with the estimation of confidence intervals via parametric bootstrapping and several robustness checks. Thirdly, we present the relationship between the proportion of irrigation systems associated with perennial and annual crops and soil moisture content to explore the mechanism through which drought may affect the timing of irrigation behavior.

### *5.1. Correlation between drought exposure and agricultural land use*

Figure 1 presents a within-region Pearson correlation between irrigated cultivated acreage and drought severity. The unit of measurement for the correlation is computed from PLS section deviations from the mean of the irrigated share of perennial crops at the PLS region in the Yakima Valley from 2015 to 2024. These deviations account for technological innovations, changes in cultivar practices, and potentially cancel out any other time-varying factors and help to eliminate any spurious correlations due to both agricultural land use and drought severity levels having trends. The first column of Figure 1 presents the correlation coefficient in response to moderate drought exposure, while the second and third columns present severe and extreme drought exposures. The change in perennial crop share is relatively stable with moderate or severe drought exposures, but it shows high fluctuation in extreme droughts. Specifically, the irrigated share of perennial crops is positively correlated with extreme drought exposure in 2017, 2018, 2020, 2023, and 2024, but negatively correlated in 2019, 2021, and 2022 (upper panel of Figure 1).

The lower panel of Figure 1 presents an estimated correlation coefficient for the irrigated share of annual crops. The share of irrigated annual crops has more volatility with moderate-or-worse droughts relative to the irrigated share of perennial crops. More specifically, extreme drought exposure has a negative correlation with the irrigated share of annual crops in 2015, 2020, 2022, 2023, and a positive correlation in 2019.

Taken together, these figures show differentiated effects of different drought severity exposure on irrigated cultivated acreage.

### *5.2. Panel estimates of drought exposure on agricultural land use*

Table 1 presents the panel estimates of drought severity effects on irrigated share of perennial and annual crops, as well as the share of fallow/idle land at the PLS sections in the Yakima Valley. The dependent variable is the irrigated share of agricultural land use, which ranges from 0 to 1 at the PLS sections from 2015 to 2024. The main explanatory variables are three different drought severity exposures: moderate, severe, and extreme. Our preferred specification includes weather and climate controls (columns 2, 4, and 6 of Table 3). Results suggest that moderate-or-worse drought exposure is negatively associated with irrigated perennial crops share, but positively associated with irrigated annual crops share, as well as the share of fallow/idle land relative to near normal conditions. More specifically, we find that a 10-unit increase in moderate drought exposure levels is associated with 0.47 percentage point (pp) decrease in irrigated perennial crop shares relative to near normal conditions. This effect translates to a 0.77% decrease from the sample mean of irrigated perennial crop share ( $=0.47/0.611$ ). Similarly, a 10-unit increase in severe and extreme drought exposure levels is associated with 0.29pp (or, 0.47%) and 0.28pp (or, 0.46%) decrease in irrigated perennial crop shares, respectively.

In contrast, irrigated annual crop shares are positively associated with moderate drought exposure level relative to near normal conditions, although the point estimate is weakly significant at the 10% significance level. The effect size is very small (0.09pp or 0.44% over the sample mean of irrigated annual crops share).

We also find that the share of fallow/idle land increases temporarily in response to moderate-or-worse droughts relative to near normal conditions. More specifically, we find that a 10-unit increase in moderate and extreme drought exposure levels, the share of fallow/idle land increases by 0.6pp (or, 6.45% over the sample mean of the share of fallow/idle land) and 0.3pp (or,

3.33%), respectively. Smaller, although statistically insignificant, the non-irrigated cultivated acreage also decreases with moderate-or-worse droughts (results not shown).

Next, to estimate drought effects on crop-specific irrigated land use, we disaggregate irrigated share of perennial and annual crops into fourteen major crops grown in the studied region. Table A4 summarizes the results obtained from the panel estimates. Results suggest that moderate-or-worse droughts have a significant and negative effect on the irrigated share of apple, pear, cherry, alfalfa hay, and beans. In contrast, moderate-or-worse droughts have a positive effect on irrigated share of corn and hops. More specifically, we find that a 10-unit increase in severe drought exposure levels is associated with 0.2pp (or, 1.94%) and 0.05pp (or, 1.79%) decrease in irrigated apple and cherry crop shares. In addition, moderate drought exposure is associated with a decrease in irrigated share of pear and alfalfa hay by 0.02pp (or, 1.18%) and 0.27pp (or, 1.44%). In addition, extreme drought exposure significantly decreases the irrigated bean crop share by 0.07pp (or, 35%). In contrast, severe and extreme drought exposures are associated with 0.15pp (or, 1.60%) and 0.1pp (or, 1.64%) increase in irrigated share of corn and hops.

Figure A5 summarizes the marginal effects of drought severity on fourteen major irrigated crop shares grown in the Yakima Valley.

### *5.3. Effect of lagged drought exposure on agricultural land use shares*

Figure 3 presents the marginal effects of drought severity on the irrigated share of perennial and annual crops, as well as the share of fallow/idle land. We report drought severity for two-time scales: the more recent (average drought severity index between  $t - 3$  to  $t - 1$  years) and the more distant (average drought severity index between  $t - 10$  to  $t - 4$  years). Results suggest that recent past droughts increase the effect size of contemporaneous drought exposures on irrigated agricultural land use. More specifically, we find that a 10-unit increase in moderate and

extreme drought exposure is associated with 0.55pp (or, 0.90%) and 0.36pp (or, 0.59%) decrease in irrigated share of perennial crops. For reference, the same unit of increase in moderate and extreme drought exposure is associated with 0.47pp and 0.28pp in the main results (Table 3). In contrast, a 10-unit increase in moderate and extreme drought exposure is associated with 0.13pp (or, 0.64%) and 0.11pp (or, 0.54%) increase in irrigated share of annual crops. In addition, recent past extreme drought exposure is also associated with a 0.48pp (or, 2.35%) increase in irrigated share of annual crops. Finally, a 10-unit increase in moderate and extreme drought exposure is associated with 0.7pp (or, 7.52%) and 0.3pp (or, 3.23%) increase in the share of fallow/idle land. Table A5 summarizes the effect of lagged drought exposure on irrigated share of perennial and annual crops, as well as the share of fallow/idle land.

#### *5.4. Effect of drought severity exposure on various irrigation systems share*

Figure 4 presents the marginal effects of drought severity on the use of irrigation systems for irrigated cultivated acreage. Results suggest that moderate-or-worse droughts are negatively associated with the use of surface and sprinkler irrigation systems for perennial crops, but extreme drought exposure is positively associated with the use of low volume irrigation systems for perennial crops. Additionally, moderate drought exposure is positively associated with the use of surface irrigation systems for annual crops. More specifically, we find that a 10-unit increase in moderate, severe, and extreme drought exposure is associated with 0.48pp (or, 1.28%), 0.37pp (or, 1%), and 0.44pp (or, 1.18%) decrease in the use of sprinkler irrigation systems for perennial crops. In contrast, moderate drought exposure is associated with 0.13pp (or, 2.32%) increase in the use of surface irrigation systems for annual crops and extreme drought exposure is associated with 0.14pp (or, 2%) increase in the use of low volume irrigation systems for perennial crops.

Table A6 summarizes the drought severity effects on various irrigation systems share of irrigated perennial and annual crops at the PLS sections from 2015 to 2024.

Next, we disaggregate the irrigated cultivated acreage into crop-specific shares of agricultural land used for each irrigation technology and repeat the panel regression separately for each crop (Table A8 and Figure A6). We provide a summary of the results here. First, moderate-or-worse droughts decrease the use of sprinkler irrigation systems for apple trees. In contrast, moderate-or-worse droughts increase the use of low volume irrigation systems for apple trees. Severe drought exposure also increases the use of low volume irrigation systems for grapes. In addition, the use of sprinkler irrigation systems decreases for cherry in response to severe drought. Second, moderate drought decreases the use of surface irrigation systems for alfalfa hay crop. In addition, extreme drought increases the use of sprinkler irrigation systems for corn but decreases it for grain.

Figure 5 shows the relationship between the proportion of irrigation systems for irrigated cultivated acreage and soil moisture content. The use of surface irrigation systems in drier-than-normal soil decreases for perennial crops but it increases for annual crops. While the use of surface and sprinkler systems for annual crops increases in drier-than-normal soil. The use of low volume irrigation systems increases in non-drier-than-normal soil for both perennial and annual crops.

### *5.5. Effect of drought exposure on crop diversification strategies*

We employ three different crop diversity indicators: (1) crop richness index, (2) crop evenness index, and (3) crop specialization index. Each indicator captures different aspect of crop diversification. For example, the richness index identifies the number of different crops grown. Evenness index captures the spatial distribution of crops grown, and finally the specialization

index captures the crop concentration in the studied region. Table 2 presents the effects of drought severity on various indicators of crop diversification at the PLS sections from 2015 to 2024. We find that differentiated cropland adjustment in response to moderate-or-worse droughts. For example, extreme drought exposure is associated with a decrease in crop richness and crop evenness indices. But we also find a shift towards lower crop specialization; particularly moderate drought exposure lowers specialization values (Figures A7 and A8). Specifically, a 10-unit increase in moderate drought exposure is associated with 0.37pp (or, 0.36%) decrease in specialization index, indicating a shift towards crop mix. But extreme drought exposure is associated with a 0.81pp (or, 0.35%) decrease in crop count, measured by richness index, and a 0.17pp (or, 1.10%) decrease in evenness index.

Taken together, moderate drought exposure is associated with a potential crop-rotation diversification strategy. While extreme drought exposure suggests a decrease in the number of different crops grown and an increase in spatial scattering of irrigated cultivated acreage.

## **6. Conclusions**

This paper examined the impacts of drought on the irrigated agricultural land use and irrigation systems in the Yakima Valley in south-central Washington State. First, field-level agricultural land use data from 2015 to 2024 were used in the panel data analysis to estimate the effects of different drought severity exposures on the irrigated agricultural land use. Second, we disaggregated perennial and annual crop shares into fourteen major crop groups grown in the studied region and estimated crop-specific land use decisions in response to different drought severity exposures. Third, we take advantage of field-level information on irrigation systems and estimate to what extent the irrigation switches from efficient irrigation systems to inefficient

irrigation systems. Finally, we created various crop diversification metrics to explore adaptation strategies at the field-level.

Study results show that drought exposure levels have significant and negative association with irrigated share of perennial crops but have significant and positive association with irrigated shares of annual crops, as well as the share of fallow/idled land relative to near normal conditions. More specifically, the irrigated share of apple, pear, cherry, and alfalfa hay crops decreases in response to different drought severity exposure levels. In contrast, the irrigated share of corn, grain, and hops increases. We find that growers adapt to crop diversification strategies, particularly moderate drought exposure lowers specialization values but reduces the number of crops grown and decreases the crop evenness index in response to extreme drought exposure. We also find that efficient irrigation systems are more resilient in response to drought exposure compared to inefficient irrigation systems, which reduce during drought periods.

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## Tables and Figures

**Table 1.** Effects of drought severity on agricultural land use in the Yakima Valley in South-Central Washington State, 2015 – 2024

|   | Irrigated perennial crops share       |   | Irrigated annual crops share        |                                    | Share of fallow/idled land           |  |
|---|---------------------------------------|---|-------------------------------------|------------------------------------|--------------------------------------|--|
|   | (1)                                   | (2)                                     | (3)                                 | (4)                                | (5)                                  | (6)                                    |
| Moderate Drought<br>( $-2.0 \leq \text{PDSI} \leq -2.9$ ) | -0.00061***<br>(0.00010)<br>[0.00012] | -0.00047***<br>(0.00011)<br>[0.00012]   | 0.00013**<br>(0.00006)<br>[0.00007] | 0.00009<br>(0.00004)*<br>[0.00007] | 0.00067***<br>(0.00019)<br>[0.00011] | 0.00060***<br>(0.00017)<br>[0.00010]   |
| Severe Drought<br>( $-3.0 \leq \text{PDSI} \leq -3.9$ )   | -0.00037**<br>(0.00016)<br>[0.00012]  | -0.00029<br>(0.00014)*<br>[0.00011]**   | 0.00013*<br>(0.00007)<br>[0.00008]  | 0.00011<br>(0.00007)<br>[0.00008]  | 0.00026<br>(0.00017)<br>[0.00010]*** | 0.00020<br>(0.00017)<br>[0.00010]**    |
| Extreme Drought<br>( $\text{PDSI} \leq -4.0$ )            | -0.00032***<br>(0.00010)<br>[0.00009] | -0.00028<br>(0.00010)**<br>[0.00009]*** | 0.00009<br>(0.00006)<br>[0.00006]   | 0.00006<br>(0.00006)<br>[0.00006]  | 0.00031**<br>(0.00014)<br>[0.00008]  | 0.00031<br>(0.00013)**<br>[0.00008]*** |
| Weather controls  | No                                    | Yes                                     | No                                  | Yes                                | No                                   | Yes                                    |
| Climate normal controls                                   | No                                    | Yes                                     | No                                  | Yes                                | No                                   | Yes                                    |
| Mean dep. var.  | 0.611                                 | 0.611                                   | 0.204                               | 0.204                              | 0.093                                | 0.093                                  |
| Observations  | 16,400                                | 16,400                                  | 16,400                              | 16,400                             | 16,400                               | 16,400                                 |
| R-squared   | 0.901                                 | 0.901                                   | 0.912                               | 0.912                              | 0.706                                | 0.706                                  |

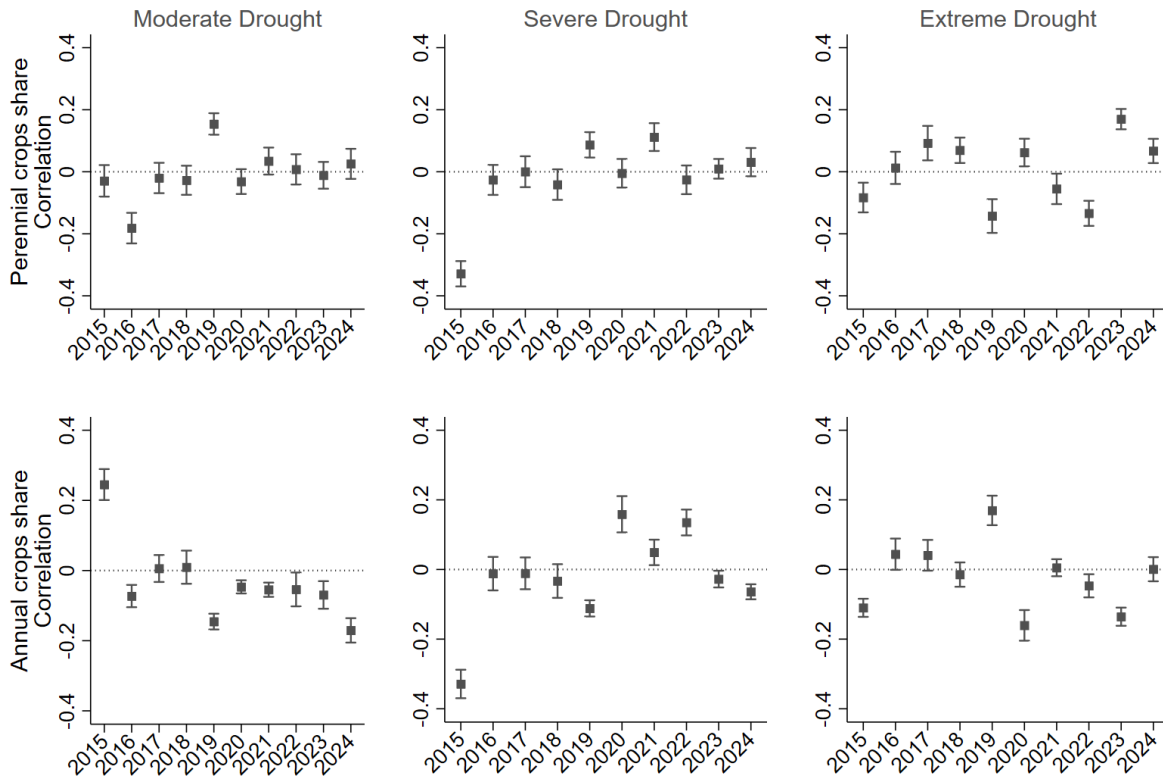
*Notes:* Standard errors presented in parentheses are clustered at the PLS regions (16 in total). Square brackets report standard errors clustered at the irrigation district level (23 in total) using bootstrapping with 1,000 replications. The dependent variable is the share of agricultural land use, which ranges from 0 to 1 at the PLS sections from 2015 to 2024. We define drought exposure as the total number of 5-day weeks of PDSI in each category for a year. Weather controls include the growing degree days and heat degree days, and the averages of solar radiation and wind speed. Climate normal includes 30-year moving averages of total precipitation levels and maximum temperature. All regressions include PLS sections and year fixed effects. Level of significance: \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ .

**Table 2.** Effects of drought severity on crops diversification in the Yakima Valley in South-Central Washington State, 2015 – 2024

|                                      | Richness index<br>(1)   | Evenness index<br>(2)   | Specialization index<br>(3) |
|--------------------------------------|-------------------------|-------------------------|-----------------------------|
| Moderate Drought<br>(-2.0≤PDSI≤-2.9) | -0.00068<br>(0.00042)   | 0.00001<br>(0.00007)    | -0.00037**<br>(0.00013)     |
| Severe Drought<br>(-3.0≤PDSI≤-3.9)   | -0.00050<br>(0.00047)   | -0.00010<br>(0.00009)   | -0.00008<br>(0.00017)       |
| Extreme Drought<br>(PDSI≤-4.0)       | -0.00081**<br>(0.00028) | -0.00017**<br>(0.00007) | -0.00003<br>(0.00010)       |
| Mean dep. var.                       | 2.230                   | 0.480                   | 0.336                       |
| Observations                         | 16,400                  | 16,400                  | 16,400                      |
| R-squared                            | 0.934                   | 0.919                   | 0.855                       |

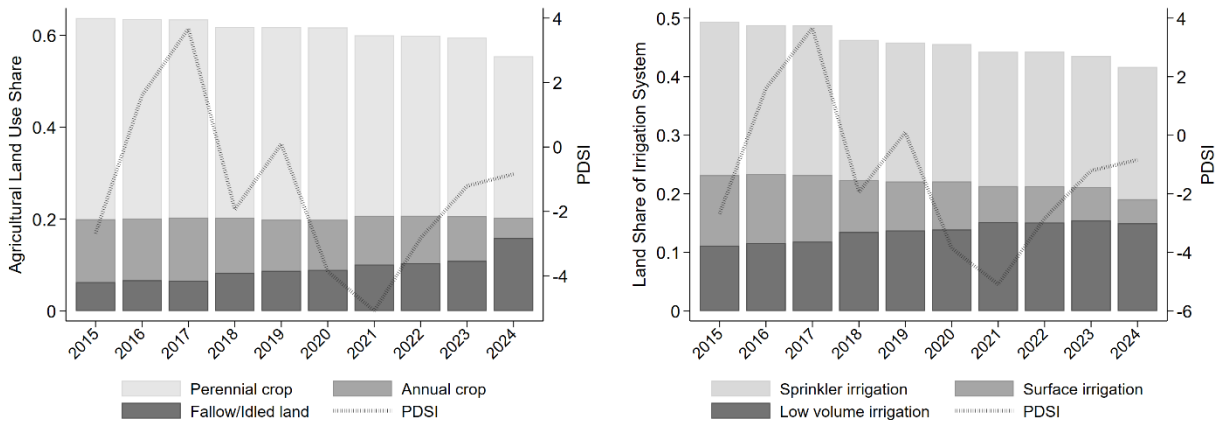
*Note:* Standard errors presented in parentheses are clustered at the PLS regions (16 in total). Richness index represents the count of crops in a particular PLS section. Evenness index represents the Shannon crop index, which is defined as the  $\sum \left( \frac{a_{ji}}{a_i} \right) * \ln \left( \frac{a_{ji}}{a_i} \right)$  where  $a_{ji}$  is the area of PLS section with crop  $j$  and  $a_i$  is the total area of PLS section (~640 acres); and the Specialization index represents the Herfindahl-Hirschman crop index (HHI), which is defined as the  $\sum (a_{ji}/a_i)^2$ . HHI values range from 0 to 1. Shannon index represents spatial diversity, while Herfindahl-Hirschman index represents concentration-specific diversity. Higher values of the Shannon crop index and lower values of the HHI index mean higher crop diversity. All regressions include weather and climate normal controls, as well as PLS sections and year fixed effects. Weather controls include the growing degree days and heat degree days, and the averages of solar radiation and wind speed. Climate normal includes 30-year moving averages of total precipitation levels and maximum temperature. Level of significance: \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ .

## Within-Region Irrigated Cultivated Crops Share Correlation with Drought Exposure



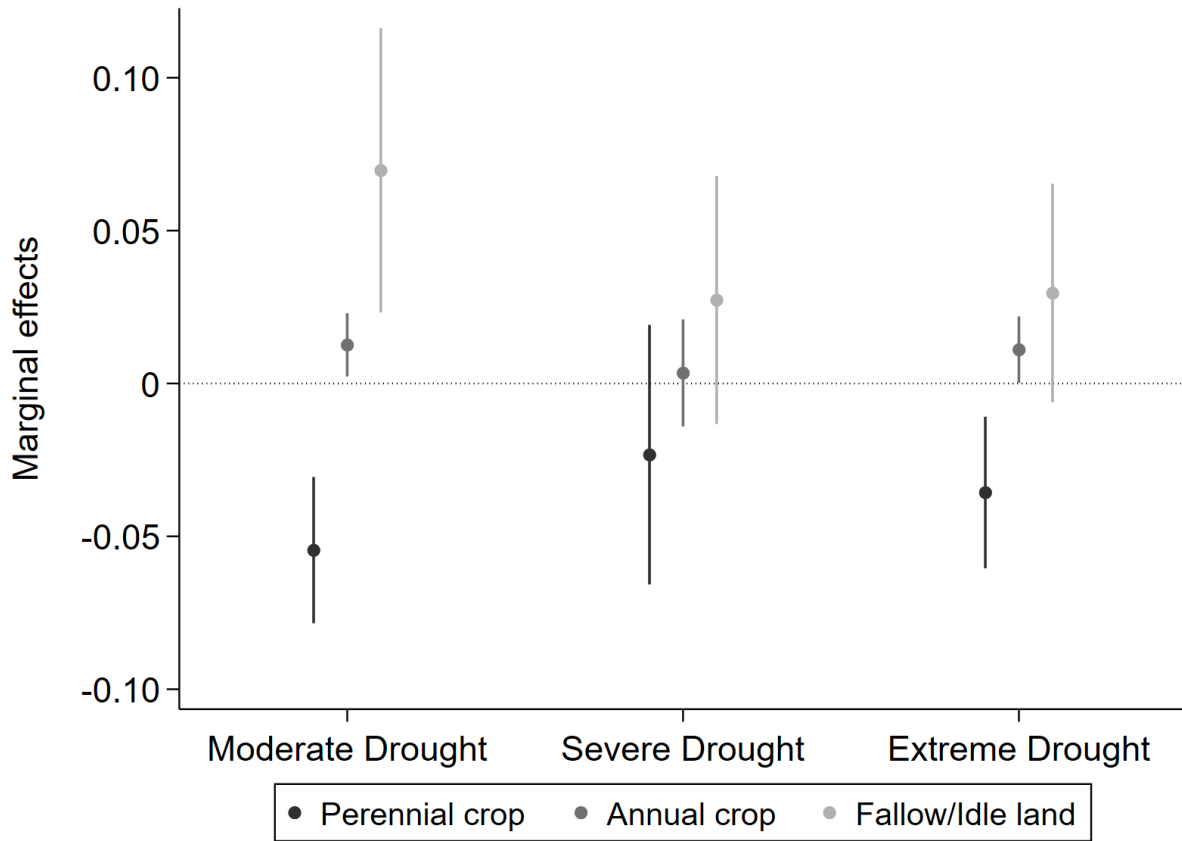
**Figure 1.** Correlation between the share of irrigated perennial crops (upper panel) and annual crops (lower panel) and drought exposure within the PLS regions in the Yakima Valley in South-Central Washington State

*Note:* The y-axis represents the estimated correlation coefficient. The within-region Pearson correlation is computed from PLS section deviations from the region mean of the share of irrigated perennial crops and annual crops. The 95% confidence interval is obtained from 1,000 bootstraps. We define severe and extreme drought exposure as the total annual number of 5-day weeks of PDSI in each category: severe drought ( $-3.0 \leq \text{PDSI} \leq -3.9$ ) and extreme drought ( $\text{PDSI} \leq -4.0$ ).



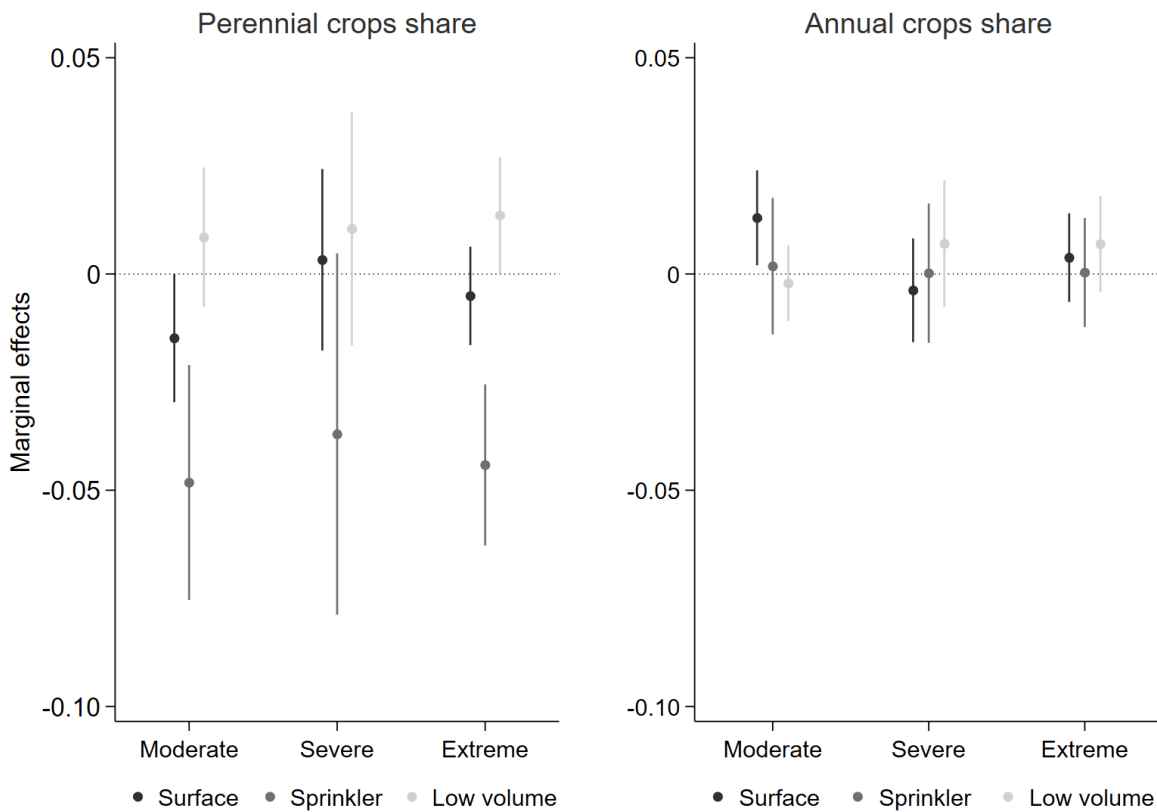
**Figure 2.** Palmer Drought Severity Index (PDSI) compared to irrigated agricultural land use (left) and land share associated with irrigation systems (right) in the Yakima Valley in South-Central Washington State, 2015 – 2024

*Note:* PDSI and land share of irrigation systems are averaged across PLS sections by year. We define a surface irrigation system when irrigated agricultural lands are irrigated by systems such as rill/furrow irrigation, wild flood, wheel line sprinklers followed by rill irrigation, and hand sprinklers followed by rill irrigation. Sprinkler irrigation systems include solid set, wheel line, hand move, big-gun, center pivot, and sprinkler irrigation systems. Low volume irrigation includes drip and micro- or mini- sprinklers.



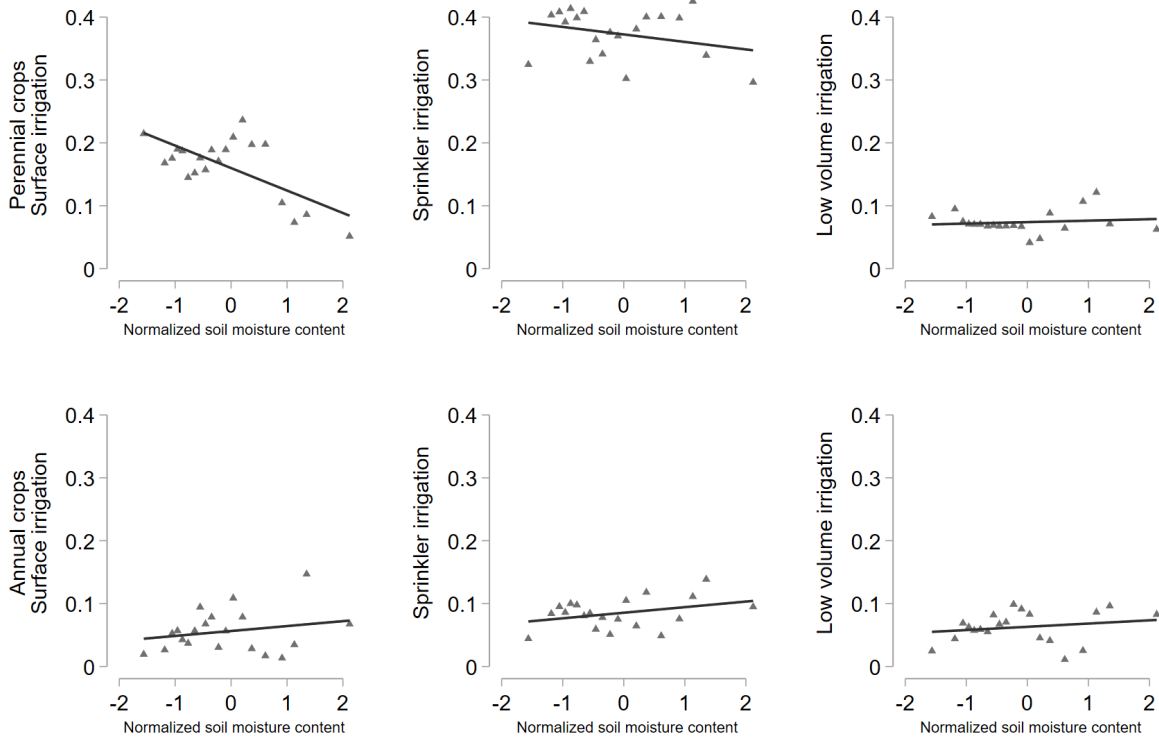
**Figure 3.** Marginal effects of drought exposure on the share of irrigated perennial and annual crops, as well as the share of fallow/idle land at the PLS sections in the Yakima Valley in South-Central Washington State

*Note:* The figure plots the point estimate in percentage points and 95% confidence intervals, obtained from Table A5, for each drought exposure effect on agricultural land use. The dependent variable is the share of agricultural land use, which ranges from 0 to 1 at the PLS sections from 2015 to 2024. We define drought exposure as the total annual number of 5-day weeks of PDSI in each category: (a) Moderate drought ( $-2.0 \leq \text{PDSI} \leq -2.9$ ), (b) Severe drought ( $-3.0 \leq \text{PDSI} \leq -3.9$ ), and (c) Extreme drought ( $\text{PDSI} \leq -4.0$ ).



**Figure 4.** Marginal effects of drought exposure on land use share of irrigation systems at the PLS sections in the Yakima Valley in South-Central Washington State

*Note:* The figure plots the point estimate in percentage points and 95% confidence intervals, obtained from Table A6, for each drought exposure effect on irrigation systems for perennial and annual crops. The dependent variable is the share of irrigated agricultural land using surface, sprinkler, and low volume irrigation systems, which range from 0 to 1 at the PLS sections between 2015 and 2024. We define drought exposure as the total annual number of 5-day weeks of PDSI in each category: (a) Moderate drought ( $-2.0 \leq \text{PDSI} \leq -2.9$ ), (b) Severe drought ( $-3.0 \leq \text{PDSI} \leq -3.9$ ), and (c) Extreme drought ( $\text{PDSI} \leq -4.0$ ).



**Figure 5.** Relationship between the proportion of irrigation systems associated with perennial and annual crops and soil moisture content

*Note:* The figure shows binscatter plots of the proportion of irrigation systems for perennial and annual crops and normalized soil moisture content. The normalized soil moisture content is calculated by subtracting soil moisture from the average of the long run growing season (April to October) from 1950 to 2005 and then divide the difference term by the standard deviation of soil moisture content over the same time period.

## Appendix Figures and Tables



Figure A1. Yakima Basin in South-Central Washington State

*Note:* The Yakima Basin is shown in the shaded part, with the names of counties displayed.

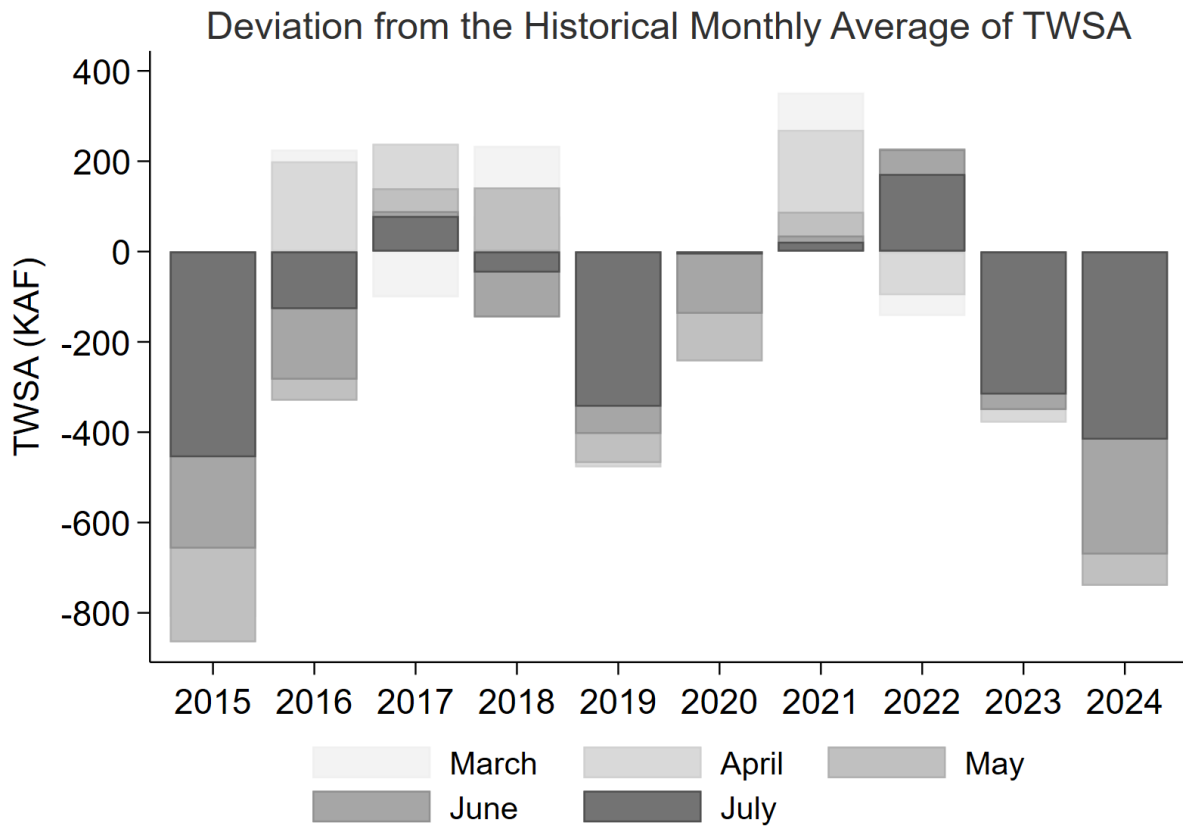


Figure A2. Deviation from the historical monthly average of total water supply available (TWSA) estimates in Yakima Basin

*Note:* The plot shows the monthly deviations from their historical monthly averages. The historical monthly averages are based on 1990 to 2014. Source: U.S. Department of the Interior U.S. Bureau of Reclamation.

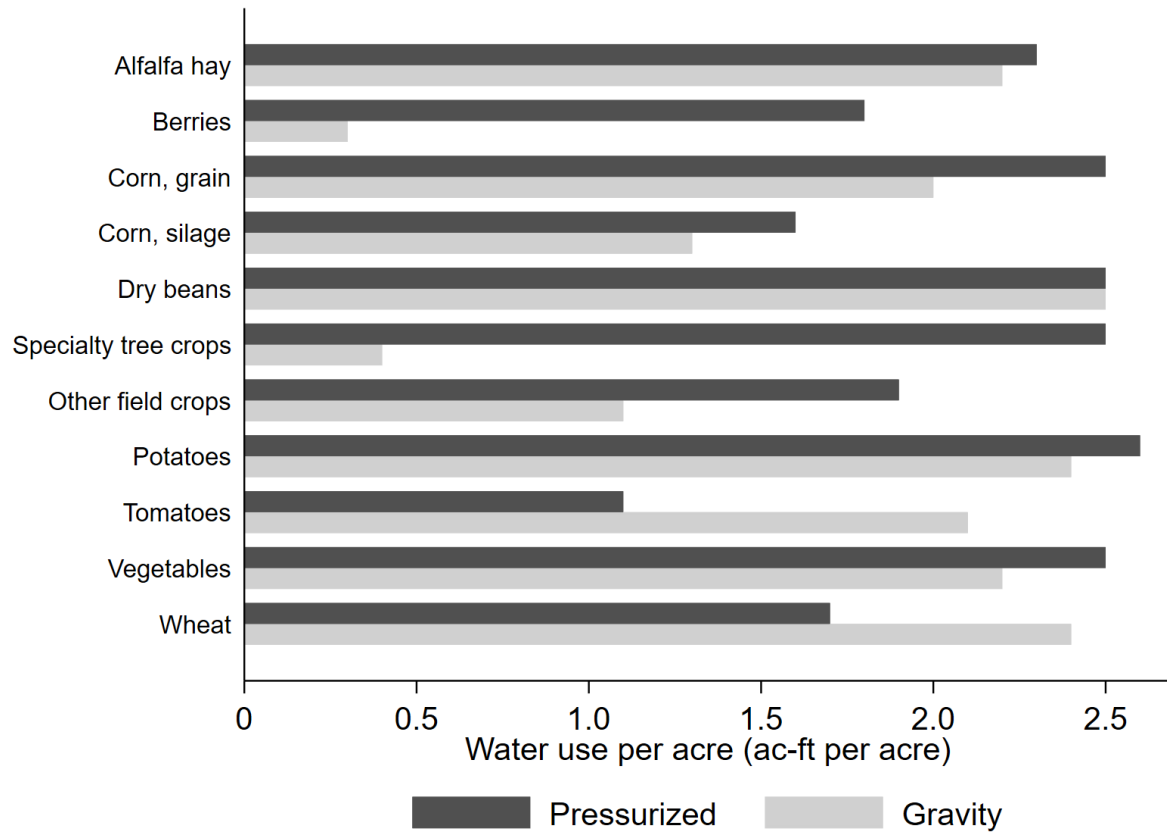


Figure A3. Field water distribution for selected crops in Washington State, 2018

*Note:* The figure shows the average water applied per acre irrigated across selected crops and irrigation system types in Washington State.

Source: USDA, National Agricultural Statistics Service, 2018 Irrigation and Water management Survey (FRIS, Table 36)

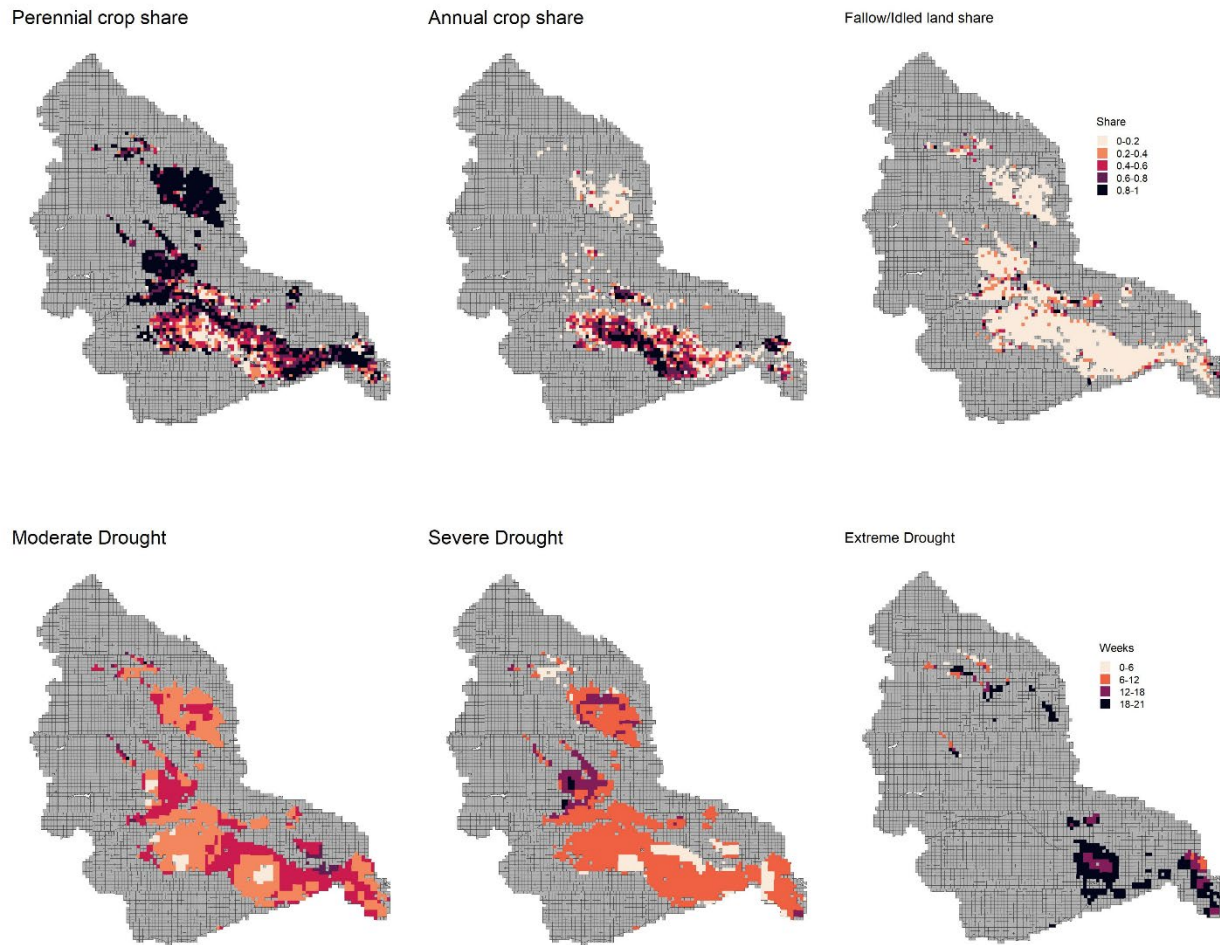


Figure A4. Agricultural land use shares and different drought severity exposures in the Yakima Valley in South-Central Washington State, 2015 – 2024

*Note:* The upper panel left represents perennial crop shares, the upper panel center represents annual crop shares, and the upper panel right represents fallow/idled land shares. The bottom panel left represents moderate drought exposure, the bottom panel center represents severe drought exposure, and the bottom panel right represents extreme drought exposure. To create the maps above, we calculated the average irrigated agricultural land use for 1640 unique PLS sections between 2015 and 2024. There is no data represented in the gray PLS section.

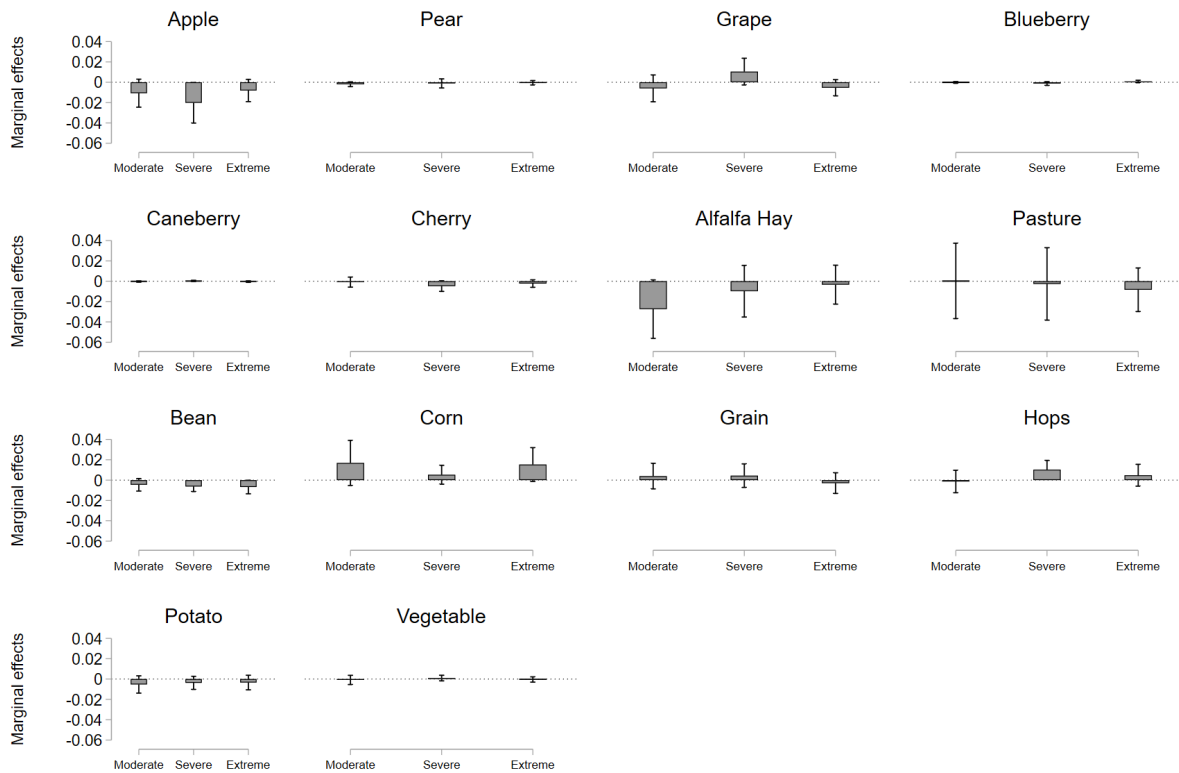


Figure A5. Marginal effects of drought exposure on the crop-specific irrigated share of land use

*Note:* The figure plots the point estimate in percent and 95% confidence intervals, obtained from Table A2. The dependent variable is the IHS-transformed irrigated share of crop-specific land use at the PLS sections level from 2015 to 2024. We define drought exposure as the total annual number of 5-day weeks of PDSI in each category: (a) Moderate drought ( $-2.0 \leq \text{PDSI} \leq -2.9$ ), (b) Severe drought ( $-3.0 \leq \text{PDSI} \leq -3.9$ ), and (c) Extreme drought ( $\text{PDSI} \leq -4.0$ ). All regressions include weather and climate normal controls, as well as PLS sections and year fixed effects. Weather controls include the growing degree days and heat degree days, and the averages of solar radiation and wind speed. Climate normal includes 30-year moving averages of total precipitation levels and maximum temperature.



Figure A6. Marginal effects of different drought severity exposure on the crop-specific land use share in each irrigation system

*Note:* The figure plots the point estimate in percent and 95% confidence intervals. The dependent variable is the IHS-transformed share of irrigated agricultural land using surface, sprinkler, and low volume irrigation systems, which range from 0 to 1 at the PLS sections between 2015 and 2024. We define a surface irrigation system when irrigated agricultural lands are irrigated by systems such as rill/furrow irrigation, wild flood, wheel line sprinklers followed by rill irrigation, and hand sprinklers followed by rill irrigation. Sprinkler irrigation systems include solid set, wheel line, hand move, big-gun, center pivot, and sprinkler irrigation systems. We define drought exposure as the total annual number of 5-day weeks of PDSI in each category: (a) Moderate drought ( $-2.0 \leq \text{PDSI} \leq -2.9$ ), (b) Severe drought ( $-3.0 \leq \text{PDSI} \leq -3.9$ ), and (c) Extreme drought ( $\text{PDSI} \leq -4.0$ ). All regressions include weather and climate normal controls, as well as PLS sections and year fixed effects. Weather controls include the growing degree days and heat degree days, and the averages of solar radiation and wind speed. Climate normal includes 30-year moving averages of total precipitation levels and maximum temperature.

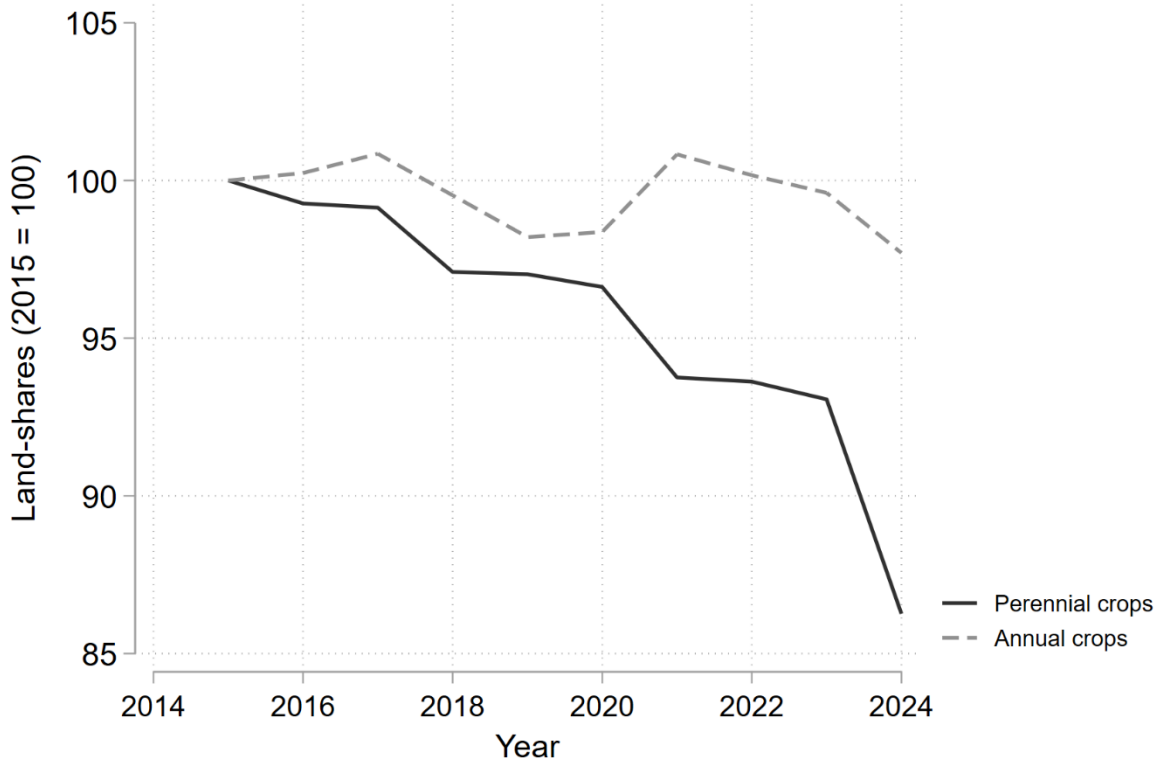


Figure A7. Trends in agricultural land use shares in the Yakima Valley

Source: Authors' calculations are based on data from Washington Department of Agriculture for the years 2015 to 2024.

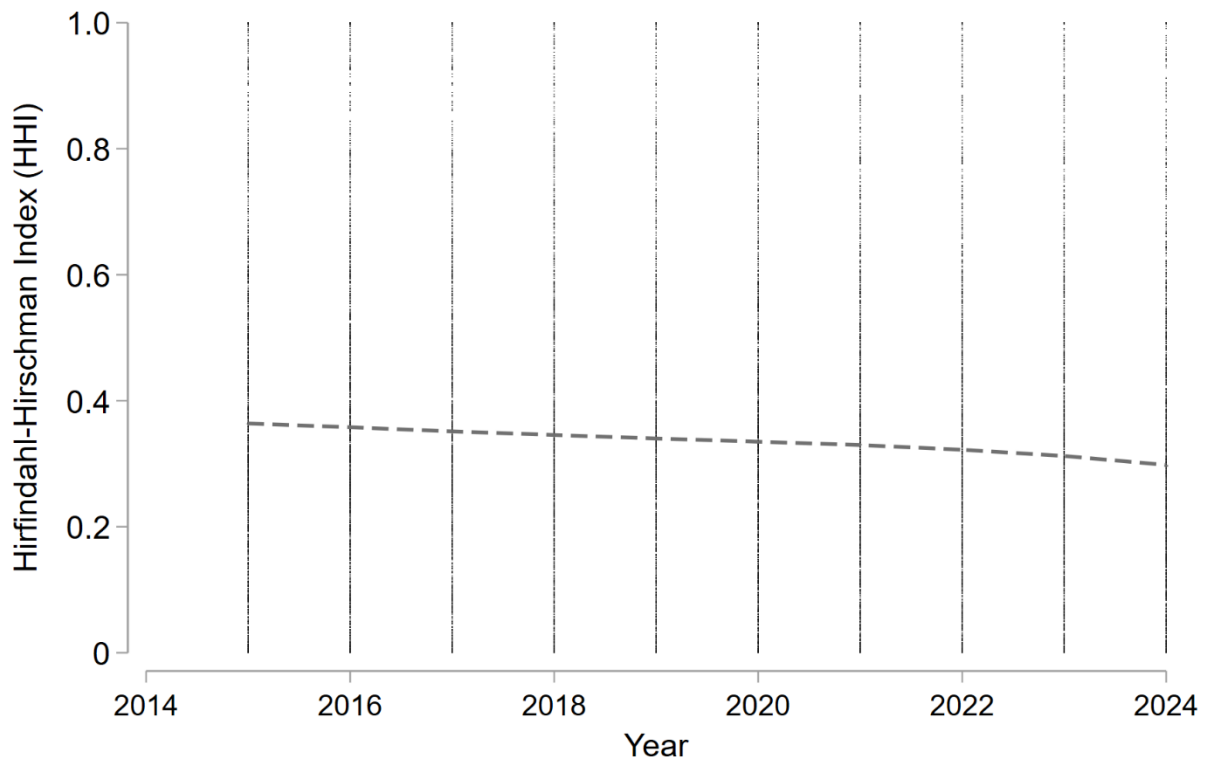


Figure A8. Trends in crop diversity index

*Note:* Herfindahl-Hirschman Index (HHI) is calculated on cultivated area of 14 major crops and fallow/idled land obtained from Washington Department of Agriculture for the years 2015 to 2024.

Table A1. Summary statistics for crops (Irrigated versus Non-Irrigated)

|  | Irrigated    | Non irrigated |
|--|--------------|---------------|
| <i>Panel A: Share of perennial crops (%)</i>   |              |               |
| Apple  | 10.27        | 0.03          |
| Pear   | 1.71         | 0.00          |
| Grape  | 7.13         | 0.04          |
| Blueberry                                      | 0.29         | 0.00          |
| Caneberry                                      | 0.01         | 0.00          |
| Cherry   | 2.77         | 0.02          |
| Alfalfa Hay                                    | 18.70        | 0.95          |
| Pasture  | 20.13        | n.a.          |
| <b>Total</b>                                   | <b>61.01</b> | <b>1.04</b>   |
| <i>Panel B: Share of annual crops (%)</i>      |              |               |
| Bean   | 0.20         | 0.00          |
| Corn   | 9.57         | 0.03          |
| Grain  | 3.01         | 8.38          |
| Hops   | 6.10         | 0.03          |
| Potato   | 0.84         | 0.00          |
| Vegetable                                      | 0.71         | 0.00          |
| <b>Total</b>                                   | <b>20.41</b> | <b>8.41</b>   |
| <i>Panel C: Share of fallow/idled land (%)</i> |              |               |
| Fallow/Idled land                              | 3.80         | 5.46          |
| <i>Panel D: Share of irrigation system (%)</i> |              |               |
| <i>Perennial crops:</i>                        |              |               |
| Surface irrigation                             | 16.35        | n.a.          |
| Sprinkler irrigation                           | 37.37        | n.a.          |
| Low volume irrigation                          | 7.37         | n.a.          |
| <i>Annual crops:</i>                           |              |               |
| Surface irrigation                             | 5.56         | n.a.          |
| Sprinkler irrigation                           | 8.46         | n.a.          |
| Low volume irrigation                          | 6.26         | n.a.          |
| <i>Panel E: Crop diversification</i>           |              |               |
| Richness index                                 | 2.23         | n.a.          |
| Evenness index                                 | 0.50         | n.a.          |
| Specialization index                           | 0.34         | n.a.          |

*Note:* The unit of measurement is a PLS section, which is a grid cell that measures 1 mile by 1 mile (~640 acres). The mean value across all PLS sections from 2015 to 2024 is reported. The crop share is calculated by dividing the crop and total cropland in that PLS section. The total cropland includes both irrigated and non-irrigated agricultural land, as well as fallow and idled land in that PLS section. We define a surface irrigation system when irrigated agricultural lands are irrigated by systems such as rill/furrow irrigation, wild flood, wheel line sprinklers followed by rill irrigation, and hand sprinklers followed by rill irrigation. Sprinkler irrigation systems include solid set, wheel line, hand move, big-gun, center pivot, and sprinkler irrigation systems. Low volume irrigation includes drip and micro- or mini-sprinklers.

Table A2. Summary statistics of measures of drought exposure and weather variables

|  | Mean    | Std. Dev. | Min.   | Max.    |
|--|---------|-----------|--------|---------|
| <i>Measure of drought: Total number of 5-day weeks in a year</i> |         |           |        |         |
| Near normal ( $-1.9 \leq \text{PDSI} \leq 1.9$ )                 | 21.64   | 22.17     | 0      | 73      |
| Moderate drought ( $-2.0 \leq \text{PDSI} \leq -2.9$ )           | 11.53   | 14.72     | 0      | 71      |
| Severe drought ( $-3.0 \leq \text{PDSI} \leq -3.9$ )             | 8.81    | 13.30     | 0      | 62      |
| Extreme drought ( $\text{PDSI} \leq -4.0$ )                      | 27.71   | 27.98     | 0      | 73      |
| <i>Other weather variable</i>                                    |         |           |        |         |
| GDD (10C – 29C; April through October)                           | 1550.79 | 229.91    | 730.15 | 2147.25 |
| HDD (above 29C; April through October)                           | 3.03    | 5.89      | 0      | 53.80   |
| Total precipitation (mm)   | 234.54  | 105.85    | 86.00  | 1252.18 |
| Solar radiation (Watts/m <sup>2</sup> )                          | 185.49  | 2.73      | 177.89 | 192.25  |
| Wind speed (m/s)   | 3.39    | 0.45      | 2.53   | 5.11    |
| <i>30-year average climate normal</i>                            |         |           |        |         |
| Total precipitation (mm)   | 248.28  | 94.66     | 175.10 | 1232.38 |
| Maximum temperature (K)  | 290.42  | 1.40      | 285.72 | 292.23  |

*Note:* The unit of measurement is a PLS section, which is a grid cell that measures 1 mile by 1 mile (~640 acres). The mean value across all PLS sections from 2015 to 2024 is reported. The Palmer Drought Severity Index (PDSI) 5-day weekly gridded data is used to measure drought severity.

Table A3. Annual change in agricultural land use

| Share of agricultural land (%)                          | 2015-<br>2016 | 2016-<br>2017 | 2017-<br>2018 | 2018-<br>2019 | 2019-<br>2020 | 2020-<br>2021 | 2021-<br>2022 | 2022-<br>2023 | 2023-<br>2024 |
|---|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| Irrigated ( $t+1$ ) – Irrigated ( $t$ )                 | 0.01          | 0.08          | -1.70         | -0.42         | -0.09         | -0.85         | -0.05         | -0.53         | -4.45         |
| Non irrigated ( $t+1$ ) – Non irrigated ( $t$ )         | -0.42         | 0.01          | 0.001         | -0.005        | -0.12         | -0.31         | -0.23         | 0.006         | -0.52         |
| Fallow/idled land ( $t+1$ ) – Fallow/Idled land ( $t$ ) | 0.41          | -0.09         | 1.70          | 0.43          | 0.21          | 1.16          | 0.27          | 0.53          | 5.00          |

*Note:* The unit of measurement is a PLS section, which is a grid cell that measures 1 mile by 1 mile (~640 acres). For each transition type, we report the annual mean difference in percent. To calculate the annual change in agricultural land, we take the difference between the share of agricultural land in year  $t+1$  and the share of agricultural land in year  $t$ .

Table A4. Effects of drought severity on crop-specific irrigated land use in the Yakima Valley in South-Central Washington State, 2015 – 2024

|                                      | Apple<br>(1)            | Pear<br>(2)             | Grape<br>(3)            | Blueberry<br>(4)        | Caneberry<br>(5)        | Cherry<br>(6)          |
|--------------------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|------------------------|
| Moderate Drought<br>(-2.0≤PDSI≤-2.9) | -0.00011<br>(0.00006)   | -0.00002*<br>(0.00001)  | -0.00006<br>(0.00006)   | -0.000002<br>(0.000004) | -0.000003<br>(0.000003) | -0.00001<br>(0.00002)  |
| Severe Drought<br>(-3.0≤PDSI≤-3.9)   | -0.00020**<br>(0.00009) | -0.00001<br>(0.00002)   | 0.00010<br>(0.00006)    | -0.00001<br>(0.00001)   | 0.000003<br>(0.000003)  | -0.00005*<br>(0.00002) |
| Extreme Drought (PDSI≤-4.0)          | -0.00008<br>(0.00005)   | -0.00001<br>(0.000010)  | -0.00005<br>(0.00004)   | 0.00001<br>(0.00001)    | -0.000004<br>(0.000003) | -0.00002<br>(0.00002)  |
| Mean dep. var.                       | 0.103                   | 0.017                   | 0.072                   | 0.003                   | 0.0001                  | 0.028                  |
| Observations                         | 16,400                  | 16,400                  | 16,400                  | 16,400                  | 16,400                  | 16,400                 |
| R-squared                            | 0.926                   | 0.933                   | 0.962                   | 0.957                   | 0.327                   | 0.911                  |
|                                      | Alfalfa Hay<br>(7)      | Pasture<br>(8)          | Bean<br>(9)             | Corn<br>(10)            | Grain<br>(11)           | Hops<br>(12)           |
| Moderate Drought<br>(-2.0≤PDSI≤-2.9) | -0.00027*<br>(0.00013)  | -0.000003<br>(0.000153) | -0.00005<br>(0.00003)   | 0.00017<br>(0.00010)    | 0.00004<br>(0.00006)    | -0.00001<br>(0.00005)  |
| Severe Drought<br>(-3.0≤PDSI≤-3.9)   | -0.00010<br>(0.00012)   | -0.00003<br>(0.00017)   | -0.00006**<br>(0.00002) | 0.00005<br>(0.00004)    | 0.00004<br>(0.00005)    | 0.00010**<br>(0.00004) |
| Extreme Drought (PDSI≤-4.0)          | -0.00003<br>(0.00009)   | -0.00008<br>(0.00010)   | -0.00007**<br>(0.00003) | 0.00015*<br>(0.00008)   | -0.00003<br>(0.00005)   | 0.00005<br>(0.00005)   |
| Mean dep. var.                       | 0.187                   | 0.202                   | 0.002                   | 0.094                   | 0.030                   | 0.061                  |
| Observations                         | 16,400                  | 16,400                  | 16,400                  | 16,400                  | 16,400                  | 16,400                 |
| R-squared                            | 0.854                   | 0.945                   | 0.278                   | 0.842                   | 0.554                   | 0.928                  |
|                                      | Potato<br>(13)          | Vegetable<br>(14)       |                         |                         |                         |                        |
| Moderate Drought<br>(-2.0≤PDSI≤-2.9) | -0.00005<br>(0.00004)   | 0.00001<br>(0.00002)    |                         |                         |                         |                        |
| Severe Drought<br>(-3.0≤PDSI≤-3.9)   | -0.00004<br>(0.00003)   | 0.00001<br>(0.00001)    |                         |                         |                         |                        |
| Extreme Drought (PDSI≤-4.0)          | -0.00003<br>(0.00003)   | 0.000004<br>(0.00001)   |                         |                         |                         |                        |

|                |        |        |
|----------------|--------|--------|
| Mean dep. var. | 0.008  | 0.007  |
| Observations   | 16,400 | 16,400 |
| R-squared      | 0.609  | 0.715  |

*Notes:* Standard errors presented in parentheses are clustered at the PLS regions (16 in total). The dependent variable is the inverse hyperbolic sine (IHS) transformed share of crop-specific land use at the PLS sections from 2015 to 2024. We define drought exposure as the total number of 5-day weeks of PDSI in each category for a year. All regressions include weather and climate normal controls, as well as PLS sections and year fixed effects. Weather controls include the growing degree days and heat degree days, and the averages of solar radiation and wind speed. Climate normal includes 30-year moving averages of total precipitation levels and maximum temperature. Level of significance: \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ .

Table A5. Effects of lagged drought exposure on agricultural land use in the Yakima Valley in South-Central Washington State, 2015 – 2024

|  | Irrigated share of perennial crop<br>(1) | Irrigated share of annual crop<br>(2) | Share of fallow/idled land<br>(3) |
|--|--|---------------------------------------|-----------------------------------|
| Moderate Drought<br>( $-2.0 \leq \text{PDSI} \leq -2.9$ )  | -0.00055***<br>(0.00011)                 | 0.00013**<br>(0.00005)                | 0.00070***<br>(0.00022)           |
| Severe Drought<br>( $-3.0 \leq \text{PDSI} \leq -3.9$ )  | -0.00024<br>(0.00020)                    | 0.00003<br>(0.00008)                  | 0.00028<br>(0.00019)              |
| Extreme Drought ( $\text{PDSI} \leq -4.0$ )  | -0.00036***<br>(0.00012)                 | 0.00011**<br>(0.00005)                | 0.00030*<br>(0.00017)             |
| <i>Lagged drought index: average drought severity index for the past <math>t - 3</math> to <math>t - 1</math> years</i>  |  |                                       |                                   |
| Moderate Drought   | -0.00059<br>(0.00050)                    | 0.00050*<br>(0.00026)                 | 0.00078<br>(0.00079)              |
| Severe Drought   | -0.00031<br>(0.00040)                    | -0.00004<br>(0.00026)                 | 0.00054<br>(0.00057)              |
| Extreme Drought  | -0.00037<br>(0.00031)                    | 0.00048***<br>(0.00016)               | -0.00007<br>(0.00044)             |
| <i>Lagged drought index: average drought severity index for the past <math>t - 10</math> to <math>t - 4</math> years</i> |  |                                       |                                   |
| Moderate Drought   | 0.00007<br>(0.00056)                     | -0.00053*<br>(0.00029)                | 0.00109<br>(0.00084)              |
| Severe Drought   | 0.00063<br>(0.00105)                     | -0.00076<br>(0.00065)                 | 0.00108<br>(0.00145)              |
| Extreme Drought  | -0.00077<br>(0.00060)                    | -0.00024<br>(0.00040)                 | 0.00046<br>(0.00069)              |
| Observations   | 16,400                                   | 16,400                                | 16,400                            |
| R-squared  | 0.900                                    | 0.912                                 | 0.707                             |

*Notes:* Standard errors presented in parentheses are clustered at the PLS regions (16 in total). The dependent variable is the share of agricultural land use, which ranges from 0 to 1 at the PLS sections from 2015 to 2024. We define drought exposure as the total number of 5-day weeks of PDSI in each category for a year. All regressions include weather and climate normal controls, as well as PLS sections and year fixed effects. Weather controls include the growing degree days and heat degree days, and the averages of solar radiation and wind speed. Climate normal includes 30-year moving averages of total precipitation levels and maximum temperature. Level of significance: \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ .

Table A6. Effects of drought severity on various irrigation systems in the Yakima Valley in South-Central Washington State, 2015 – 2024

|  | Irrigated perennial crops share |                              |                               | Irrigated annual crops share |                              |                               |
|--|---------------------------------|------------------------------|-------------------------------|------------------------------|------------------------------|-------------------------------|
|  | Surface irrigation systems      | Sprinkler irrigation systems | Low volume irrigation systems | Surface irrigation systems   | Sprinkler irrigation systems | Low volume irrigation systems |
|  | (1)                             | (2)                          | (3)                           | (4)                          | (5)                          | (6)                           |
| Moderate Drought (-2.0≤PDSI≤-2.9)  | -0.000148**<br>(0.000070)       | -0.000482***<br>(0.000127)   | 0.000085<br>(0.000076)        | 0.000130**<br>(0.000052)     | 0.000018<br>(0.000074)       | -0.000022<br>(0.000041)       |
| Severe Drought (-3.0≤PDSI≤-3.9)  | 0.000033<br>(0.000098)          | -0.000370*<br>(0.000196)     | 0.000105<br>(0.000127)        | -0.000038<br>(0.000056)      | 0.000002<br>(0.000076)       | 0.000070<br>(0.000069)        |
| Extreme Drought (PDSI≤-4.0)  | -0.000051<br>(0.000057)         | -0.000442***<br>(0.000087)   | 0.000136**<br>(0.000063)      | 0.000038<br>(0.000048)       | 0.000003<br>(0.000059)       | 0.000069<br>(0.000052)        |
| <i>Lagged drought index: average drought severity index for the past t – 3 to t – 1 years</i>  |                                 |                              |                               |                              |                              |                               |
| Moderate Drought   | -0.000001<br>(0.000170)         | -0.000689*<br>(0.000363)     | 0.000094<br>(0.000269)        | 0.000303*<br>(0.000148)      | 0.000307<br>(0.000206)       | -0.000107<br>(0.000166)       |
| Severe Drought   | -0.000207<br>(0.000160)         | -0.000948*<br>(0.000465)     | -0.000434*<br>(0.000214)      | -0.000470***<br>(0.000157)   | 0.000170<br>(0.000234)       | 0.000257<br>(0.000267)        |
| Extreme Drought  | -0.000169<br>(0.000167)         | -0.000533**<br>(0.000243)    | -0.000330*<br>(0.000181)      | 0.000213<br>(0.000153)       | 0.000174<br>(0.000150)       | 0.000097<br>(0.000155)        |
| <i>Lagged drought index: average drought severity index for the past t – 10 to t – 4 years</i> |                                 |                              |                               |                              |                              |                               |
| Moderate Drought   | 0.000889***<br>(0.000257)       | -0.01022<br>(0.000762)       | 0.000202<br>(0.000471)        | -0.000358<br>(0.000296)      | -0.000398<br>(0.000295)      | 0.000228<br>(0.000334)        |
| Severe Drought   | -0.001176**<br>(0.000531)       | -0.001255<br>(0.001200)      | -0.000715<br>(0.000481)       | -0.000652*<br>(0.000310)     | -0.000316<br>(0.000557)      | 0.000202<br>(0.000269)        |
| Extreme Drought  | -0.000058<br>(0.000451)         | -0.001346**<br>(0.000541)    | -0.000635**<br>(0.000281)     | 0.000141<br>(0.000259)       | -0.000636<br>(0.000503)      | 0.000252<br>(0.000384)        |
| Mean dep. var.   | 0.163                           | 0.374                        | 0.074                         | 0.056                        | 0.085                        | 0.063                         |
| Observations   | 16,400                          | 16,400                       | 16,400                        | 16,400                       | 16,400                       | 16,400                        |

|           |       |       |       |       |       |       |
|-----------|-------|-------|-------|-------|-------|-------|
| R-squared | 0.962 | 0.894 | 0.918 | 0.911 | 0.838 | 0.918 |
|-----------|-------|-------|-------|-------|-------|-------|

*Note:* Standard errors presented in parentheses are clustered at the PLS regions (16 in total). The dependent variable is the share of irrigated agricultural land using surface, sprinkler, and low volume irrigation systems, which range from 0 to 1 at the PLS sections between 2015 and 2024. We define a surface irrigation system when irrigated agricultural lands are irrigated by systems such as rill/furrow irrigation, wild flood, wheel line sprinklers followed by rill irrigation, and hand sprinklers followed by rill irrigation. Sprinkler irrigation systems include solid set, wheel line, hand move, big-gun, center pivot, and sprinkler irrigation systems. Low volume irrigation includes drip and micro- or mini- sprinklers. All regressions include weather and climate normal controls, as well as PLS sections and year fixed effects. Weather controls include the growing degree days and heat degree days, and the averages of solar radiation and wind speed. Climate normal includes 30-year moving averages of total precipitation levels and maximum temperature. Level of significance: \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ .

Table A7. Robustness Check: After dropping observations from outside irrigation districts

|                                      | Irrigated share of<br>perennial crop<br>(1) | Irrigated share of<br>annual crop<br>(2) | Share of<br>fallow/idled land<br>(3) |
|--------------------------------------|---|--|--------------------------------------|
| Moderate Drought<br>(-2.0≤PDSI≤-2.9) | -0.00074***<br>(0.00014)                    | 0.00031***<br>(0.00010)                  | 0.00035***<br>(0.00012)              |
| Severe Drought<br>(-3.0≤PDSI≤-3.9)   | -0.00026**<br>(0.00012)                     | 0.00017*<br>(0.00009)                    | 0.00009<br>(0.00010)                 |
| Extreme Drought<br>(PDSI≤-4.0)       | -0.00044***<br>(0.00011)                    | 0.00030***<br>(0.00009)                  | 0.00005<br>(0.00008)                 |
| Mean dep. var.                       | 0.617                                       | 0.285                                    | 0.088                                |
| Observations                         | 9,230                                       | 9,230                                    | 9,230                                |
| R-squared                            | 0.902                                       | 0.918                                    | 0.713                                |

*Notes:* Standard errors presented in parentheses are clustered at the irrigation district level (23 in total) using bootstrapping with 1,000 replications. The dependent variable is the share of agricultural land use, which ranges from 0 to 1 at the PLS sections from 2015 to 2024. We define drought exposure as the total number of 5-day weeks of PDSI in each category for a year. All regressions include PLS sections and year fixed effects. Level of significance: \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ .

Table A8. Summary statistics of the proportion of land used with each of the irrigation technologies

|   | Surface irrigation | Sprinkler irrigation | Low volume irrigation |
|---|--------------------|----------------------|-----------------------|
| <i>Panel A: Perennial crops share in each irrigation system (%)</i> |                    |                      |                       |
| Apple   | 0.058              | 7.984                | 2.240                 |
| Pear  | 0.027              | 1.322                | 0.350                 |
| Grape   | 0.650              | 1.968                | 4.538                 |
| Blueberry   | n.a.               | 0.067                | 0.221                 |
| Caneberry   | n.a.               | 0.004                | 0.006                 |
| Cherry  | 0.024              | 2.750                | 0.00003               |
| Alfalfa Hay   | 5.820              | 12.887               | 0.016                 |
| Pasture   | 9.772              | 10.387               | 0.002                 |
| <b>Total</b>  | <b>16.350</b>      | <b>37.368</b>        | <b>7.374</b>          |
| <i>Panel B: Annual crops share in each irrigation system (%)</i>    |                    |                      |                       |
| Bean  | 0.080              | 0.122                | 0.004                 |
| Corn  | 3.961              | 5.300                | 0.173                 |
| Grain   | 1.044              | 1.904                | 0.030                 |
| Hops  | 0.160              | 0.088                | 5.862                 |
| Potato  | 0.049              | 0.790                | n.a.                  |
| Vegetable   | 0.270              | 0.252                | 0.200                 |
| <b>Total</b>  | <b>5.563</b>       | <b>8.457</b>         | <b>6.258</b>          |

*Note:* Mean values are reported. The proportion of land used for each irrigation technology is calculated by dividing the crop-specific irrigation systems by the total cropland in that PLS section. We define a surface irrigation system when irrigated agricultural lands are irrigated by systems such as rill/furrow irrigation, wild flood, wheel line sprinklers followed by rill irrigation, and hand sprinklers followed by rill irrigation. Sprinkler irrigation systems include solid set, wheel line, hand move, big-gun, center pivot, and sprinkler irrigation systems. Low volume irrigation includes drip and micro- or mini- sprinklers.