Water Supply and Water Allocation Strategy in the Arid U.S. West: Evidence from the Eastern Snake River Plain Aquifer

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Abstract.

This article analyzes how irrigating farmers change their micro-level water allocation in response to water supply variations under institutional water constraints and project the irrigation percentage and farm income under future climate scenarios. We use a highly-detailed data sample of irrigation status, water rights, water supply and agricultural land use from Idaho's Eastern Snake River Plain Aquifer area. Results indicate that 1-unit increase in irrigation percentage leads to ~US$18/ha increase in crop revenue. Compared to crop revenue, micro-level irrigation percentage is more prone to changes under long-term water stress. Seasonal water supply variations only have limited impact on the productivity of the irrigated agricultural sector as a whole. We postulate that average irrigation percentage and farm income will, in effect, increase under Idaho's institutional water governance in the long run, when junior farmers stop irrigated agriculture practices due to persistent water shortage.

1. Introduction

Water supply significantly influences farmers' land use decision-making and subsequent crop productivity and farmland value (Cai *et al.* 2003a; Schlenker *et al.* 2007). In the arid and semi-arid climate zones, securing adequate water supply is challenging, primarily because of the spatial and temporal gaps between precipitation and irrigation, where water is stored naturally and artificially in the high-elevation upstream area during the cold season and is released to the low-elevation downstream area during the warm season (Luce *et al.* 2013). In recent years, efforts to secure water supply also have come under pressure from expanding irrigated land and competing water uses caused by urbanization, industrialization, and environmental protection.

To cope with seasonal water shortage and adapt to persistent drought in the long term, farmers usually limit irrigation to specific crops during designated periods. This strategy is necessary and effective because it helps farmers to find a proper balance between a substantial loss in fully irrigated, water use-intensive crops and a lower yield of limited irrigated, drought-tolerant crops (English and Nuss 1982; Geerts and Raes 2009; Homayounfar *et al*. 2014). As a result, the irrigation percentage of the harvest area will decrease in the short term. If water stress persists in the long run, the amount of idled or abandoned land will increase and consequently contract the irrigated landscape in size. Micro-level irrigation strategy is important to understanding the vulnerability and adaptive capacity of irrigated agriculture and communities in these affected regions. This understanding will facilitate policymaking regarding water conservation, agricultural development, and community sustainability (Smit and Wandel 2006; Reidsma *et al.* 2010). This article builds on the pioneering study of English (1990), Cai *et al.* (2003a), and Schlenker *et al.* (2007) in agricultural water allocation and climate change impact analysis and extends the existing literature with new empirical evidence at the micro level.

Idaho's Eastern Snake River Plain Aquifer (ESPA) area is the prime agricultural region in the state (Fig. 1). (See abbreviations used in this article in Table S1 of the electronic supporting material.) Like many arid regions in the U.S. West, agriculture in the ESPA is critically dependent on irrigation. Irrigation water use accounts for approximately 83.8% of the total water use (withdrawals) in the ESPA and 64.0% of the total use in Idaho (USGS, Water Use Data for Idaho 2005). Water appropriation in the ESPA, same as the rest of the state, follows the priority rule under the Prior Appropriation Doctrine, a water sharing rule adopted by the majority of Western United States (Bretsen and Hill 2009; Hutchins 1968 and 1977; Thompson 1993). In comparison to strong institutional water governance, the water market is immature and market-based water

allocation is less relevant (Hadjigeorgalis 2009; Rosegrant 1999; also see our discussion in the Appendix of the electronic supporting material).

Future climate change will add to the uncertainties for secure water supplies and pose more challenges for irrigated agriculture (Adams 1989; Cai *et al*. 2003a; Qiu and Prato 2012; Reidsma *et al.* 2009; Schlenker *et al.* 2006 and 2007). Agricultural adaptation has been gaining momentum in the recent decades, and great efforts have been made to develop strategies to sustain the natural and human environment. At the local level, socio-economic factors can influence the ability of sectors and communities to undertake adaptations (Smit and Wandel 2006). As the essential representation of the institutional environment of water governance in the U.S. West, the effects of irrigation water rights priorities are captured and reflected not only by the micro-level allocative strategies, cropping patterns, and farm income in the short term, but also by farmland value and agricultural landscape change in the long run.

While the literature extensively dedicated to climate change adaptation strategies, most of the existing studies have overlooked either the micro-level water allocation strategy or the effects of water governance structure on agricultural land use decision-making or both. Many factors have led to this oversight. On a large geographic scale, for instance, water rights laws in the U.S. West are context-specific and thus vary from state to state (Hutchins 1977; Thompson 1993). On a small geographic scale, a lack of high-quality data related to both irrigation diversion and water rights has hindered efforts to perform micro-level analysis, mostly due to rising concerns over privacy and property rights and strict data management regulations.

1.1 Objective

In this study, we investigate how farmers change micro-level water allocation in response to water supply variations and project the irrigation percentage and farm income under future climate scenarios. We use highly-detailed data of irrigation status, water rights, water supply, and agricultural land use from the ESPA in Idaho. We address three questions: (1) How do long-term and seasonal water supply variations influence micro-level water allocation, and how does the change in micro-level water allocation subsequently influence average farm income? (2) How do water allocation strategies vary with the priorities of water rights portfolios? (3) How will irrigation percentage and farm income change under future climate scenarios?

1.2 Literature

The current literature uses both mechanistic and empirical models to evaluate and project the impact of climate change on crop yields, farm income, and other agricultural performance

indicators (Easterling *et al.* 2007; Reidsma *et al.* 2009). The research of climate change impact has been performed at both the global, continental, and national scale (Adams 1989; Adams *et al.* 1990, 1995 and 1999; Deschênes and Greenstone 2007; Mendelsohn *et al.* 1994; Schlenker *et al.* 2005; Schlenker and Roberts 2009) and at the local scale (Iglesias *et al.* 2011; Qiu and Prato 2012; Reidsma *et al.* 2009; Rodríguez Díaz *et al.* 2007; Schlenker *et al.* 2006 and 2007; Tubiello *et al.* 2000). Compared to studies dealing with large geographic scopes, research that focuses on local specificity is more relevant to regional policymaking (Adams 1989).

The literature has used hydro-economic modeling in combination with various concepts, designs, and applications and abounds in those that look at the impact of water supply change on micro-level water allocation. (See the literature review in Harou *et al.* 2009.) Yet most studies address the water supply-water allocation issue using modeling and simulation techniques (for example, Cai *et al.* 2003a; Rosegrant *et al.* 2000 and 2005). A lack of empirical evidence at the micro level is common (with a few exceptions, for example, Oerink *et al.* 1997). On the other hand, only a few studies address how institutional water governance (including water supply and water rights) influences agricultural performance and farmland value (He and Horbulyk 2012; Schlenker *et al.* 2007; Xu *et al.* 2014a).

1.3 Contributions

This article addresses the lack of empirical evidence and makes two contributions. First, we develop a model of agricultural land use constrained by limited water resources and investigate how farmers change their water allocation in response to water supply variations. Modeling water allocation with water supply, water rights, climate, and other agricultural covariates can provide a deeper insight into the direct impact of water shortages on irrigated agriculture than modeling through farm income can. This is particularly relevant to local irrigation water allocation structures. Second, we combine a highly-detailed irrigation status data from the Idaho Department of Water Resources (IDWR) with data for water rights, water supply and agricultural land use and outputs in this analysis. We focus primarily on the micro-level water allocation and its subsequent impact on farm income and the projection of irrigated agriculture performance under future climate scenarios.

This article concentrates on micro-level irrigation water allocation, which distinguishes itself from our previous studies (including, Xu and Lowe 2011; Cobourn *et al.* 2013; Xu *et al.* 2014a). We develop empirical models under a structural equation model framework and estimate with the limited dependent variable approach with instrumental variables. We use a data set of different

variables, spatial scale, and temporal scope. With the newly available irrigation status data, we adjust our data compilation method by differentiating crop yields with and without irrigation.

2. Materials and methods

In this section, first we present the data and the descriptive statistics of the panel data set used in this analysis. We focus on irrigation status, water rights, water supply and climate trends, and agricultural outcomes. We present the variable definitions and their associated data sources as well as the descriptive statistics in Tables S2 and S3 of the electronic supporting material, respectively. Then, we develop the theoretical and empirical models and we discuss modeling and estimation constraints.

2.1 Data and descriptive statistics

Farm water allocation

Our micro-level water allocation data come from the geo-spatial layers of the ESPA Irrigated Land Cover from the IDWR. The data layers cover the ESPA and its close vicinity, providing irrigation status information (irrigated, partially irrigated, and non-irrigated). (See Figs. S1 and S2 in the electronic supporting material.) The IDWR provides data at the level of the Common Land Unit by the Farm Service Administration (IDWR 2006). The data differentiate agricultural land (irrigated and non-irrigated land parcels) from residential land (partially irrigated land parcels). This allows us to concisely identify irrigated farms in the concerned study area. The data of irrigation status are available in the year of 1986, 1996, 2000, 2002, 2006, and 2008-2010 (as of June 30, 2014). We use the layers from 2008 to 2010 to match the available water supply and land use data.

Water supply and climate trends

Our water supply data include both long-term and seasonal measures. We use the annual April-September adjusted streamflow data to measure the total surface water supply (evaluated at both the mean and standard deviation for 1971–2000). The Natural Resources Conservation Service (NRCS) of the U.S. Department of Agriculture compiles the adjusted streamflow data at the basin level. The NRCS also provides the basin-level Water Supply Outlook (WSO) Report six to seven times each year during the growing season. We use the WSO evaluated for the same April-September timeframe as the forecast of surface water supply.

We obtain the water level below land-surface datum at individual irrigation wells from the Hydro-Online data portal of the IDWR. We select the wells with observation after the year of 2000 and generate the ground water level data using the Kriging interpolation. Climate data are originally developed by the Parameter-Elevation Regressions on Independent Slopes Model Climate Group. We use the minimum temperature in April and calculate its mean and standard deviation during the same timeframe as the long-term climate trend.

Water rights and farm boundaries

The IDWR compiles and manages the water rights geospatial data regularly. We use the Water Rights *Place-of-Use* layer in the ESPA. This data layer contains water rights features, including ownership, priority date, water source, place of use, point of diversion, and water right boundary. We identify a total of 18,484 distinctive water rights as irrigation-related in the ESPA.

We use the same sampling-consolidation method which was presented in Xu *et al.* (2014a). In brief, we merge the polygons of this layer by ownership in ArcGIS and construct the basic unit of this analysis—farms. We generate a uniform sampling grid, overlay the sampling grid on targeted base layers to obtain point-wise information, and consolidate the point-wise information within individual farms. We identify the maximum diversion volume, dominant water source, and water right priority date (including the average and the most senior) for each farm.

Agricultural land use

The farm-level features of agricultural land use include cropping pattern, crop revenue, and soil quality. We apply the sampling-consolidation method to calculating and identifying agricultural land use features. These base layers include the Cropland Data Layers of Idaho (2008–2010), which the National Agricultural Statistics Service (NASS) of the U.S. Department of Agriculture compiles in order to identify farm-level cropping patterns. They also include the U.S. General Soil Map for Idaho by the NRCS in order to calculate soil quality. We focus on the 14 major non-fruit crops surveyed by the NASS (Table S2). To match the irrigation status, we distinguish crops yields under irrigation and non-irrigation conditions.

Descriptive statistics

We identify a total of 5,133 irrigated farms in our ESPA data sample, with an average size of 249 hectares (Table S3). For these identified farms, the 30-year average precipitation in April is 25.26 millimeter (mm) during the timeframe from 1971 to 2000; the average minimum temperature is –0.97 ℃ and the average maximum temperature is 14.05 ℃ during the same timeframe. When water rights of both ground and surface sources are included, the average farm-

level water rights priority date is 1941. Approximately 44.7% of the farms have water rights to surface water-only sources, 21.2% have water rights to ground water-only sources, and 34.0% have water rights to both sources. The average irrigation percentage in the harvest area is high, ranging from ~91.0% to ~93.7% during 2008 to 2010. The average crop revenue ranges from ~US\$ 1,397 ha^{-1} to ~US\$ 1,449 ha^{-1} from 2008 to 2010. We use the nominal average crop revenue or as a proxy for farm income because inflation is negligible during this short period.

We observe marked differences in water rights features, irrigation status, and agricultural land use across regions. For example, more farmers on average have water rights in the Snake River Basin from Idaho Falls to American Falls (SR1) than in the Snake River Basin from American Falls to Twin Falls (SR2) (that is, ~82.1% versus ~61.4%). A higher percentage in ground water availability contributes, in part at least, to a higher level of farm income in the SR1, where farmers take advantage of the secure supply of water from ground water sources and grow higher-valued, water use-intensive crops like potatoes and sugarbeets. In areas further away from the major streams (for example, the Big Lost River Basin), where irrigation facilities (canals, dams, and reservoirs) of large capacities are less available, both irrigation percentage and farm income are lower than those in the areas close to major streams.

2.2 Theoretical model

The following conceptual framework formalizes farmers' profit maximization problem with respect to land and water resources, which has been considered a more practical criterion than yield maximization in determining the optimal irrigation strategy (Bras and Cordova 1981; Dudley *et al.* 1971; English 1990). We extend the framework of English (1990) by distinguishing crops of high- and low-valued crops under irrigation and non-irrigation conditions. We simplify the model by focusing on the water scarcity case, in which water is insufficient to allocate to all available land. This is a representative situation in the arid U.S. West. We present the details of the model setups, derivations and modeling constraints discussions in the Appendix. For the discussion covering land scarcity case in which land is insufficient compared to total available water, see Xu *et al*. (2014b).

We assume that competitive irrigators own farms of a fixed size (L) and take prices as given. They grow both water use-intensive and drought-tolerant crops and allocate their water accordingly. They can adopt the non-irrigation option only for drought-tolerant crops. The operating expenses and crop revenues are identifiable and separable for individual crops. We also assume that water is a scarce resource and that all is allocated. Water appropriation at the farm

level is determined by the priority principle based on water rights priorities and water cannot be exchanged through market.

Following English (1990), we posit that farmers maximize the total profits of their crop bundles by choosing their land allocation strategies ($\{(\delta,\gamma)\,|\,0<\delta,\gamma<1\}$) subject to their water constraints

$$\max_{(\delta,\gamma)} \pi^e = f_{II}(\delta L, \mathbf{Z}_{-L}) + f_{DI}((1-\delta-\gamma)L, \mathbf{Z}_{-L}) + f_{DN}(\gamma L, \mathbf{Z}_{-L})$$
$$s.t. \qquad W^e_{II} + W^e_{DI} \leq W^e \tag{1}$$

where π^e is the expected total profit and f_i is the profit from growing crop i. The crops can be categorized as irrigated water use-intensive crops (II), irrigated drought-tolerant crops (DI), and non-irrigated drought-tolerant crops (DN). δ stands for the percentage of land devoted to irrigated water use-intensive crops and γ for the percentage of land devoted to non-irrigated drought-tolerant crops. $\mathbf{Z}_{-L}$ is a set of fixed, non-allocable farm-specific features. W^e is the expected total available water and W^e_i is the expected total available water allocated to the crop i.

The equilibrium conditions imply that the partial derivatives of the optimal profits (π^{e*}) with respect to the expected total water supply (W^e) is positive ($\partial \pi^{e*}/\partial W^e > 0$). When operating cost is constant or changing slowly over time, the profit maximization is equivalent to the revenue maximization in the search for the optimal water allocation strategy of (δ^*, γ^*). That is, $\partial R^{e*}/\partial W^e > 0$.

To determine the expected total water supply at the farm level, we follow Burness and Quirk (1979 and 1980) and posit that increased long-term and seasonal water supply and higher priorities of water rights will not decrease the total expected water supply

$$\frac{\partial W^e}{\partial \bar{W}} \geq 0, \ \frac{\partial W^e}{\partial W^f} \geq 0, \text{ and } \frac{\partial W^e}{\partial V} \geq 0, \tag{2}$$

where $\bar{W}$ is defined as the long-term water supply, W^f as the seasonal water supply forecast, and V as the priority of farmers' portfolios of irrigation water rights. We apply the chain rule and obtain the partial derivatives of the R^{e*} with respect to V, W^f, and $\bar{W}$

$$\frac{\partial R^{e*}}{\partial \bar{W}} \geq 0, \ \frac{\partial R^{e*}}{\partial W^f} \geq 0, \text{ and } \frac{\partial R^{e*}}{\partial V} \geq 0. \tag{3}$$

2.3 Empirical model

The essential issue in assessing farmers' response of micro-level water allocation is to model water allocation and agricultural outcomes as functions of water rights, water supply, and other agricultural covariates. Based on our simplifying analytical model presented in Section 2.2, we presume that farm income is a function of optimal non-irrigation percentage and water rights, water supply variations, and other agriculture-related factors that affect farm income directly or through farmers' optimal non-irrigation allocation. We use the following structural modeling approach to formulate this decision-making of irrigation and subsequent agricultural outcomes:

$$R = g(\gamma, \mathbf{Z}_1) + \varepsilon_1, \tag{4-a}$$

$$\gamma = f(\bar{W}, W^f, V, \mathbf{Z}_2) + \varepsilon_2, \tag{4-b}$$

where $\mathbf{Z}_1$ and $\mathbf{Z}_2$ contains vectors of non-allocable agricultural covariates. ε_i is the associated stochastic term.

Under this specification we use a Wald Test to examine if the endogenous explanatory variable γ is in fact exogenous (Woodridge 2002). The Wald test confirms our earlier assumption of this endogeneity, with the estimated correlation of 0.0824 and the Wald statistic of 52.74 ($p < 0.0001$). As a robustness check, we consider an alternative specification, in which farm income is influenced by water rights directly:

$$R' = g(\gamma, \bar{W}, W^f, V, \mathbf{Z}_1') + \varepsilon_1'. \tag{4-a'}$$

(We note that the function of $f(\cdot)$ must have at least one more variable than $g(\cdot)$ does in order to solve the structural equation properly.) This specification is less satisfactory. Almost all coefficients of the explanatory variables of $\bar{W}$, W^f, and V from Eq. (4-a') are statistically insignificant. Under this specification, we cannot reject the null hypothesis that γ is in fact exogenous at 5% level (with the Wald statistic = 0.07 and $p = 0.7884$).

Variable identification

Besides irrigation status and associated farm income, the identification of water supply variations including both $\bar{W}$ and W^f are of primary interest in this article. We use the average total available water during the April-September growing season to represent the long-term water supply condition $\bar{W}$. This measure incorporates both the adjusted annual streamflow between April and September and the maximal reservoir carryover at the end of March. We use the annual April-September WSO as the water supply forecast (W^f). The WSO is highly correlated with $\bar{W}$. We use a relative measure—a decimal between 0 and 2, which the NRCS reports as the annual

value compared to the 25- to 30-year moving average of the long-term water supply. Irrigation diversion data at the farm level could improve the empirical estimation; however, access to such data is restricted.

Water rights priorities are important control variables in the empirical specification. We use a combination of water rights priorities measures. We include the mean priority date directly in the model specification to account for the priority effects in water appropriation among farmers. We also identify the oldest water right for each farm, separate farms into different groups of prior-to-1890, 1890-1930, and 1930-to-present based on this oldest priority date, and create indicator variables accordingly. We validate the feasibility of this division method by using the Kolmogorov-Smirnov Test (KS-test; see Table S4 in the electronic supporting material). We multiply these indicator variables with WSO in explaining different responses to seasonal water supply forecast. In addition, we include the indicators of water source (ground water-only, surface water-only, and dual-sourced or conjunctive) and the maximum diversion volume as controls for potential endogeneity resulting from the interaction between cropping patterns and irrigation water sources.

Climate variables are also important control variables in our analysis. But they are highly correlated in terms of Pearson correlation coefficients. (The Pearson correlation coefficients are not presented in this article but are available upon request.) The correlation exists among different climate variables (precipitation, minimum temperature, and maximum temperature), between the annual and 30-year averages of one climate variable, and using one climate variable measured between two months (for example, April and July). We use the April minimum temperature in our model because it has been proven to effectively capture climate variability in this region (Brown and Kipfmueller 2012).

Empirical estimation issues

We conduct our empirical estimation by using the limited dependent variable model approach with instrumental variables (Greene 2010; Hajivassiliou 1993; Woodridge 2010). In our model, the non-irrigation percentage in the harvest area (γ) is the endogenous regressor. Water supplies, water rights, and climate variables work as instrumental variables too, in addition to their role as explanatory variables of interest.

We note that the farm income has zero-valued observations due to non-continuously operated farms. We therefore regard the observations as censored for estimation consistency and technical simplicity. The limited dependency feature applies to the observations of the non-irrigation

percentage γ too, which can only take the range of $[0,1]$. Accordingly, we use the limited dependent variable model approach to handle this situation. Potential endogeneity of non-irrigation percentage complicates this situation and we introduce instrumental variables to the estimation in addition to using a structural equation framework.

Like any hedonic panel data analysis, misspecification and omitted variable bias could be potential problems and may introduce additional endogeneity to the empirical estimation (Greene 2010; Maddala 1983; Woodridge 2010). We cross-examine the robustness of our findings by varying the model specifications and using alternative explanatory variables. These variables includes annual, short-term (5- and 10-year averages), and long-term (30-year average) measures of climate variables (precipitation, maximum temperature, and minimum temperature) and surface water supplies (for example, annual versus 5-, 10-, and 30-year averages). We present the results of cross-validation where they apply in this article. In summary, we do not find sufficient evidence that could lead us to change our overall conclusions presented in the following section.

3. Results

In this section, first we present the empirical estimates of our panel data analysis. Table 1 reports the estimated impact of non-irrigation percentage in the harvest area (hereafter, non-irrigation percentage) on average farm income in the reduced form of Eq. (4-a), while controlling for basic farm features. Table 2 reports the estimates of water supply, water rights, climate, and other farm features on non-irrigation percentage, as specified in Eq. (4-b). Next, we present the projected changes of non-irrigation percentage and farm income under the future climate change scenarios downscaled to the ESPA. Finally, we present parameters of these climate scenarios and the associated projections in Table S7 of the electronic supporting material.

3.1 Empirical estimation

The regression results in Table 1 indicate that a 1-unit increase in the non-irrigation percentage will decrease average farm income at the 1% level (by US$17.65 ha^{-1}). This result is consistent with the existing literature that concludes irrigation generally improves agricultural outcomes of crop productivity and farmland value in the arid and semi-arid regions (Cai *et al.* 2003a; Geerts and Raes 2009; Homayounfar *et al.* 2014; Schlenker *et al.* 2007; Xu *et al.* 2014a).

Long-term climate and water supply trend

We find that a 1 ℃ increase in the average April minimum temperature will decrease non-irrigation percentage by 14.81 units. (This result is not sensitive to an alternative specification with

quadratic temperature.) In lieu of the positive relationship between irrigation percentage and farm income identified in Table 2, a higher average April minimum temperature will subsequently increase average farm income. Irrigating farmers respond to climate variations, too. A 1 ℃ increase in the standard deviation will increase the non-irrigation percentage by 56.04 units, and hence lead to a decline in average farm income.

The estimated effects of long-term water supply are similar to those of the long-term climate variables of the April minimum temperature. A 1 billion cubic meter (BCM) increase in the average total surface water supply will decrease the non-irrigation percentage by 51.40 units. This finding is consistent with the existing literature (Cai *et al.* 2003a; He and Horbulyk 2010; Schlenker *et al.* 2007), a consensus which believes that a higher level of irrigation water supply positively influences agricultural performance including short-term yield and farm income as well as long-term farmland value. In comparison, a 1 BCM increase in the standard deviation of surface water supply will substantially increase non-irrigation percentage by 243.65 units. The standard deviation of the long-term water supply along the Snake River is evaluated at ~1.54 BCM, implying that long-term water supply variations, although historically being stable over time (Dittmer 2013), plays an important role in determining farmers' water allocation strategy and the resulting agricultural outcomes.

As an important control, we find that ground water level influences micro-level water allocation only for farmers with deep wells, as the increase in the distance to ground water level will increase the non-irrigation percentage by 0.07 units once the maximum diversion has been controlled for. Deeper wells have more stable water levels than shallower ones. This security feature enables farmers to grow water use-intensives crops that are sensitive to irrigation scheduling, particularly during the peak growing stage when the risk of water shortage is greatest. On the other hand, the more secure the water supply, the higher the water intensity, where all else holds constant. Irrigation percentage will decline, because a fixed maximum diversion volume and the beneficial use requirement jointly limit total irrigation diversion.

Our findings indicate that long-term climate and water supply trends have significant impact on farmers' irrigation strategies. More important, the level of variations and the exposure of irrigating farmers to these changes will play a leading role in determining the impact of climate change on farm performance. If future climate scenarios introduce a higher level of volatility, *ceteris paribus*, losses in average farm income will eventually dominate the outcome of climate change impact.

Seasonal water supply and heterogeneous responses

Using WSO, we assess farmers' seasonal water allocation strategy based on their priorities of water rights portfolios. Inclusion of seasonal water supply forecast is necessary because irreversible cropping decisions are generally made at the early stage of growing seasons and farmers use WSO updates to make adjustment in cropping patterns and irrigation status. We use a set of interaction terms between WSO and water rights priority group indicators, which serves as a proxy for time-invariant fixed effects of local water rights governance structures since they are stable over time.

We hypothesize, *ceteris paribus*, that farmers respond to seasonal water supply information with respect to their water rights portfolios. Our estimates support this hypothesis. For the farmers group with the most senior water rights priorities (prior to 1890), seasonal water supply forecast has statistically significant and positive impact, although very limited, on farmers' micro-level water allocation. A 10% increase in the seasonal water supply forecast reduces the non-irrigation percentage by 0.77 units (–7.70 in Table 2). Farmers in the group with the priority date between 1890 and 1930 respond to incremental water supply change in the opposite way: increasing their irrigation percentage by 3.63 units (36.32). This behavioral response is understandable. Farmers in the less senior group are more prone to late-season irrigation curtailment than the group with the most senior priorities. Also, the increase in the WSO is likely to disproportionately increase the irrigation diversion of the most senior farmers and will therefore reduce the water allocated to junior farmers.

By contrast, a large portion of the farmers in the 1930-to-present group possess water rights that grant them access to ground water. For instance, in SR1, 89.47% of the irrigation water rights dated after 1930 are ground water rights and in SR2, we observe a figure of 74.46%. For farmers having access to ground water, irrigation is more dependent on ground water than on surface water. The increase in the WSO works primarily as an additional supply than can improve seasonal growing conditions and subsequently decrease non-irrigation percentage (–5.57). The responses of farmers' water allocation and land use to seasonal water supply forecast are measured relative to the average response per se. In other words, these responses reflect the behavior of representative farmers, or the average.

The estimated micro-level water allocation in response to seasonal water supply forecast differ from the responses evaluated directly by using farm income; the latter also reflects the heterogeneous influences of crop-specific average revenue per acre. With an increase in seasonal water supply forecast, the market supply of water use-intensive crops will increase. Because Idaho

leads the U.S. in producing crops like potatoes, sugarbeets, and alfalfa (USDA NASS 2012), prices of these higher-valued crops are subject to higher market fluctuation; so local markets strongly influence the prices of these crops. Senior farmers will choose crops that are less volatile in price or that have higher technology barrier than popular water use-intensive crops with lower technology barrier in order to alleviate the impact of market fluctuation. As a result, an increase in irrigation percentage will be disproportionate to the increase in farm income.

The estimated responses to water supply forecast at the micro-level are small, which we attribute primarily to the degree of difficulty that irrigating farmers have in predicting individual water appropriation under local water governance systems. In addition, this situation may also reflect the fact that seasonal water supply forecast cannot have a significant impact for the majority of irrigating farmers region wide. To test this hypothesis, we use an alternative specification in which we replace the WSO-priority group variables with WSO alone; the estimate of WSO is small and statistically insignificant. We therefore postulate that seasonal water supply information only influences the redistribution of regional water resources and productivity among farmers instead of influencing either irrigation percentage or farm income across the entire region.

In addition, we control for the water rights priority effects by directly including the mean priority dates in the model specification. We find that water rights priorities positively influence irrigation percentage, particularly for water rights of low seniority; but the priority impact of water rights is nonlinear. This non-linearity is caused by the varied impacts of water rights priorities between farmers of different priority groups. In an alternative specification, we interact the mean priority date with the priority group indicator and find all the estimated parameters of the priority dates indicate positive effects on irrigation percentage. Nonetheless, we keep the present specification, considering both the technical simplicity and the primary focus of this article.

3.2 Projection

The existing literature predicts major changes in the climate and water supply trends, both globally and locally. In the Western United States, these changes include declining total availability of surface water resources (Brown and Kipfmueller 2012; Elsner *et al.* 2010; IPCC 2007; Mote 2003; Pederson *et al.* 2011; Stewart *et al.* 2005) and increased inter- and intra-annual variations (Cayan *et al.* 2001; Stewart *et al.* 2005; Bales *et al.* 2006; Mote 2006; Regonda *et al.* 2005).

By combining our estimated coefficients of minimum temperature and water supply with the projected parameter deviation from the *status quo* trends of climate and water supply documented

in the leading climate literature, we speculate on the potential impact of future climate change scenarios on the irrigated agriculture in the ESPA. Following Schlenker *et al.* (2007) and Schlenker and Roberts (2009), we only consider the projections under different temperature and water supply variations while holding everything else unchanged (including carbon emissions, land use patterns, water governance structures, and ground water use). For an analysis that considers additional factors such as the combined effects of elevated atmospheric CO_2 level and climate change-induced warming pattern, see Tubiello *et al.* (2000). We focus on the impact on the non-irrigation percentage and place the farm income projection of secondary importance. This focus will allow us to connect the projection of micro-level water allocation to local water rights structures in order to better understand and interpret the impact of climate change on local water governance structure.

We use the temperature projection of Mote and Salathé (2010), in which the temperature range is expected to increase by 1.1 ℃ to 2.9 ℃ in the Western United States by the end of the 21st century. For the total water supply, Elsner *et al.* (2010) projected the run-off in Washington during the growing season will decrease 16.4% to 19.8% in the near term by the 2020s, 23% to 29.6% in the midterm by the 2040s, and 34.4% to 44.2% in the long term by the 2080s. This water supply projection is relevant to the Snake River, because the Snake is the largest tributary of the Columbia River and the Columbia is the primary water source for the state of Washington. The standard deviation projections are difficult to obtain. We use the projected range of –0.5 ℃ to 1 ℃ for the temperature extremes (IPCC 2007) and the observed historical realization of stream flow variation (Dittmer 2013), assuming an increase of 5% in the standard deviation of water supply.

Our projections use 18 combinations of future climate and water scenarios (Table S7). We elaborate on three outcomes in Fig. S3 of the electronic supporting material. Our projections indicate substantial changes in the non-irrigation percentage and subsequent farm income. Our general conclusions are consistent with Xu *et al.* (2014a), who found average farm income will decline by up to 32%. Our finding is also in line with climate change impact literature such as Tubiello *et al.* (2000), who found that dry matter accumulation and crop yields can be reduced by 10% to 40% and Schlenker *et al.* (2007) who found that farmland value in California can be subject to losses by up to 40.7%.

Different from Xu *et al.* (2014a), we find that the irrigated agriculture in the ESPA is more vulnerable than we anticipated. Our projections indicate that even when the changes in the climate and water supply trends are modest (for example, as shown in Scenario (5)), the losses to average

farm income will exceed the worst scenario projected by Xu *et al.* (2014a). Any scenario involving greater deviation from the current climate and water supply trends will lead to even greater losses to farm income and will exceed the adaptive capacity of the community and cause farmers to irrigate less land. While most communities and sectors can cope with normal climatic variations and adapt to moderate deviations from the norm, communities may not be able to cope with extreme events, leading to projections based on such events less convincing (Smit and Wandel 2006).

Although Table S7 suggests that some favorable climate change scenarios would cause a moderate increase in irrigation percentage and farm income, they are less likely to occur because the irrigation percentage is high in the ESPA and the threshold effects will lead farmers to allocate additional water to previously dry land and thus constrain the room to increase irrigation percentage or improve productivity (English and Nuss 1982; English 1990).

The impact of climate change will differ substantially with farmers' water rights portfolios in our projections, and will be reflected by changes to local water governance structures. Idaho water rights law mandates the priorities in water appropriation of senior users over junior ones; therefore, the impact of climate change-induced water shortage on farmers' water use is contingent on the priorities of their water rights. Declining water availability leads to an earlier diversion cut-off date and the requirement of higher seniority to access irrigation water resources (for example, from 1939 to 1895; see illustration in Figs. S4.1-3 of the electronic supporting material). As a result, a larger number of irrigating farmers with junior water rights have less irrigation water at an earlier stage and for the entire growing season. Senior farmers will be less affected by water shortage or increased water supply volatility; they may even benefit from agricultural commodity price increases caused by reduced yields and market supplies.

One interesting yet less conspicuous outcome, resulting from persistent water shortages or increased volatility under the dominant water sharing rule, is the potential increase in both irrigation percentage and average farm income under several future climate change scenarios. This situation will occur when junior farmers withdraw from irrigated agriculture due to prolonged water stress. This outcome is a typical representation of the survivor effect or survivorship bias, a selection process in which those who stay in this sector are more productive and those who are less productive farmers eventually stop farming. Future research could make more precise projections in order to achieve a better understanding of the direct impact of climate change on local water governance structures.

4. Discussion and policy implication: climate change adaptation

Exposure, sensitivity, and adaptive capacity are the three essential aspects to consider when measuring the impact of future climate change (Smit and Wandel 2006; Willaume *et al.* 2014). In general, exposure and sensitivity are almost inseparable properties of a system or community; they depend not only on the interaction between the characteristics of the system but also on the attributes of the climate stimulus (Smit and Wandel 2006). The ability to undertake adaptations can be attributed to many factors in the ESPA and the entire state, especially to institutional factors such as irrigation infrastructures and institutional water governance structures that we are particularly interested in. The adaptations are also relevant to the capability of spatial and temporal reallocation of water resources between water uses of agricultural and non-agricultural purposes.

Water trading, including short-term water transactions and long-term water rights transfers can improve water use efficiency, reduce water application on marginal land, and ease water stress during persistent droughts (Rosegrant 1990). Water trading, however, may unexpectedly expand irrigated landscape, increase water consumption and the dependency of regional economies on irrigation, and adversely deteriorate the local water supply situation and sustainability. Fleskens *et al.* (2013) showed evidence of such in an analysis of the Inter-Basin Water Transfer (IBWT) schemes from Marcia, Spain.

The literature also expressed mixed points of view regarding the reform of water management methods within existing system. Some interventions have demonstrated higher rates of economic returns, whereas others have been much less effective (Rosegrant 1990; Rosegrant and Svendsen 1993; Rosegrant and Bingswanger 1994). A major concern arises over water governance reform because water trading may be contradictory to fundamental principle such as under the Prior Appropriation Doctrine in the U.S. West (Rosegrant and Bingswanger 1994). If farmers sell their unused water, they may be in violation of the beneficial-use principle (Rosegrant and Bingswanger 1994). Therefore, state administrator or judicial systems will take away rights to the water allowance they sell. Market-based reform efforts are expected to incur substantial legal hurdles in establishing new water management schemes.

To overcome the intra-seasonal variations in water supply (the shifting pattern of streamflow towards cold seasons), flexible scheduling is recommended, with positive evidence from Italy (Tubiello *et al.* 2000) and France (Willaume *et al.* 2014). Flexible scheduling, however, may not be immediately available for agricultural practice in the ESPA and other regions in Idaho. First of

all, counter-evidence from irrigated agriculture in nearby Montana suggests that flexible scheduling has no significant impact on farm productivity (Qiu and Prato 2012). More importantly, flexible scheduling requires moving the start date of agricultural diversion to earlier in the year. This strategy will work against Idaho's current water management schemes, under which water rights in Idaho have a fixed period of use and water supply in cold seasons is critical for hydropower, environmental protection, and other primary purposes. Adjusting the diversion date will interfere with the needs of other groups or sectors. We can foresee immense legal and administrative difficulties based on past experiences elsewhere in Idaho.

It seems that it will be difficult to adopt new strategies to adapt to future climate change. In our opinion, it will be particularly difficult if these strategies are undertaken separately without a system view. In other words, climate change adaptation and vulnerability reduction will be most effective if being undertaken in combination with other strategies and plans at various levels (Smit and Wandel 2006).

5. Concluding remarks

In this article we analyze how irrigating farmers change their micro-level water allocation in response to water supply variations under institutional water constraints and project the irrigation percentage and farm income under future climate scenarios from Idaho's Eastern Snake River Plain Aquifer area. We model water allocation with water supply, water rights, climate, and other agricultural covariates and investigate the direct impact of water stress on irrigated agriculture and local irrigation water management structures. Our results indicate that long-term climate and water supply trends significantly influence micro-level irrigation decision-making. Irrigated agriculture is vulnerable under future climate change scenarios, as substantial degradation in irrigated land and losses to farm income will occur when long-term climate and water supply trends modestly change. Farmers respond to seasonal water supply forecast in various ways based on their water rights portfolios; however, seasonal water supply only influences the redistribution of regional water resources and productivity but cannot generate overall benefits for all irrigated agricultural sectors due to institutional water constraints. Climate change-induced water shortage or increased water supply variations will cause unexpected consequences in both irrigation percentage and farm income under the Prior Appropriation Doctrine if water stress prolongs.

Our conclusions are subject to multiple constraints. First, we do not consider CO_2 fertilization, land use pattern change, water trading, and ground water level change in our empirical estimation

and projections. Second, our projections lack detailed information about the variations of climate and water supply trends under future climate change scenarios. Last, there is a need for more fine-scale data of micro-level irrigation diversion and crop prices and yields in order to achieve a better projection in relation to the climate change impact on farmers with different water rights priorities.

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Table 1.

Tobit estimation of non-irrigation percentage on farm income (Obs=15,399) Unit: US\$ ha^{-1}

Farm Income Model	Estimated Parameters	Standard Errors	*p*-value
Intercept	973.433	81.518	<.0001
Non-irrigation percentage (scaled up by 100)	-17.650	0.267	<.0001
Other control variables			
Crop varieties	Yes		
Farm size indicators	Yes		
Hydrological basins	Yes		
Distances to surface waters and urbanized areas	Yes		
Soil quality	Yes		

Note: We control for other covariates such as short-term crop pattern (varieties), farm size, hydrological basins, distance to major surface water bodies and urbanized areas, and soil quality. See Table S5 in the electronic supporting material.

Table 2.

Truncated regression estimation in non-irrigation percentage (Obs=15,399) Unit: Percentage (Scaled up by 100)

Non-irrigation Percentage Model	Estimated Parameters	Standard Errors	*p*-value
Intercept	158.275	68.018	0.0200
Climate and water supply indicators			
Long-term minimum temperature			
– Mean (˚C)	– 14.810	0.936	<.0001
– Standard deviation (˚C)	56.038	9.629	<.0001
Long-term surface water supply			
– Mean (BCM) [a]	– 51.395	8.293	<.0001
– Standard deviation (BCM) [a]	243.646	38.071	<.0001
Ground water levels			
– Depth <= 60 meters (m)	– 0.082	0.068	0.2273
– Depth > 60 meters (m)	0.070	0.037	0.0595
Seasonal water supply-water rights priority group interactions			
WSO_prior to 1890	– 7.695	3.995	0.054
WSO_1890 -1930	36.319	5.761	<.0001
WSO_1930 to date	– 5.574	2.529	0.028
Water rights features			
Mean priority date (scaled down by 10) [a]	– 10.428	5.187	0.0444
Mean priority date sq. adj. term (scaled down by 100) [a]	0.223	0.106	0.0353
Maximum diversion volume (MCM) [a]	– 1.512	0.360	<.0001
Water source – dominant condition			
– Surface	46.221	4.152	<.0001
– Ground	0.915	1.982	0.6442
Other control variables			
Crop varieties	Yes		
Farm size indicators	Yes		
Hydrological basins	Yes		
Distances to surface waters and urbanized areas	Yes		
Soil quality	Yes		

Note: [a] We scale down these variables to fulfill the convergence requirements of the *SAS QLIM* procedure.

We control for other covariates such as short-term crop pattern (varieties), farm size, hydrological basins, distance to major surface water bodies and urbanized areas, and soil quality. See Table S6 in the electronic supporting material.
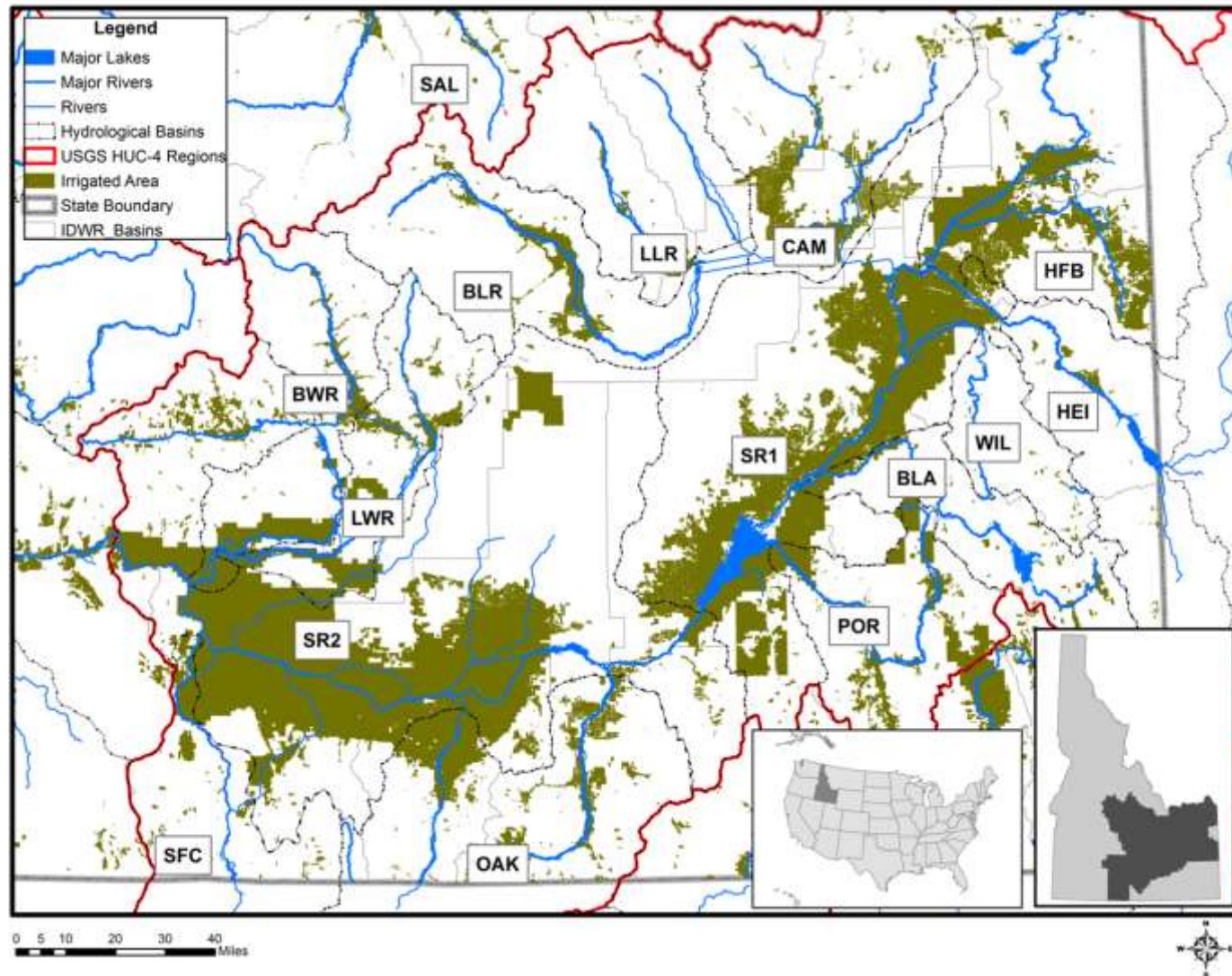
Figure 1. Spatial distribution of irrigated land in major agricultural regions in the ESPA. Data sources: Water Rights Place-of-Use Layers, Snake River Plain Aquifer Layer, and Major River and Lake Layers of the IDWR; 1:250k-scale Hydrologic Unit Code of USA of the USGS

Electronic Supporting Material

Appendix, Supplementary Tables and Supplementary Figures

used in

"Water Supply and Water Allocation Strategy in the Arid U.S. West: Evidence from the Eastern Snake River Plain Aquifer"

Section 1

Appendix

Theoretical Framework

We assume that competitive farmers own farms of a fixed size (L) and take prices as given. They grow only two types of crops (water use-intensive vs. drought-tolerant) and allocate their water accordingly. They can practice limited irrigated only on drought-tolerant crops by using the limited irrigation method. The operating expenses and crop revenues are identifiable and separable for individual crops. Water appropriation strictly follows the priority principle and water cannot be obtained through market-based transactions. Water resources depend on the total water resources at the regional level and their priorities in appropriation. Water is a scarce resource and all is allocated.

Follow English (1990), we posit that farmers maximize their total expected profit (π^e) with respect to the land allocation strategy $\{(\delta, \gamma) \mid 0 < \delta, \gamma < 1\}$ subject to the limited delivery of the expected total available water (W^e), given L and $\mathbf{Z}_{-L}$. Farmers' expected total profit is the sum of the profits from growing the two crops with limited irrigation adopted for drought-tolerant crops. For each crop i, the profit is defined as $\pi_i^e = f_i(L_i, \mathbf{Z}_{-L})$, where $\{L_i \mid 0 < L_i < L\}$ is the land allocated to this crop under a specific irrigation condition. The crops thus include irrigated water use-intensive crops (II), irrigated drought-tolerant crops (DI), and non-irrigated drought-tolerant crops (DN). We assume that marginal return from crop production is positive (that is, $f_i' > 0$) and the marginal returns of crops under different irrigation strategy follow that $f_{II}' > f_{DI}' > f_{DN}'$.

We characterize farmers' land allocation strategy as follows

$$\max_{(\delta, \gamma)} \pi^e = f_{II}(\delta L, \mathbf{Z}_{-L}) + f_{DI}((1 - \delta - \gamma)L, \mathbf{Z}_{-L}) + f_{DN}(\gamma L, \mathbf{Z}_{-L})$$

$$s.t. \quad W_{II}^e + W_{DI}^e \leq W^e$$

(A-1)

where

π^e – Expected total profit

f_i – Expected profit from growing crop i

δ – The percentage of land devoted to irrigated water use-intensive crops

γ – The percentage of land devoted to non-irrigated drought-tolerant crops.

$\mathbf{Z}_{-L}$ – A fixed set of non-allocable, farm-specific features

W^e – Expected total available water

W_i^e – Expected total available water allocated to crop i

For the crops that are irrigated, farmers allocate the expected total water in accordance to a reference such as crop water coefficient, representing crop physiological needs. Crop water coefficient is considered relatively constant (see, for example, Blum 2009; Cai *et al.* 2003b; French and Schultz 1984; Howell 2001; Wichelns 1999). Therefore, we use $W_i^e = \bar{w}_i L_i$ to represents the water allocated to individual crop i, where $\bar{w}_i$ is proportional to crop (water use) coefficient Kc_i (that is, $\bar{w}_i \propto Kc_i$). It also follows that $\bar{w}_{II} > \bar{w}_{DI}$.

The objective function implies that all land will be used in the production, because marginal returns from crop production are positive. The water constant implies that

$$\gamma = 1 - \delta - \frac{W^e - \delta \bar{w}_{II} L}{\bar{w}_{DI} L} \tag{A-2}$$

When equilibrium is reached, we have

$$\pi^{e*} = f_{II}(\delta^* L, \mathbf{Z}_{-L}) + f_{DI}((1 - \delta^* - \gamma^*)L, \mathbf{Z}_{-L}) + f_{DN}(\gamma^* L, \mathbf{Z}_{-L}) \tag{A-3}$$

We substitute Eq. (A-2) to Eq. (A-3)

$$\pi^{e*} = f_{II}(\delta^* L, \mathbf{Z}_{-L}) + f_{DI}(\frac{W^e - \bar{w}_{II}\delta^* L}{\bar{w}_{DI}}, \mathbf{Z}_{-L})$$

$$+ f_{DN}(L - \delta^* L - \frac{W^e - \bar{w}_{II}\delta^* L}{\bar{w}_{DI}}, \mathbf{Z}_{-L}) \qquad \text{(A-4)}$$

We use $\partial \pi^{e*}(\delta^*, L, \mathbf{Z}_{-L})/\partial W^e$ to evaluate the effects of water supply W^e on the optimal

level of the total expected profit π^{e*}. We expect that farmers will adjust their land allocation

strategy (δ^*) in accordance with the total expected water supply (W^e) (that is, $\partial \delta^*/\partial W^e \neq 0$).

In particular, in our model $\partial \delta^*/\partial W^e > 0$, which states that farmers will choose to allocate a

larger portion of their land to water use-intensive crops when drought is not expected and water

supply increases. Alternatively, if δ^* is not affected by W^e, the conclusion of $\partial \pi^{e*}/\partial W^e > 0$

follows directly from Eq. (A- 4).

The partial derivative of the optimal profits (π^{e*}) with respect to the expected total water

supply (W^e) is given by

$$\frac{\partial \pi^{e*}}{\partial W^e} = \underbrace{\left(f_{II}' - f_{DI}' \cdot (\frac{\bar{w}_{II}}{\bar{w}_{DI}}) + f_{DN}' \cdot (\frac{\bar{w}_{II} - \bar{w}_{DI}}{\bar{w}_{DI}}) \right)(\frac{\partial \delta^*}{\partial W^e})L}_{a} + \underbrace{\frac{1}{\bar{w}_{DI}}(f_{DI}' - f_{DN}')}_{b} \qquad \text{(A-5)}$$

If the optimal solution is an interior one, the F.O.C. condition holds as follow

$$f_{II}' - f_{DI}' \cdot (\frac{\bar{w}_{II}}{\bar{w}_{DI}}) + f_{DN}' \cdot (\frac{\bar{w}_{II} - \bar{w}_{DI}}{\bar{w}_{DI}}) = 0 \qquad \text{(A-6)}$$

We substitute (A-6) into (A-5) and have part (a) of Eq. (A-5) equal to zero. Because

$f_{II}' > f_{DI}' > f_{DN}' > 0$, it follows that $\partial \pi^{e*}(\delta^*, L, \mathbf{Z}_{-L})/\partial W^e > 0$. If the optimal solution is a corner

one, then the sign of $\partial \pi^{e*}(\delta^*, L, \mathbf{Z}_{-L})/\partial W^e$ is indefinite.

In addition, we use the following equation to evaluate the impact of water supply change on the equilibrium portion of the non-irrigated land (γ^*)

$$\frac{\partial \gamma^*}{\partial W^e} = \frac{1}{\overline{w}_{DI} L}[(\overline{w}_{II} - \overline{w}_{DI})L \cdot (\frac{\partial \delta^*}{\partial W^e}) - 1] \qquad \text{(A-7)}$$

Eq. (A-7) indicates that the effects of water supply on the percentage of non-irrigated land depends on the effects of water supply on the percentage of the drought-tolerant crops $\partial \delta^* / \partial W^e$, the difference in the crop water use between drought-tolerant and water use-intensive crops ($\overline{w}_{II} - \overline{w}_{DI}$), and the farm size. Suppose that farms are small and the difference of $\overline{w}_{II} - \overline{w}_{DI}$ is narrow and the effects of water supply on the percentage of the drought-tolerant crops are insignificant, we expect that farmers will reduce the equilibrium percentage of non-irrigated land when total expected water supply increases ($\partial \gamma^* / \partial W^e < 0$).

Because water appropriation strictly follows the priority rule under the Prior Appropriation Doctrine, the determination of water supply at the farm level is independent from the determination of the farm profit maximization and is represented by

$$W^e = W^e(\overline{W}, W^f, V, \mathbf{Z}_0) \qquad \text{(A-8)}$$

Where $\overline{W}$ is defined as the long-term water supply, W^f as the seasonal water supply forecast, and V as the priority of the farmers' portfolios of irrigation water rights. $\mathbf{Z}_0$ contains a set of non-allocable, farm-specific features which may also influence the expected water supply but be different from $\mathbf{Z}_{-L}$.

Following Burness and Quirk (1979 and 1980), we posit that increased long-term and seasonal water supply and higher priorities of water rights will not decrease the total expected water supply

$$\frac{\partial W^e}{\partial \bar{\bar{W}}} \geq 0,\ \frac{\partial W^e}{\partial W^f} \geq 0,\ \text{and}\ \frac{\partial W^e}{\partial V} \geq 0 \tag{A-9}$$

We apply the chain rule and obtain the partial derivatives of the optimal total expected profit with respect to V, W^f, and $\bar{W}$

$$\frac{\partial \pi^{e*}}{\partial \bar{\bar{W}}} \geq 0,\ \frac{\partial \pi^{e*}}{\partial W^f} \geq 0,\ \text{and}\ \frac{\partial \pi^{e*}}{\partial V} \geq 0 \tag{A-10}$$

Modeling constraints

Our modeling approaching relies on the basic assumption that water availability is only dependent on the institutional water allocation based on water rights priorities, and water is not available through market-based water transactions. To test the feasibility of this assumption we evaluate the most recent water transaction records from 2005 to 2013. The statistics in Table S8 indicates that water transactions, for the short-term water supply banking and long-term water rights transfers, plays very limited influence in regional water resources allocation and agricultural water appropriation in terms of the number of water rights in transaction and the designated place-of-use area of irrigation water rights.

Micro-level cost information is among the most difficult to obtain. Farm operating expenses change slowly over time. A study of a similar irrigated agriculture in the nearby region in Montana by Qiu and Prato (2012) reveals that operating expenses possess an insignificant portion in the total cost, the latter of which is dominated by the sunken cost related to irrigation

system. Rosegrant *et al.* (2000) pointed out that agricultural water withdrawals are not sensitive to the cost of irrigation technology. Therefore, we believe that it is feasible to regard the operating cost as constant. Under this situation, the profit maximization problem can be solved by a revenue maximization problem. Rosegrant *et al.* (2000) also claimed that profits from irrigation vary only slightly with changes in technology cost. In addition, we find that farmers in the ESPA have widely adopted the sprinkler irrigation system and the differences of the irrigated land percentage with sprinkler system are small across the counties in the ESPA, particularly for the counties along the Snake River that host the largest irrigated agriculture, according to the most recent statistics of Idaho's Water Use (USGS, Water Use Data for Idaho 2005). We therefore leave out the irrigation technology covariate (that is, the land percentage of sprinkler irrigation) in both the theoretical framework and the empirical specification.

The effects of water supply and water rights on agricultural outcomes in the short term are consistent with their effects in the long run, because the short-term profits will be consistently and systematically captured in and reflected by farmland values due to the profit maximizing behaviors (Renshaw 1958; Schlenker *et al.* 2007; Xu *et al.* 2012). We note, however, that indirect modeling of agricultural outcomes by way of micro-level irrigation allocation strategy will overlook the opportunity cost under non-irrigation conditions, which may yield higher returns from other land use patterns such as urbanization and industrialization.

Section 2

Supplementary Tables

Table S1.

Acronyms used in this article and the electronic supporting material

Acronym	Description
Hydrological Region/Basins	
ESPA	Eastern Snake River Plain Aquifer
BEA	Bear River Basin, measured at the Bear River at the Stewart Dam
BLA	Blackfoot River Basin, measured at the Snake River at Heise
BLR	Big Lost River area, measured at the Big Lost River Below Mackay Reservoir
BRU	Bruneau River Basin, measured at the Bruneau River near Hot Spring
BWR	Big Wood River area, measured at the Big Wood River below Magic Reservoir
CAM	Medicine Lodge-Camas Basin (Mud Lake) area, measured at the Snake River at Heise
HEI	Snake River near Heise and measure here
HFB	Henry's Fork River basin, measured at Henry's Fork near Ashton
LLR	Little Lost River area, measured at the Little Lost River near Howe
LWR	Little Wood River area, measured at the Little Wood River near Carey
POR	Portneuf River Basin, measured at the Snake River at Heise
SAL	Salmon River Basin, measured at Salmon River at Whitebird
SFC	Salmon Falls Creek area, measured at the Salmon Falls Creek near San Jacinto, Nevada
SR1	Heise-Idaho Falls area, measured at the Snake River at Heise
SR2	Idaho Falls-American Falls area, measured at the Snake River at Heise
SR3	American Falls-Boise area, measured at the Snake River at Heise
WIL	Willow River area, measured at the Snake River at Heise
Others	
CDLs	Cropland Data Layers
CLU	Common Land Unit
GCM	Global Circulation Model
FSA	Farm Service Administration
ICCDCD	Irrigated Land Capability Classification - Dominant Condition
IDWR	Idaho Department of Water Resources
IPCC	Intergovernmental Panel on Climate Change
KCM	Thousand Cubic Meters
LSD	Land Surface Datum
MCM	Million Cubic Meters
NASS	National Agricultural Statistics Service
NICCDCD	Non-Irrigated Land Capability Classification - Dominant Condition
NRCS	Natural Resources Conservation Service
PRISM	Parameter-Elevation Regressions on Independent Slopes Model
WSO	Water Supply Outlook

Table S2.

Variable definition and data sources

Variables	Description/Definition	Data sources
Dependent variables		
Non-Irrigation percentage (dependent variable; %)	Average irrigation percentage of the harvest area for major crops within a single farm	IDWR, ESPA Irrigation Status (2008-2010) and Water Rights Place-of-Use data layers
Crop revenue (dependent variable; US$/ha)	Average crop revenue per hectare, per farm. We focus on 14 major crops: alfalfa, barley, corn, beans, hay, lentils, oats, onions, peas, potatoes, sugar beets and wheat (durum wheat, spring wheat, and winter wheat). We use the average yield data of corn, hay, and oats from Montana and Wyoming when the lack of such data in Idaho is present.	USDA NRCS, Quick stats of crop price received and yield data and Cropland Data Layers; IDWR, Water Rights Place-of-Use data layers
Water supply and climate indicators		
Long-term surface water supply (Mean and Standard Deviation; MCM)	The 30-year, basin-level surface water supply (including total adjusted streamflow and maximum possible reservoir carryover) during the April-Sept growing seasons from 1971 to 2000	USDA NRCS (Snow Survey), Surface Water Supply Index (SWSI)
Ground water levels (m)	The depth to ground water by interpolating state-wide water levels below land surface datum at irrigation wells	IDWR, Hydro Online and Water Rights Place-of-Use data layers
Long-term minimum temperature (Mean and Standard deviation; ˚C)	The 30-year, average April minimum temperature from 1971 to 2000	PRISM Climate Group, PRISM
Seasonal water supply -- Water rights priority groups interactions	An interaction term by using the product of the seasonal water supply forecast, Water Supply Outlook Report (WSO), and the priority group indicator identified based on the farm-level water right of the oldest vintage	USDA NRCS (Snow Survey), Water Supply Outlook Report (WSO)
Water rights features		
Priority date - Mean (year)	The mean priority date of water rights for individual farms	IDWR, Water Rights Place-of-Use data layers; USGS, 1:250k-scale Hydrologic Unit Code of USA
Priority date - Oldest (year)	The oldest priority date of water rights for individual farms	IDWR, Water Rights Place-of-Use data layers; USGS, 1:250k-scale Hydrologic Unit Code of USA
Maximum diversion volume (KCM)	The maximum diversion volume evaluated on a per-farm basis	IDWR, Water Rights Place-of-Use data layers
Water Source -- Dominant condition	A set of indicators of farm-level dominant water source, calculated based on the percentage of spatial coverage of water rights of each source	IDWR, Water Rights Place-of-Use data layers
Other farm features		
Crop varieties	A set of indicators of crop varieties being used during the study period on a farm basis	USDA NRCS, Cropland Data Layers; IDWR, Water Rights Place-of-Use data layers
Farm size indicators	A set of indicators of farm size approximated by counting the sampling points within each farm	IDWR, Water Rights Place-of-Use data layers
Distance to Census 2010 Urbanized Areas (decimal degree)	The shortest Euclidian distance to the Census 2010 Urbanized Areas	USDC Bureau of Statistics, Census 2010 Urbanized Areas; IDWR, Water Rights Place-of-Use data layers
Distance to major waters (km)	The shortest Euclidian distance to the major waters (lake and river)	IDWR, Major River and Lake layer and Water Rights Place-of-Use data layers
Soil quality - Dominant type	The dominant soil type within each farm based on the spatial coverage	USDA NRCS, U.S. General Soils; IDWR, Water Rights Place-of-Use data layers

Note: The compilation of the variables used in this article has been presented in Xu *et al.* (2012).

Table S3.

Irrigation, water rights, and agricultural land use and outcomes in the ESPA

	ESPA	Snake River Basin 1	Snake River Basin 2	Henry's Fork-Teton	Big Lost River Basin
# of Observations	5,133	1,144	1,270	447	443
Mean farm area (ha)	249	263	382	252	92
Water rights features					
Mean priority date – Min	1870	1874	1876	1879	1880
– Max	2008	2003	2008	1991	1989
– Mean	1941	1959	1952	1936	1919
Water source – dominant type					
– Ground only	21.2%	44.3%	12.4%	17.9%	4.7%
– Surface only	44.7%	17.9%	38.6%	65.5%	45.8%
– Conjunctive	34.0%	37.8%	49.1%	16.6%	49.4%
Climatic conditions in April					
Precipitation (mm)	25.26	25.58	22.22	36.85	19.52
Max temp (˚C)	14.05	14.57	16.18	11.80	11.96
Min temp (˚C)	− 0.97	− 0.53	1.00	− 2.73	− 2.92
Soil – Dominant Type (>20%)	2, 3, & 5+	2	2 & 3	3 & 5+	3 & 5+
Average Groundwater Levels (m)	47.01	44.92	80.08	80.21	26.01
Average Distance to Major Waters (km)	5.32	7.18	7.09	3.75	2.15
Average Distance to Census 2010 Urbanized Area (Decimal degrees)	1.34	0.60	1.83	0.71	1.58
Average irrigation percentage of harvest area [a]					
2008 average (%)	92.6%	94.0%	92.8%	89.1%	89.3%
2009 average (%)	91.0%	93.2%	91.9%	86.3%	83.1%
2010 average (%)	93.7%	94.3%	94.1%	91.5%	88.2%
Average per-farm, per-acre crop revenue [a]					
2008 average (US$/ha)	1397	1672	1403	1522	992
2009 average (US$/ha)	1361	1732	1468	1410	796
2010 average (US$/ha)	1449	1734	1501	1472	1001

Note: [a] We remove all zero or missing values when calculating the average irrigation percentage and crop revenue.

Table S4.

Kolmogorov-Smirnov Test statistics (*p-value*) for the average irrigation percentage and crop revenue of different priority groups in the ESPA

	All	Cropping year 2008	Cropping year 2009	Cropping year 2010
Irrigation percentage				
Priority Group (prior to1890) vs. Priority group (1890-1910)	<.0001	<.0001	<.0001	<.0001
Priority group (1890-1910) vs. Priority group (1910-1930)	0.2205	0.5039	0.9323	0.1116
Priority group (1910-1930) vs. Priority Group (1930 to present)	<.0001	<.0001	<.0001	<.0001
Crop revenue				
Priority Group (prior to1890) vs. Priority group (1890-1910)	<.0001	<.0001	<.0001	<.0001
Priority group (1890-1910) vs. Priority group (1910-1930)	0.183	0.460	0.112	0.082
Priority group (1910-1930) vs. Priority Group (1930 to present)	<.0001	<.0001	<.0001	<.0001

Table S5.

Tobit estimation of non-irrigation percentage on farm income (Obs=15,399) Unit: US$/ha

Farm Income Model	Estimated Parameters	Standard Errors	*p*-value
Crop varieties			
Alfalfa	51.18	34.29	0.1356
Barley	− 151.28	22.31	<.0001
Bean	− 12.43	20.88	0.5516
Corn	− 153.45	20.48	<.0001
Hay	− 54.00	14.40	0.0002
Oat	− 119.42	17.10	<.0001
Pea	− 91.33	23.71	0.0001
Sugar beet	308.50	24.26	<.0001
Potato	498.62	26.03	<.0001
Wheat	35.37	24.26	0.1448
Farm size indicators			
20 to 40 ha	29.37	23.71	0.2154
40 to 200 ha	− 24.44	20.01	0.2221
200 to 400 ha	− 43.11	27.49	0.1169
400 to 800 ha	− 88.51	33.21	0.0077
>= 800 ha	− 119.09	40.15	0.0030
Hydrological basins			
SR1	112.72	28.51	<.0001
SAL	− 290.22	29.04	<.0001
Others			
Distance to Census 2010 Urbanized Areas (decimal degree)	− 2.00	15.68	0.8987
Distance to major waters (km)	− 0.48	1.22	0.6924
Soil quality – Dominant type	163.68	34.23	<.0001
Soil quality – Dominant type sq. adj. term	− 15.87	3.77	<.0001

Table S6.

Truncated regression estimation in non-irrigation percentage (Obs=15,399) Unit: Percentage (Scaled up by 100)

Non-irrigation Percentage Model	Estimated Parameters	Standard Errors	*p*-value
Crop varieties			
Alfalfa	− 141.36	4.58	<.0001
Barley	− 65.59	4.34	<.0001
Bean	− 5.34	2.54	0.0353
Corn	− 40.40	4.43	<.0001
Hay	− 3.95	1.54	0.0100
Oat	1.71	1.21	0.1578
Pea	0.67	1.26	0.5942
Sugar beet	− 0.37	1.34	0.7841
Potato	− 87.48	5.05	<.0001
Wheat	− 74.57	5.10	<.0001
Farm size indicators			
20 to 40 ha	− 44.64	4.96	<.0001
40 to 200 ha	− 39.50	4.49	<.0001
200 to 400 ha	− 36.29	4.61	<.0001
400 to 800 ha	− 27.01	5.73	<.0001
>= 800 ha	1.00	11.91	0.9333
Hydrological basins			
SR1	− 2.16	4.26	0.6115
SAL	− 342.43	45.55	<.0001
Others			
Distance to Census 2010 Urbanized Areas (decimal degree)	5.05	3.03	0.0952
Distance to major waters (km)	0.25	0.18	0.1516
Soil quality – Dominant type	9.32	5.86	0.1113
Soil quality – Dominant type sq. adj. term	0.67	0.66	0.3124

Table S7.
Projected changes in irrigation percentage of harvest area and farm income under future climate scenarios in the ESPA

Scenarios	Temperature		Surface Water Supply		Non-Irrigation Percentage (%)	Farm Income (US$ ha^{-1})
	Mean	Volatility	Mean	Volatility	Increase/Decrease	Gain/Loss
1	+ 1 ℃	− 0.5 ℃	− 5%	+ 5%	-13.30	234.76
2			− 10%	+ 5%	1.06	-18.65
3		0 ℃	− 5%	+ 5%	14.72	-259.77
4			− 10%	+ 5%	29.08	-513.18
5		0.5 ℃	− 5%	+ 5%	42.74	-754.31
6			− 10%	+ 5%	57.09	-1007.72
7	+ 2 ℃	− 0.5 ℃	− 5%	+ 5%	-28.11	496.17
8			− 10%	+ 5%	-13.75	242.76
9		0 ℃	− 5%	+ 5%	-0.09	1.63
10			− 10%	+ 5%	14.27	-251.78
11		0.5 ℃	− 5%	+ 5%	27.93	-492.90
12			− 10%	+ 5%	42.28	-746.31
13	+ 3 ℃	− 0.5 ℃	− 5%	+ 5%	-42.92	757.57
14			− 10%	+ 5%	-28.56	504.16
15		0 ℃	− 5%	+ 5%	-14.90	263.04
16			− 10%	+ 5%	-0.55	9.63
17		0.5 ℃	− 5%	+ 5%	13.12	-231.50
18			− 10%	+ 5%	27.47	-484.91

Note: We assume that carbon emissions, land uses, crop prices, water governance structures, and ground water levels are held constant, and the standard irrigation status and farm income are under actual 2008-2010 realizations. We also assume that the pattern of the standard deviation of water supply is based on observations from the past 100 years.

Table S8.
Summary statistics of irrigation water transactions in the ESPA from 2005 to 2013 in terms of the water rights place-of-use data layers

|	Annual average (9-year)	9-year total water rights in transactions grouped by priority date (Year)													
		1870s & Prior	1880s	1890s	1900s	1910s	1920s	1930s	1940s	1950s	1960s	1970s	1980s	1990s	2000s
Water banking (Rental)															
# of water rights	32	-	21	3	-	2	5	5	29	34	63	17	2	104	-
Ratios - Total number	0.17%	-	0.11%	0.02%	-	0.01%	0.03%	0.03%	0.16%	0.18%	0.34%	0.09%	0.01%	0.56%	-
Total designated acreage (kha)	134.42	-	123.98	43.97	-	2.54	17.42	17.58	155.98	193.31	345.51	74.13	0.70	234.63	-
Ratios - Total designated acreage	0.60%	-	1.38%	0.49%	-	0.03%	0.19%	0.20%	1.73%	2.14%	3.83%	0.82%	0.01%	2.60%	-
Water banking (Lease)															
# of water rights	81	2	101	30	23	26	7	19	18	104	136	175	78	10	2
Ratios - Total number	0.44%	0.01%	0.55%	0.16%	0.12%	0.14%	0.04%	0.10%	0.10%	0.56%	0.74%	0.95%	0.42%	0.05%	0.01%
Total designated acreage (kha)	41.06	0.00	5.68	1.87	10.44	1.67	0.22	66.70	2.97	116.90	96.85	44.03	21.31	0.84	0.05
Ratios - Total designated acreage	0.18%	0.00%	0.06%	0.02%	0.12%	0.02%	0.00%	0.74%	0.03%	1.30%	1.07%	0.49%	0.24%	0.01%	0.00%
Water rights transfers [a]															
# of water rights	84	9	113	63	65	35	12	10	23	105	126	118	66	15	-
Ratios - Total number	0.46%	0.05%	0.61%	0.34%	0.35%	0.19%	0.06%	0.05%	0.12%	0.57%	0.68%	0.64%	0.36%	0.08%	-
Total designated acreage (kha)	242.27	5.05	683.60	447.73	589.57	31.47	145.26	18.34	69.01	53.38	59.59	44.08	31.15	2.22	-
Ratios - Total designated acreage	1.09%	0.06%	7.58%	4.97%	6.54%	0.35%	1.61%	0.20%	0.77%	0.59%	0.66%	0.49%	0.35%	0.02%	-

Note: [a] Water right transfers are defined broadly in Idaho, which include the changes in place of use, point of diversion, ownership, area, water source, purpose of use, and other essential water rights features. Water right ownership transfers account for an even smaller portion of the portion in relation to all irrigation water rights in the ESPA with respect to the total number and area.
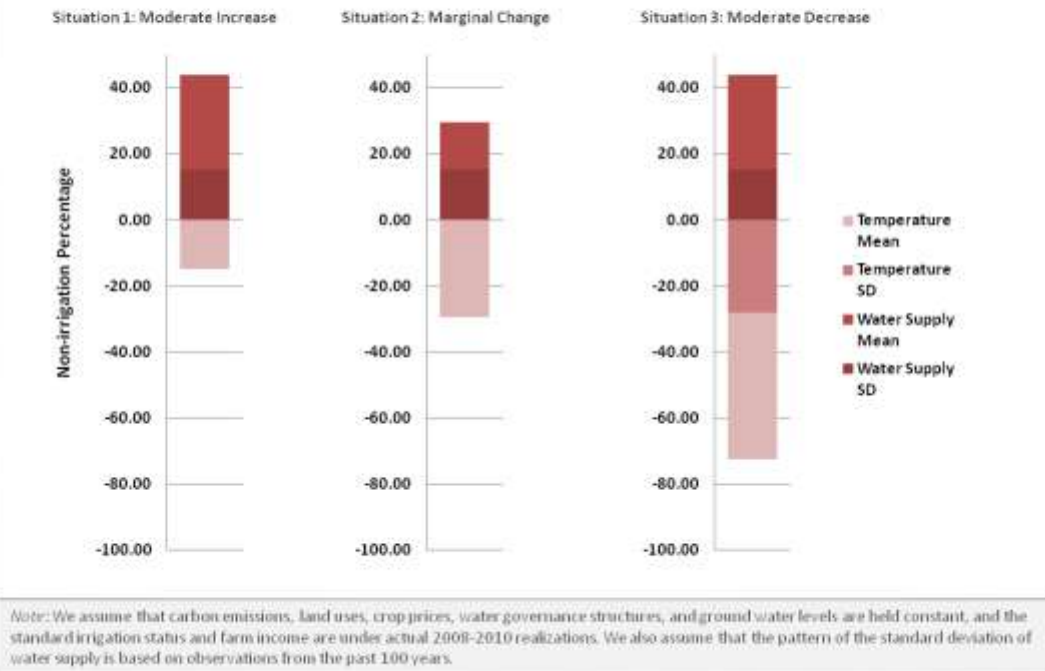
Section 3

Supplementary Figures
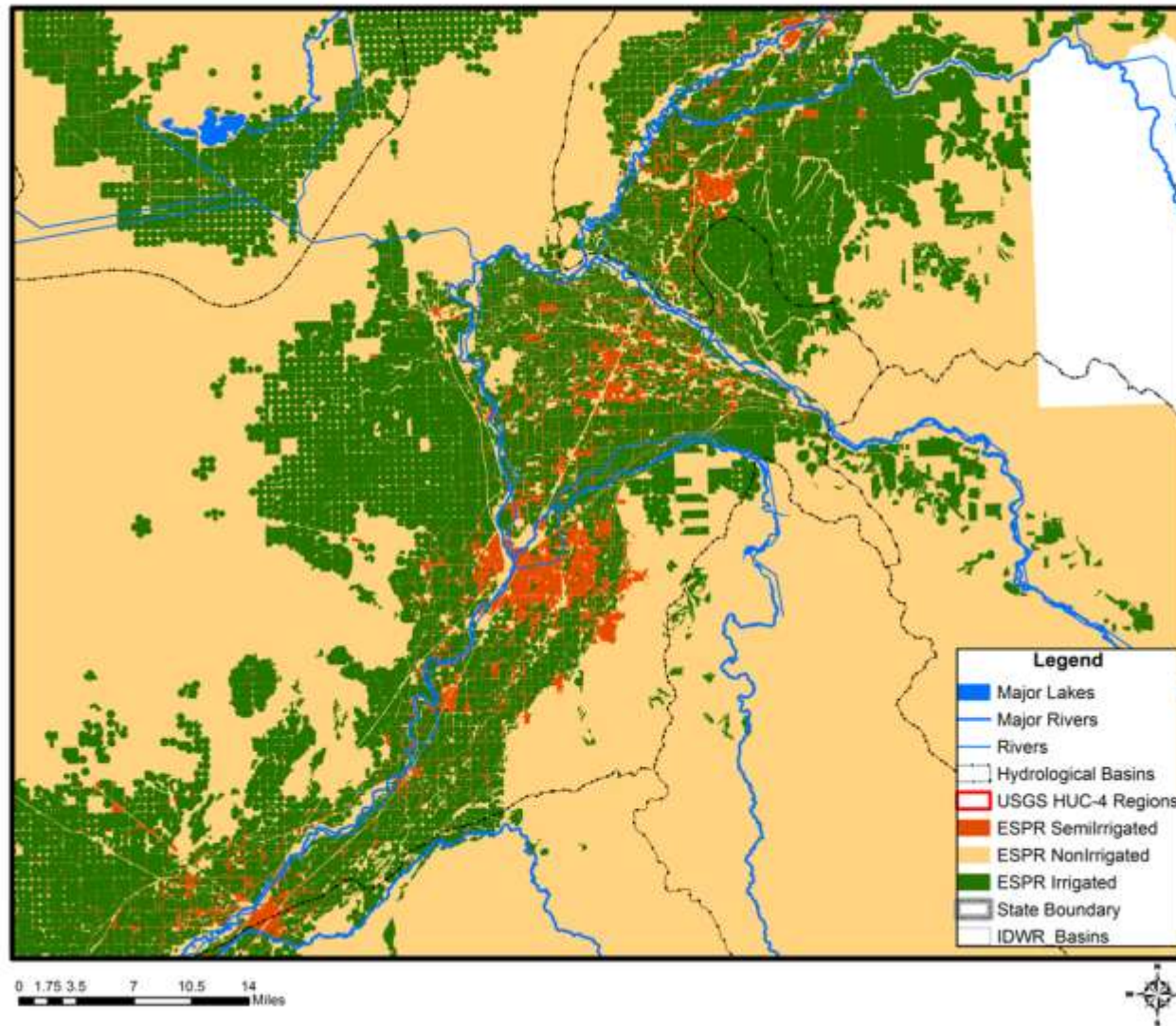
Fig. S1 Irrigation status in the ESPA (SR1). Data source: the Eastern Snake River Plain Aquifer Irrigated Land layer, Land Cover and Vegetation of the IDWR
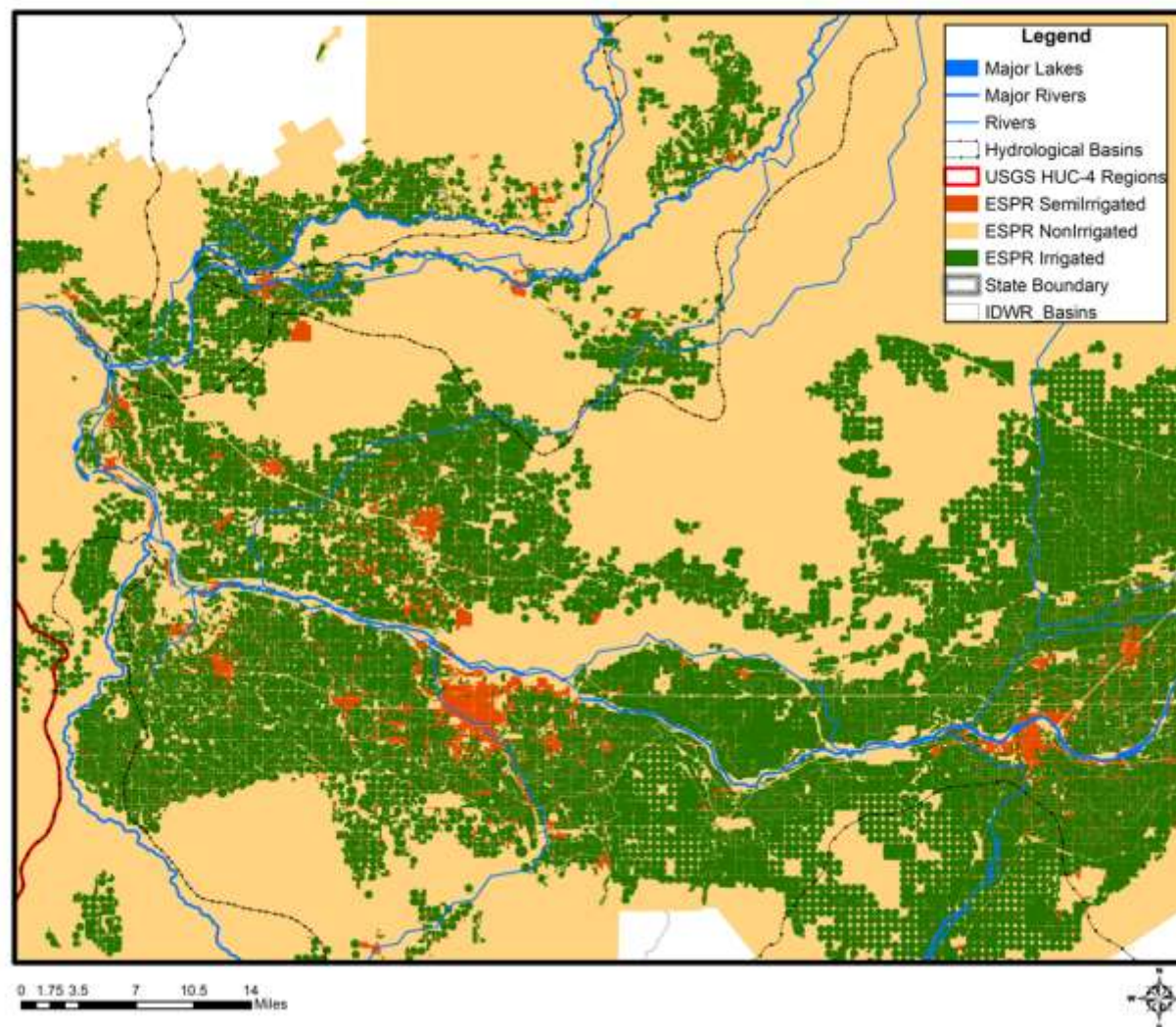
Fig. S2 Irrigation status in the ESPA (SR2). Data source: the Eastern Snake River Plain Aquifer Irrigated Land layer, Land Cover and Vegetation of the IDWR

Fig. S3 Projected average gains/losses in non-irrigation percentage under three different scenarios of climate change. Note: The three different outcomes, from left to right, describe a moderate increase (Scenario 4), a marginal change (Scenario 9), and a moderate decrease (Scenario 14) in non-irrigation percentage, respectively. We use red color with different darkness to represent the contribution from the four sources of the changes in the level and standard deviation of minimum temperature and water supply.
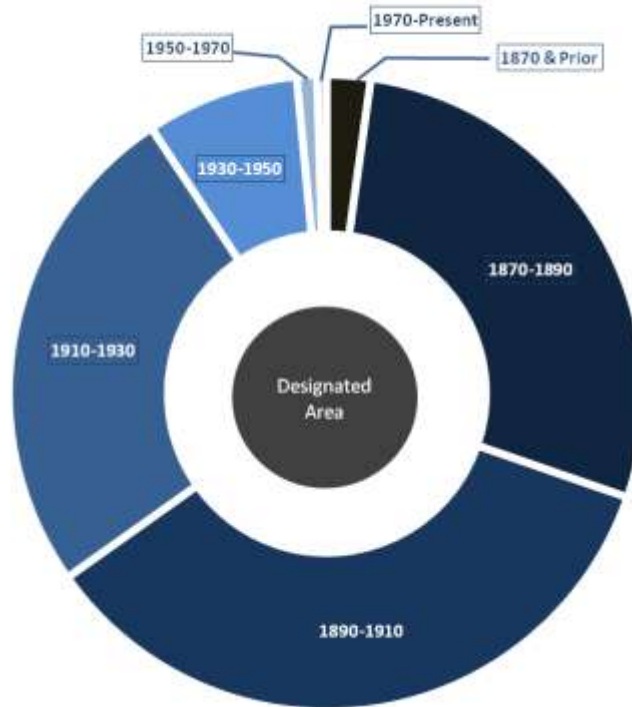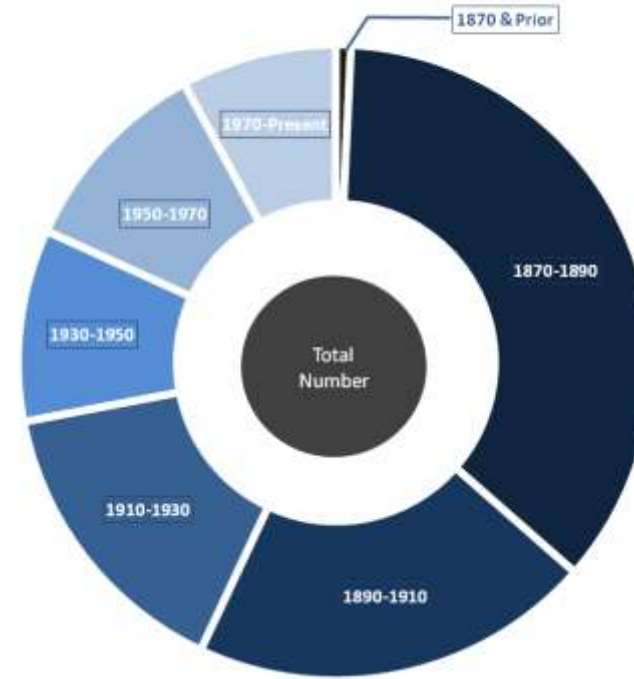
Fig. S4.1 Water shortage impact on farmers' irrigation diversion based on water right priority date in the ESPA: Distribution of surface water rights based on the water rights designated areas (A0) and total number (B0) in the SR1 and SR2 regions. Note: Darker color means water rights with higher priorities. Data sources: Water Rights Place-of-Use Layers and Water District 01 End of Year Accounting from the IDWR.
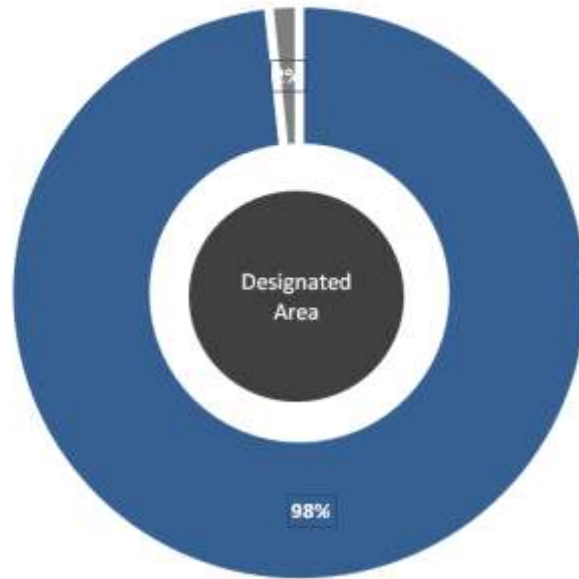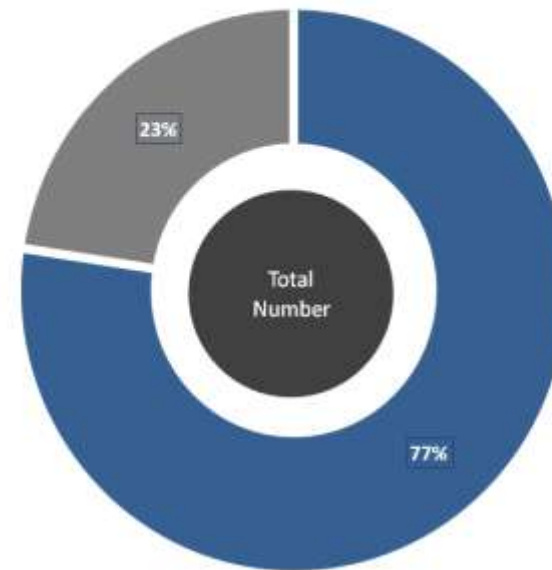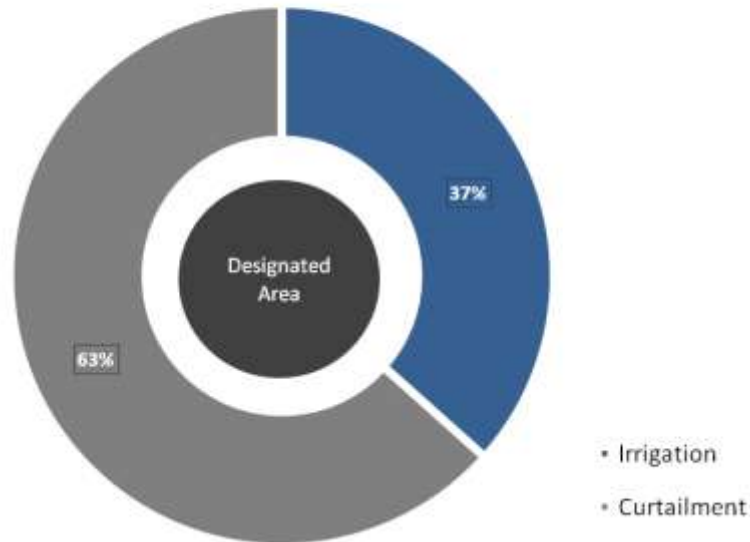
Fig. S4.2 Water shortage impact on farmers' irrigation diversion based on water right priority date in the ESPA: Distribution of surface water rights under irrigation and curtailment based on the water rights designated areas (A1) and total number (B1) in the SR1 and SR2 regions when the cut-off date was 1939 as of July 1, 2008 in the Water District 01. Note: A cut-off date is the priority date bench mark to determine if a farmer under a particular water right is able to receive water. Water District 01 primarily is comprised of the SR1 and SR2 regions. Data sources: Water Rights Place-of-Use Layers and Water District 01 End of Year Accounting from the IDWR.
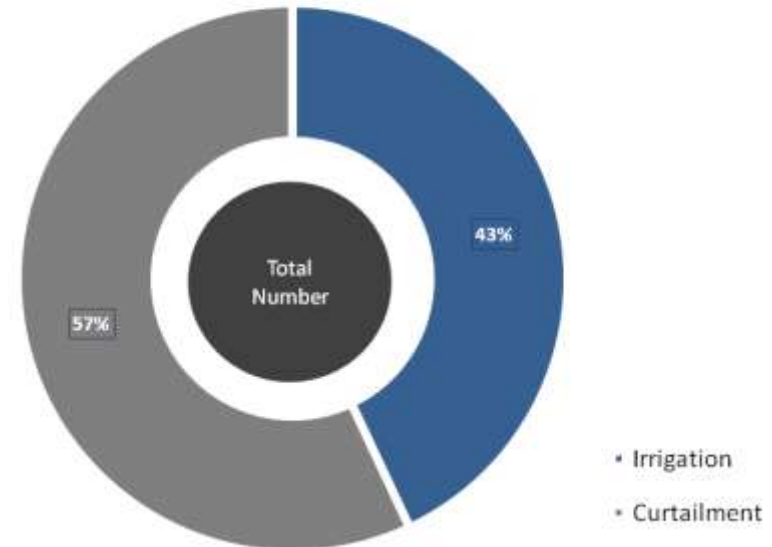
Fig. S4.3 Water shortage impact on farmers' irrigation diversion based on water right priority date in the ESPA: Distribution of surface water rights under irrigation and curtailment based on the water rights designated areas (A2) and total number (B2) in the SR1 and SR2 regions when the cut-off date was 1895 as of the July 1, 2013 in the Water District 01. Note: In comparison with Fig. S4.2, a more senior cut-off date (1895) led to a substantial increase of water rights under curtailment. Farmers who possess the irrigation water rights under curtailment will be unable to receive water to irrigate. Data sources: Water Rights Place-of-Use Layers and Water District 01 End of Year Accounting from the IDWR.