Water right seniority, economic efficiency and land allocation decisions

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Abstract: The doctrine of prior appropriation, used throughout the western United States to administer water rights based on seniority, introduces heterogeneity in the risk of a water shortage among otherwise similar agricultural irrigators. This heterogeneity in risk potentially gives rise to an economic inefficiency by constraining the land-allocation decisions of irrigators with less secure property rights to water. Using a fine-scale dataset of spatially referenced surface water rights for the Eastern Snake River Plain in Idaho, we find empirical evidence that those farms with the most secure (senior) rights choose a land allocation that involves less extensive fallowing and the choice of more drought-sensitive crops than those with less secure (junior) rights. We find that ownership of a portfolio of water rights that diversifies across seniority is associated with a more profitable land allocation but does little to mitigate this seniority effect. In contrast, a portfolio providing access to correlative water rights, such as those held by irrigation districts, mitigates the effect of seniority nearly entirely. This is likely due to numerous reasons, including more homogeneous risk sharing in correlative systems and access to informal water markets. (*JEL* codes: Q15, Q12, C35)

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Agricultural production across the semi-arid to arid western United States is highly dependent on supplemental irrigation to improve yields and prevent crop failures. In contrast to other inputs to production, water in the western U.S. cannot be freely bought and sold because it is allocated subject to water rights that are managed according to the legal doctrine of prior appropriation. Each prior appropriation water right is comprised of a bundle of attributes that define and limit water diversions and use, including a priority date. This date, which corresponds to the first date on which water was diverted for use in irrigation under a right, forms the basis for water allocations based on the principle of "first in time, first in right." Under this allocation system, those rights established earliest in time (senior rights) receive first access to scarce water resources. If there is insufficient water to fulfill all rights, those established latest in time (junior rights) are curtailed, i.e., water deliveries under those rights are cut off for some or all of a growing season. The most senior water rights are likely to be fulfilled regardless of water availability in any particular growing season and thus provide the most stable access to water, all else equal.

The economic literature establishes theoretically that if there is not a competitive market in water rights, prior appropriation creates the potential for economically inefficient resource use because it introduces heterogeneity in the risk of water availability faced by otherwise similar irrigators (Burness and Quirk 1979).[1] However, the empirical evidence on the presence and

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[1] Burness and Quirk (1979) demonstrate that the allocation of water across farmers under the doctrine of prior appropriation is inefficient because irrigators cannot equalize their risk, for example by trading water rights within a competitive market. Some areas of the country do have limited water market and trade. A number of studies demonstrate the potential for alternative institutional arrangements, e.g., water markets and banks, to yield efficiency

magnitude of these effects is limited and the conclusions vary across regions (Brent 2016; Mukherjee and Schwabe 2015). The foremost obstacle to empirical study of prior appropriation is the considerable complexity of western water rights and a corresponding dearth of high-quality data on water rights attributes at the scale of the individual irrigator. As a result, existing studies rely on aggregate data at the scale of the irrigation district or region (Brent 2016; Mendelsohn and Dinar 2003; Moore and Negri 1992; Mukherjee and Schwabe 2015; Schlenker, Hanemann, and Fisher 2005, 2007).

Recent research suggests that such aggregation fails to account for unobservable effects operating at the scale of the individual irrigator and may bias estimates of the value of irrigation water toward zero (Buck, Auffhammer, and Sunding 2014). Aggregation also obscures variation in water rights attributes at the scale at which prior appropriation doctrine is applied. Furthermore, the institutional characteristics governing water deliveries differ for irrigation districts and for individual owners of water rights. Irrigation districts represent a group of irrigators who may share proportionally in a water shortfall, which is an example of a correlative water rights system. Compared with the strict application of prior appropriation doctrine, used to administer individual water rights, a correlative system more evenly distributes risk across producers within the district. In addition to the sharing of risk, irrigation districts offer benefits that are not available outside their bounds, such as the ability to informally trade water among members. These differences between correlative and appropriative systems imply that seniority is unlikely to have the same importance for irrigators within districts as those without.

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gains over prior appropriation (e.g., Elbakidze *et al*. 2012; Ghosh, Cobourn, and Elbakidze 2014; Howe, Schurmeier, and Shaw 1986; Jaeger 2004).

Our objective in this article is to develop insight into the magnitude of the economic inefficiency that arises from the seniority based structure of prior appropriation. To do so, we take advantage of a detailed geospatial dataset of water rights in the Eastern Snake River Plain, Idaho to analyze empirically the effect of seniority on irrigator decision making at the scale of the individual water right. We thus contribute to the literature an empirical analysis that captures variation in water rights seniority at a finer scale than previously considered. We also leverage the water rights dataset to identify cases in which land may be irrigated under two types of water rights portfolios: one in which water rights to irrigate the same land diversify across priority dates (stacked water rights; Ghosh, Cobourn, and Elbakidze 2014), and one in which the same land may be irrigated under private water rights and shares from an irrigation district. We test empirically whether access to either or both types of portfolios mitigates the effect of seniority on producer decision making, contributing to the literature on the effect of portfolio ownership in the context of prior appropriation (Mukherjee and Schwabe 2015). Furthermore, considering differences in irrigator behavior inside and outside of irrigation districts allows us to draw parallels with the existing empirical literature that uses irrigation districts as the unit of analysis.

Herein, we combine and extend the analyses of Moore and Negri (1992) and Burness and Quirk (1979) to develop new theoretical and empirical models that incorporate the effect of water rights seniority and portfolio ownership on the land-allocation decisions of individual irrigators. Moore and Negri (1992) examine how changes in water availability under the doctrine of prior appropriation affect land-allocation decisions in a multi-crop system. They include diversion limits under prior appropriation in their theoretical and empirical models by treating water as a fixed, allocable input within a multi-output model of farm production. They find evidence that surface water availability is a strong determinant of regional crop supply and land-allocation decisions. Moore, Gollehon, and Carey (1994) conclude that modeling crop choice and land-allocation decisions provides clear insight into farm-level responses to changes in water availability. While both Moore and Negri (1992) and Moore, Gollehon, and Carey (1994) consider how prior appropriation affects the treatment of water in a multi-crop model of production, they do not model the effect of seniority on land-allocation decisions, nor do they or account for the effect of water right portfolios.[2]

We extend the model of Moore and Negri (1992) to include the effect of seniority on water diversion constraints and production, following Burness and Quirk (1979). To do so, we model the effect of seniority on the probability that water rights are fulfilled and thus on the total amount of water available for irrigation at the scale of the individual farmer. In addition, we extend the literature by examining how portfolio ownership affects water availability and land-allocation decisions. We are not aware of a study that examines portfolios that diversify across seniority or across private and correlative water rights, though the empirical literature is suggestive of the importance of holding portfolios that diversify across risk in water availability. Mukherjee and Schwabe (2015) note that farmers may hold a portfolio of water rights from a single source or from multiple sources (e.g. surface or groundwater). They show that access to multiple sources of water is capitalized into higher farmland values and ownership of a water portfolio may mitigate the negative impact of variation in water availability. Our approach differs in that we focus on the effect of a portfolio on annual land-allocation decisions rather than

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[2] Moore, Gollehon, and Carey (1994) discuss that farmers use water from different sources and that some sources may be more secure in terms of water provision. However, they do not examine the construction of water portfolios or the behavior of senior versus junior water rights owners.

on property values.[3] We explicitly model how the characteristics of individual water rights and portfolios influence land-allocation decisions, which is one factor that drives heterogeneity in land values across otherwise similar farms with different water rights.

Our empirical analysis demonstrates that farms with senior surface water rights have systematically different land-allocation patterns than farms with junior rights, controlling for heterogeneity in land quality, weather, climate, and annual variation in crop prices. Parcels irrigated under junior rights are, on average, more heavily allocated toward fallow and drought-resilient crops (alfalfa and winter wheat). This difference in crop mix and extent comes at a cost in terms of a reduction in annual profit (a "seniority effect") of up to 5.51%.[4] Access to a portfolio of stacked water rights, which diversifies across priority date, is associated with a more profitable land allocation on average—an increase of 4.57-5.53% relative to no portfolio—but does little to offset the effect of seniority. Access to correlative water rights through an irrigation district is associated with a land allocation generates a more substantial increase in annual profit—14.08-15.68% relative to no portfolio—and nearly entirely offsets the effect of seniority on land-allocation decisions. Benefits to membership in an irrigation district may arise due to several reasons, including more equitable risk sharing across irrigation district members and access to informal water markets.

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[3] That land values reflect differences in water rights is consistent with Moore and Negri's argument that under prior appropriation, "the surface water right usually becomes attached to the land on which the water is applied initially, with surface water rents reflected implicitly in land prices rather than explicitly in water prices" (1992, p. 30).

[4] The approximate profit associated with a predicted land allocation is calculated using average historical crop prices (2005-2015; USDA NASS 2016a), and region-specific estimates of crop yields and costs of production from state extension budgets.

Theoretical Framework

We develop a theoretical model that builds on the framework proposed by Moore and Negri (1992) in which land and water are treated as fixed, allocable inputs within a multi-crop agricultural firm. The treatment of water as a fixed, allocable input is consistent with the way in which surface water rights are administered under the doctrine of prior appropriation. Specifically, water rights constrain the expected amount of water available for use as an input into irrigated crop production. Our focus is on modeling short-run adjustments in the allocation of land in response to seasonal changes in expected water availability.[5] We extend the model of Moore and Negri (1992) to capture how the seniority of water rights affects a farmer's expected water deliveries during the growing season. We also incorporate the potential for ownership of a water right portfolio composed of rights that may differ in terms of seniority, and thus their probability of fulfillment. The portfolio of rights together forms a constraint on the expected availability of water for irrigation.

The theoretical model presented in this section is for a stylized system with two crops. The choice of a two-crop system is a departure from the multi-crop model presented by Moore and Negri (1992). In their model, Moore and Negri (1992) remain agnostic about the marginal productivity of water across multiple crops, which yields indeterminate comparative statics results for how a change in water rights diversion constraints affects land and water-allocation decisions. However, in practice the most drought sensitive, irrigated crops tend to also be the

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[5] Long-run adjustments may involve changes in water rights characteristics or ownership. There are significant administrative costs and time lags (on the order of years to decades) associated with any substantive change to a water right's characteristics. As a result, it has not been possible to date in our study region to alter water rights in response to a short-run (annual) water shortage.

most profitable, while crops that can be produced without irrigation are more drought resilient, but also tend to be less profitable. Our model is similar to the two-crop model of Hornbeck and Keskin (2014), in which the marginal productivity of water for the crops differs so that changes in crop mix are a mechanism available to farmers to hedge against the risk of a water shortage. We capture this possibility in a model with two crops, one of which is produced with irrigation and the other on dryland.[6] These two land-allocation choices capture the endpoints on a spectrum along which crops vary in drought sensitivity and profitability.[7] Considering the two-crop case simplifies the exposition of the theoretical framework and serves to develop intuition into the more complex, multioutput land-allocation problem in the empirical analysis.

Model of the Irrigated Agricultural Firm

Consider a price-taking, risk-neutral farmer who maximizes expected profit by allocating a fixed amount of land, L, between two crops, one of which is irrigated (r) and one that is produced on dryland (d). The farmer holds a portfolio of water rights that allows diversion of $W \leq \overline{W}$ units of water that may be applied to the irrigated crop, where $\overline{W}$ is the maximum quantity of water that may be diverted under the portfolio. The restricted profit function for the irrigated crop r can be

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[6] We considered a version of the two-crop model in which both are irrigated, but doing so substantially complicates the mathematics required to analyze the effect of a water right portfolio on the land-allocation decision. We trade off complexity in the multioutput feature of the problem in order to incorporate water rights seniority and portfolios.

[7] An additional complexity arises in the multi-crop problem when considering heterogeneity in land quality. At the parcel scale, some land may be more suitable for one crop than for another, which implies that the ordering of the marginal productivity of water across crops may differ across space. It is far more tenable to impose an ordering in the marginal productivity of water for the case of irrigated versus dryland production. In arid and semi-arid regions with limited summer precipitation, it is rare that dryland production generates a greater profit per unit land area than irrigated production, either for the same crop or across different crops.

expressed as $\pi_r(W, L_r)$, where L_r is the share of land allocated to the irrigated crop (i.e. $L_r + L_d \leq 1$). Assume that the production function exhibits constant returns to scale with respect to land and can be written as $\pi_r(W, L_r) = L_r \pi(w)$, where $\pi(w)$ is the profit earned per unit land area, which is dependent on $w = W/L_r$, diversions of water per unit land area. We assume that $\pi(w)$ is globally concave, i.e., $\pi'(\cdot) > 0$ and $\pi''(\cdot) < 0$. These assumptions imply that profit per unit land area for the irrigated crop increases at a decreasing rate as more water is used to irrigate the crop.

The dryland crop d is produced without supplemental irrigation. We assume a linear restricted profit function $\pi_d(L_d) = L_d D$, which depends on the land allocated to the dryland crop and a constant profit per unit of land area, $D > 0$. Over some range of water applications, the irrigated crop is more profitable than the dryland crop, i.e., we assume there exists some minimum level of per-unit land area water applications denoted $\tilde{w}$ such that $\pi(\tilde{w}) > D$ for all $w > \tilde{w}$. This assumption is defensible in semi-arid and arid areas of the western U.S. because there is insufficient precipitation to support critical water needs for plant growth during the hot, dry summers (Schlenker, Hanemann, and Fisher 2005). As a result, many of the region's most profitable crops cannot be produced without irrigation. Crops that can be produced without irrigation exhibit dryland yields that are typically far lower than those attainable with irrigation.[8]

A farmer has rights to use water in accordance with the doctrine of prior appropriation, and possesses a water rights portfolio with $i = 1, \dots, N$ rights. The water rights in the portfolio

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[8] For example, according to the USDA Census of Agriculture for 2012 across California, Colorado, Idaho, Montana, Utah, and Wyoming, barley yields when the entire crop was irrigated averaged 96.6 bushels per acre versus 54.0 bushels per acre on dryland; for wheat, the difference is 79.1 versus 36.7 bushels per acre; for alfalfa hay, the difference is 4.1 versus 1.9 tons per acre.

differ only with respect to seniority, so that other attributes (e.g., point of diversion, maximum quantity of water diverted, time during the year diversions are permitted) are identical within the portfolio. Thus, the portfolio is one that spans water rights seniority dates, where more senior water rights within the portfolio are more likely to be fulfilled than more junior water rights within the portfolio. Each water right allows up to a maximum quantity of water, $\overline{W}/N$, to be diverted so that the maximum total quantity of water held within the portfolio is equal to $\overline{W}$. When land is allocated between crops *r* and *d*, the farmer does not know with certainty that each water right will be fulfilled up to $\overline{W}/N$. The probability that a water right *i* will be entirely fulfilled to $\overline{W}/N$, denoted $q_i \in [0,1]$, depends on the seniority of the water right as well as the expected quantity of water available for irrigation, where the latter is a function of climate.[9,10] The probability of curtailment is $1 - q_i$, where curtailment implies that water right *i* will not be fulfilled and thus the quantity of water available from that right equals zero.

Let the index of water rights within an individual portfolio be in decreasing order of seniority, so that $i = 1$ is the most senior water right and $i = N$ is the least senior water right. Under the doctrine of prior appropriation, water is allocated in a hierarchical manner according to priority date. We assume that the probability of fulfillment is non-decreasing in water right seniority such that $q_1 \geq q_2 \geq \cdots \geq q_N$. If water right *i* is curtailed, then any water right junior to

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[9] This requires that there is a known density function for water inflows and full knowledge of all water rights on a water source. In practice, each water right is characterized by a range of probability of being fulfilled, from the first drop of water $\underline{q_i}$ to the last drop of water $\overline{q_i}$. However, when $\overline{W}$ is sufficiently small, the difference between $\underline{q_i}$ and $\overline{q_i}$ is negligible. Thus, we assume that a water right can only be either fully fulfilled or completely curtailed.

[10] The likelihood of fulfillment is also a function of the availability of regional water storage infrastructure, i.e. dams and reservoirs.

i in the portfolio (any water right j where $j > i$) will also be curtailed. Thus, the farmer receives deliveries of $W = i(\overline{W}/N)$ units of water with probability $q_i - q_{i+1}$ for $i = 0, \ldots, N$ where $q_0 = 1$ and $q_{N+1} = 0$. This defines the probability mass function for the random variable W, or water diversions. The farmer receives no water with probability $1 - q_1$ and the maximum quantity of deliveries $\overline{W}$ with probability q_N.[11] The expected amount of water that a farmer may divert under the portfolio is:

$$E(W) = \sum_{i=0}^{N} (q_i - q_{i+1}) \frac{i\overline{W}}{N} = \sum_{i=1}^{N} q_i \overline{W} = \mu \overline{W} \tag{1}$$

where $\mu = \frac{1}{N} \sum_{i=1}^{N} q_i$ is the mean probability of fulfillment across the water portfolio.

The farmer's profit maximization problem can be written as:

$$\max_{L_r} E(\pi) = \sum_{i=0}^{N} (q_i - q_{i+1}) L_r \pi \left(\frac{i\overline{W}}{NL_r} \right) + (L - L_r) D \tag{2}$$

where both the land and water constraints are binding because $\pi'(\cdot) > 0$ and $D > 0$. Expected profit is determined by the sum of profit for the irrigated crop with each potential allocation of water $(0, \overline{W}/N, 2\,\overline{W}/N, \ldots, \overline{W})$ times the probability of receiving each potential allocation of water $(1 - q_1, q_1 - q_2, q_2 - q_3, \ldots, q_N)$ plus the profit earned on the dryland crop.

Taking the first derivative of expression (2) with respect to L_r yields the necessary condition for the optimal land allocation:

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[11] The probabilities of receiving each additional unit of water are bounded by 0 and 1 given that $q_i \geq q_{i+1}$, and $\sum_0^N (q_i - q_{i+1}) = 1$ given that $q_0 = 1$ and $q_{N+1} = 0$.

$$\frac{\partial E(\pi)}{\partial L_r} = \sum_{i=0}^{N} (q_i - q_{i+1}) \left[\pi\left(\frac{i\overline{W}}{NL_r}\right) - \frac{i\overline{W}}{NL_r}\pi'\left(\frac{i\overline{W}}{NL_r}\right) \right] - D = 0 \qquad (3)$$

To simplify the notation, let $A = \overline{W}/NL_r$ and let $F = \partial E(\pi)/\partial L_r$. Taking the second derivative of expression (2) with respect to L_r yields:

$$\frac{\partial F}{\partial L_r} = \sum_{i=0}^{N} (q_i - q_{i+1}) \frac{i^2 A^2}{L_r} \pi''(iA) < 0 \qquad (4)$$

The inequality in expression (4) follows from the concavity of the production function and because $q_i - q_{i+1} \geq 0$ for every i ∈ $\{1, \dots, N\}$. Thus, the maximization problem in expression (2) has a unique interior solution.[12]

Effect of Permitted Diversions

First, we are interested in how a farmer changes the optimal allocation of land in response to a change in the total quantity of water permitted for diversion by the portfolio, $\overline{W}$. An increase in $\overline{W}$ reflects an increase in the total amount of water available for irrigation, holding constant the seniority of the portfolio. Using the implicit function theorem, the change in the optimal quantity of land allocated to crop *r* in response to a change in total permitted water diversions for the water right portfolio is:

$$\frac{\partial L_r}{\partial \overline{W}} = \sum_{i=0}^{N} (q_i - q_{i+1}) \left[\frac{i^2 A}{NL_r} \pi''(iA) \right] \frac{1}{\partial F / \partial L_r} > 0 \qquad (5)$$

The inequality in (5) follows from the concavity of the production function and the inequality in (4). The result in (5) indicates that the amount of land allocated to the irrigated crop is increasing

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[12] There needs to exist one pair such that $q_i > q_{i+1}$ for the expression in (4) to be strictly negative. The assumptions that $q_0 = 1$ and $q_{N+1} = 0$ ensure that such a pair exists.

in the total amount of water permitted for diversion in a water rights portfolio. This makes intuitive sense: if a farmer is able to divert more water, more water is available to support irrigated production, and the farmer chooses to allocate more land to the higher-value irrigated crop. Expression (5) yields the testable hypothesis (*hypothesis 1*): the optimal quantity of land allocated to the irrigated crop, L_r, increases with the total quantity of water permitted for diversion under a water rights portfolio, $\overline{W}$.

Effect of Seniority

Second, we are interested in evaluating how a change in the mean probability of fulfillment within a water rights portfolio, μ, affects the optimal allocation of land. Another way to interpret μ, the mean probability of water rights fulfillment is as a measure of the mean seniority of rights within a portfolio. There is a direct relationship between seniority and probability of fulfillment, *ceteris paribus*.

The change in the optimal allocation of land with a marginal increase in the mean seniority of the water rights within a portfolio can also be described using the implicit function theorem. A change in μ is caused by a change in q_j, the probability that water right j is fulfilled. Without a loss in generality, assume the order of right j *within* the farmer's portfolio is not affected by this change (the change in seniority does however affect the right's hierarchy across farmers, hence a change in the probability that the right will be fulfilled).[13] By definition, the probability of fulfillment for an individual right j is $q_j = N\mu - \sum_{i\neq j}^{N} q_i$. Using that definition, the derivative of first-order condition (3) with respect to μ is:

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[13] This requires that $q_{j-1} > q_j$ if $d\mu > 0$ and $q_j > q_{j+1}$ if $d\mu < 0$.

$$\frac{\partial F}{\partial \mu} = \frac{\partial F}{\partial q_j}\frac{\partial q_j}{\partial \mu} = N\big\{\pi(jA) - jA\pi'(jA) - \pi\big((j-1)A\big) + (j-1)A\pi'\big((j-1)A\big)\big\} \tag{6}$$

To simplify this derivative, we rearrange the last term in brackets in expression (6) and use a first-order Taylor series expansion around the point jA. Specifically, we rewrite $\pi(jA) - \pi\big((j-1)A\big) \cong A\pi'(jA)$ and $jA\pi'(jA) - (j-1)A\pi'\big((j-1)A\big) \cong A[\pi'(jA) + jA\pi''(jA)]$. Substituting these expressions into (6) and using the implicit function theorem yields:

$$\frac{\partial L_r}{\partial \mu} = \frac{NjA^2\pi''(jA)}{\partial F/\partial L_r} > 0 \tag{7}$$

where the inequality in (7) follows from the concavity of the restricted profit function. Thus, the optimal quantity of land allocated to the irrigated crop is increasing in the mean probability of fulfillment, or seniority, of the water rights portfolio. This result also makes intuitive sense: a portfolio that is more senior on average has a greater probability of being fulfilled and, as the expected water supply increases, the farmer will optimally allocate more land to the irrigated crop. Expression (7) yields the following testable hypothesis (*hypothesis 2*): the optimal quantity of land allocated to the irrigated crop, L_r, increases with the mean seniority of the water rights portfolio, μ.

Empirical Model

We develop an empirical model to test how farmer land-allocation decisions on irrigated agricultural parcels are influenced by water rights seniority and portfolio ownership. We follow the economic literature that uses a reduced-form econometric approach to explain land-allocation decisions using a multinomial logit framework (Carpentier and Letort 2014; Wu and Segerson

1995; Miller and Plantinga 1999; Livingston, Roberts, and Rust 2008).[14] This approach is advantageous because its flexibility and empirical tractability allow us to account for defining features of our dependent variable (Carpentier and Letort 2014). The dependent variable in our analysis is the share of land allocated to each crop and/or fallow within a multi-crop farm. This proportional dependent variable has the usual features that each share is bounded by 0 and 1 and the shares within a unit of observation sum to one.[15] However, we must account for an important additional empirical challenge that arises in our analysis. Because we focus on land-allocation decisions at the level of the individual, rather than aggregating to the regional scale (e.g., Moore and Negri 1992), there are likely to be a large number of observations equal to zero for each land-allocation choice. This will occur simply because individual farmers tend to grow only a subset of all possible crops on a given parcel of land at a specific point in time.

A methodology well-suited to this problem is the fractional logit approach proposed by Papke and Wooldridge (1996). Kala, Kurukulasuriya, and Mendelsohn (2012) extend the approach of Papke and Wooldridge (1996) to the fractional multinomial logit (FMNL) case that

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[14] A reduced-form acreage share model can be derived from a farm-level profit-maximization problem in which land is treated as a fixed, allocable input (as in Moore and Negri 1992) under certain assumptions, namely that farmers are risk-neutral, the marginal short-run crop returns to land are constant in acreage, and the use of variable inputs does not depend on the quantity of quasi-fixed inputs available (Carpentier and Letort 2014). Taken together, these assumptions imply that the reduced-form approach is appropriate if in the short run farmers adapt their land allocation to water availability instead of altering production practices for a crop.

[15] A share of 0 means that a crop was not selected for production on a given land area and 1 means that a specific crop comprised 100% of production and that no part of that land parcel was allocated to other crops. Shares must sum to 1 to reflect that all land is used in the production of crops or some combination of crops and fallow. A value greater than 1 would mean that more than 100% of the land area is in production, which is impossible empirically.

accommodates a proportional dependent variable. The FMNL approach uses a multinomial logit link function that describes the relationship between a dependent variable and a linear index of independent variables. With the multinomial link function, the requirements for the quasi-likelihood estimation procedure proposed by Papke and Wooldridge (1996) are satisfied and the estimation technique fits the real-world restrictions on the values taken by our dependent variable.[16] Specifically, the original fractional logit and the FMNL extension generate predicted values in the $[0,1]$ interval, allow predicted proportions across all possible land-allocation choices to sum to 1, and accommodate the case in which the dependent variable takes the value 0 or 1 with positive probability.

Let the set of land-allocation choices (crops and fallow) be indexed by $k = 0, \dots, K$, let $m = 1, \dots, M$ index the farm, which defines the cross-section in the panel dataset, and let $t = 1, \dots, T$ index the year, which defines the time series. We are interested in estimating the nonlinear model $E(s_{kmt}|\mathbf{x}_{mt}) = G(\alpha_k + \mathbf{w}_{\boldsymbol{m}}\beta_k + \mathbf{z}_{mt}\delta_k)$, where $G(\cdot)$ is the multinomial logit function, and $\mathbf{x}_{mt}$ includes $\mathbf{w}_{\boldsymbol{m}}$, a vector of time-invariant water rights attributes, and $\mathbf{z}_{\boldsymbol{mt}}$, a vector of control variables relevant to seasonal land-allocation decisions, including site-specific characteristics, weather, climate, and expected crop prices. The predicted proportion of crop k for farm m in year t is given by:

$$\hat{s}_{kmt} = \frac{exp\left(\mathbf{x}_{mt}\hat{\beta}_k\right)}{exp\left(\sum_{k=0}^{K} \mathbf{x}_{mt}\hat{\beta}_k\right)} \tag{8}$$

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[16] The consistency of the quasi-maximum likelihood estimator (QMLE) obtained using the Bernoulli log-likelihood function is guaranteed by the assumption $E(y_i|\mathbf{x}_i) = G(\mathbf{x}_i\beta)$, where the link function $G(\cdot)$ is a known function where $0 < G(z) < 1$ for all $z \in \mathbb{R}$. Under this assumption, the consistency of the QMLE is assured regardless of the distribution of y_i conditional on $\mathbf{x}_i$ (Papke and Wooldridge 1996).

The land-allocation choice $k = 0$ is the baseline or excluded choice, i.e., $\beta_0 = 0$.

Following Kala, Kurukulasuriya, and Mendelsohn (2012), the multinomial log–likelihood function for water right m and year t is:

$$\ln L_{mt}(\mathbf{x}, s, \beta) = \sum_{k=0}^{K} s_{kmt} ln\, \hat{s}_{kmt} \tag{9}$$

where $\hat{s}_{kmt}$ is defined by equation (8). The quasi-maximum likelihood estimator (QMLE), $\hat{\beta}_k$, maximizes the sum of the log-likelihood function in equation (9). The QMLE is consistent and asymptotically normal if the link function is appropriately specified. The standard errors reported are robust to heteroscedasticity.

Study Region

We apply our empirical model to the Eastern Snake River Plain (ESRP) of Idaho. Agriculture accounts for the largest consumptive use of water within the region (Idaho Water Resources Board 2009). Approximately 850,000 ha (2.1 million acres) of the ESRP are irrigated. Of the total amount of water diverted for irrigation in the region, approximately 75% is drawn from surface water sources; the remainder is extracted as groundwater. The ESRP spans two cropping regions within Idaho (south central and east). Over an 11-year period spanning 2005-2015, the most common crops grown in terms of numbers of hectares planted were (in descending order): alfalfa, barley, spring wheat, winter wheat, potatoes, sugarbeets, and corn (USDA NASS 2016a). A small amount of land, on average 20,000 ha over the same period, was planted to oats, dry beans, and durum wheat. All land in corn, oats, potatoes, and sugarbeets is irrigated. If we consider irrigated crop production alone, the greatest number of hectares (averaged over 2005-2015) is planted to potatoes, followed by spring wheat, alfalfa, winter wheat, barley, sugarbeets, and corn. Using historical prices (USDA NASS 2016a) and average regional yields and variable costs of production from state extension publications, the most profitable crops are (in descending order): potatoes ($2,678/ha), sugarbeets ($1,976/ha), alfalfa ($1,401/ha), barley ($846/ha), winter wheat ($822/ha), spring wheat ($653/ha), and corn ($533/ha).

Water Rights

Rights to divert water for use in irrigation are administered by the Idaho Department of Water Resources (IDWR) in accordance with the doctrine of prior appropriation.[17] Surface water rights in the ESRP were established from 1869-2003, with the majority of rights claimed from 1890-1940 (Cobourn 2015).[18] In response to legal challenges from some water right holders, rights within the ESRP have already been adjudicated. The process of adjudication reduces uncertainty for irrigators by undertaking a thorough accounting of water and confirming the validity of farmers' water right(s), the amount of water they may divert, and which water rights take priority during a shortage (State of Idaho 2016). In most years, the amount of water permitted for diversion under irrigation water rights exceeds the total amount of natural surface water flows and stored water accumulated in upstream reservoirs. Enforcement of appropriation-based water rights is typical in the study region with junior rights often curtailed to ensure adequate flows to fulfill senior rights. For example, in 2015, rights dated later than 1891 (60% of the total number of rights) were curtailed from July through August in the southcentral portion of the ESRP.[19]

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[17] This principle is set forth in the Idaho Constitution (Art. XV, section 3).

[18] Groundwater rights are also administered according to the doctrine of prior appropriation. They were established in large part from 1950-1970, following technical advances in pumping technology in the 1940s. Fereday, Meyer, and Creamer (2015) supply detailed discussions of the historical development of water infrastructure and management across the region.

[19] Based on water rights accounting data for surface water gauge 13077000 (Snake River at Neeley ID; Idaho Department of Water Resources 2015).

An advantage of the ESRP as a study region is the availability of detailed records on individual, adjudicated water rights, including the spatial boundaries that define the place of use for each right. The place of use is the land area over which water can be characterized as a fixed, allocable input. There is not a one-to-one correspondence between the boundary of the water right place of use and the boundary of a farm (e.g., a farmer may own multiple water rights to irrigate different fields). Unfortunately, geospatial data on property boundaries for individual farms are not available for the study region. The lack of data on property boundaries would be most problematic if a farmer could move water from one place of use to another, but this is not permissible under Idaho water law. We proceed with our analysis using the place of use to define the cross-section (indexed by *m* in equation 8).

In this analysis, we focus solely on privately owned surface water rights. The total land area represented by place of use attributable to these rights within our study region is 412,259 ha (approximately 1.02 million acres), half of the irrigated area within the ESRP. The rationale for focusing on surface water rights is that seniority has long been used to administer these rights and the effect of seniority on expected water availability is well understood by surface water irrigators. The state's water accounting system to determine surface water right curtailments is automated and undertaken on a daily basis. Though Idaho also administers groundwater rights using prior appropriation, seniority based curtailments have not been widely used to restrict pumping in response to scarcity. There is thus little reason to suspect that seniority would affect land-allocation decisions by surface and groundwater irrigators similarly. Furthermore, in the ESRP, access to groundwater generally is not available as a means of mitigating the risk that arises from seniority based curtailments of surface water. Irrigators dependent on surface water and groundwater are largely discrete groups: of the total number of surface water rights in the region, less than 7% could be combined with groundwater resources to irrigate the same place of use, and no water rights are issued by the state that expressly allow for diversion from surface and/or groundwater sources. We therefore exclude from consideration the small subset of parcels that may be irrigated under both surface and groundwater rights and focus the empirical analysis on the role of seniority on land-allocation decisions among surface water irrigators.

We focus our analysis specifically on those surface water rights that are privately owned, in contrast to those that are owned by a group, such as an irrigation district or canal company. The structure of water rights administration fundamentally differs between private and group rights, which implies that farmers within irrigation districts are likely to respond differently to a water shortage than farmers owning exclusively private water rights. Specifically, private rights are administered using prior appropriation, whereas group rights are administered using a correlative approach. In the latter, the group collectively owns a set of water rights that permits diversions for the district as a whole, rather than to individual farmers. Within the district, each farmer owns share(s) in the total amount of water available to the district. A district's collective water right(s) may be curtailed based on seniority, but the reduction in water deliveries is absorbed by all farmers in the district in proportion to their ownership of shares.[20] This arrangement more evenly distributes among farmers the risk of a reduction in water availability, protecting district members to some extent against seniority based curtailments.

Water Rights Portfolios

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[20] Other important differences exist between districts and individuals: trading of water within an irrigation district is subject to much lower transactions costs; districts often cover an expansive land base that in some cases occupies multiple watersheds; and portfolio ownership is more diverse and complex for irrigation districts than for individuals.

Among privately owned surface water rights in the ESRP, different types of surface water rights portfolios are possible. It is prohibitively challenging to fully describe the portfolio of all water rights owned in common by a farmer in the ESRP.[21] However, there are two primary types of water rights ownership profiles that exist in our study region that we include in the empirical analysis. The first type of portfolio is a water right stack, which consists of a set of surface water rights layered one on top of another with an identical place of use (henceforth referred to as a "stacked portfolio;" Ghosh, Cobourn, and Elbakidze 2014). Each water right within a stack retains its individual characteristics, such as priority date, and can be used in combination with other right(s) in the stack to irrigate the common place of use. A portfolio of stacked surface water rights thus offers benefits from diversification in seniority. If a junior water right in the stack is curtailed, owner of a stack of rights can continue to irrigate the same land with the more senior rights in the stack.

A second type of portfolio arises when irrigators who own private surface water rights, within and outside of stacks, also have access to a group right through an irrigation district for example (henceforth referred to as a "group portfolio"). In the empirical analysis, we control for this possibility, which allows us to test whether land share differs systematically with access to a correlative system. This type of portfolio mitigates risk because a farmer may compensate for a shortfall in their private water right by diverting water from their share in irrigation district water deliveries in a dry year or *vice versa*. Beyond diversification across seniority, this type of portfolio may mitigate risk in water availability through other mechanisms. For example, a

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[21] For example, two rights for the same place of use may be registered under separate names. Determining the totality of an individual farmer's ownership of water rights most often involves a review by personnel in the field or the local knowledge of IDWR staff.

correlative system of rights administration smooths heterogeneity in risk across irrigators within a district, relative to the strict application of prior appropriation outside of irrigation districts. In addition, districts facilitate water trade within their boundaries through informal mechanisms such as bulletin board advertisements in the district office, creating a market mechanism that is likely to offset economic inefficiencies that arise under prior appropriation (Burness and Quirk 1979). A full examination of the source of benefits arising from group membership is outside of the scope of this paper. But by controlling for access to irrigation districts in the empirical analysis, we are able to capture the combined effect of the benefits to group access and draw parallels between our results and the economic literature that uses the irrigation district as the unit of analysis.

Data

This section describes the dataset constructed to estimate the empirical model. We focus our discussion on the data used to describe water rights, water rights portfolios, and land-allocation shares at the scale of the place of use for each individual water right. We present a brief description of additional control variables, such as soil quality and weather, which are commonly used in the related economic literature (e.g., Cobourn 2015; Jaeger 2004; Moore and Negri 1992; Mukherjee and Schwabe 2015). Table 1 presents summary statistics for all variables; Table 2 provides additional information summarized by quintile based on water right priority date (seniority).

Water Rights and Water Rights Portfolios

Water right attributes are obtained from Geographical Information Systems (GIS) data layers created by the Idaho Department of Water Resources (IDWR 2014). Across the ESRP, there are 2,605 surface water irrigation rights. The priority date associated with each water right is used to test whether land allocation decisions differ systematically with the seniority of a farmer's water right. The mean priority date associated with a single water right (*pryr*) is 1915 and the average place of use (*area*) covers 45.57 ha (Table 1).[22]

Stacked water rights are identified based on coincidence in the place of use from the geospatial water rights dataset from IDWR. Table 1 shows that approximately 45% of all private surface water rights are members of a stack (*stack*), representing 1,180 unique rights. The average water right stack covers a place of use (*area*) with an area of 74.87 ha, which is larger than the average across all observations (45.57 ha). The number of rights (*nrights*) within a stack is 4.22 on average. Stacked water rights tend to be more senior on average, with a mean priority year (*avgpr*) of 1905, as compared to 1915 for the full sample. The available water rights data do not include information about diversion limits which would allow for a direct test of hypothesis 1 from the theoretical model. To enable this test, we use *nrights* as a proxy for water quantity because the number of water rights within a stacked portfolio is positively correlated with the amount of water permitted for diversion. To test hypothesis 2, we use *avgpr* as a measure of μ.[23]

Water rights portfolios that provide access to both appropriative and correlative water rights are identifiable in the geospatial dataset when the place of use for a private right lies within the place of use for a correlative water right. Places of use for the latter are manually identified in the dataset based on water rights ownership information. We cannot conclusively

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[22] An increase in *pryr* corresponds to a decrease in μ, the mean probability of fulfillment from the theoretical model.

[23] We also estimate empirical models using the minimum priority date in a stack (most senior right), maximum priority date in the stack (most junior right), and median priority date. The minimum and median priority dates perform poorly in terms of predicting land shares. The maximum priority date is a significant predictor of land share, producing results similar to those for the average priority date.

determine based on the available data whether a specific individual with overlapping private and correlative rights is a member of an irrigation district, or whether they opted out of the irrigation district. However, communication with IDWR staff suggests that the former case is most likely and characterizing an overlap in place of use as indicative of joint access to the two types of water rights is appropriate (personal communication David Hoekema and Linda Davis, June 15, 2016). From Table 1, 22% of all surface water rights overlap with a group water right (*group*).

Table 2 presents additional summary statistics for surface water rights by quintile based on priority year. The first quintile includes the most senior rights (priority years 1869-1885); the fifth includes the least senior rights (priority years 1952-2003). The most senior water rights are most likely to be included in a stack: 60% of rights within quintile 1 are stacked, decreasing by quintile to 26% in the fifth. The most senior rights are also likely to have a greater number of rights within the stack, with a mean of 5.83 for quintile 2 versus 2.48 for quintile 5. Quintiles 1 and 2 also contain the greatest incidence of group access, 24% and 31% respectively, with smaller shares in quintiles 3, 4 and 5, (21%, 15% and 19% respectively).

Land Shares

The dependent variable in the empirical analysis (s_{kmt}) is the observed proportion of land devoted to each of a set of land-allocation activities. For this analysis, we consider the share of land allocated to fallow and each of the ESRP's seven most important crops, alfalfa, barley, corn, potatoes, spring wheat, sugarbeets, and winter wheat. The share of land allocated to each of these eight activities is summarized by place of use for each water right/farm (m) and year (t). Land allocation observations are obtained from the USDA's Cropland Data Layers (USDA NASS

2016b) for the years 2005-2015, excluding 2006.[24] Summary statistics (Table 1) show that on average, the majority of land defining the place of use across all water rights is planted to alfalfa (48.44%), followed by barley (13.40%), corn (9.87%), winter wheat (7.25%), spring wheat (4.55%), potatoes (4.49%), and sugarbeets (1.14%). On average, 10.85% of land in each place of use is fallowed. A probability mass exists at zero for all crops and fallow, with the mass at zero representing 65.6% of all observations.[25]

Across priority date quintiles (Table 2), the share of land in alfalfa is uniformly high, ranging between 47.69 and 50.01%. The most senior rights in quintiles 1 and 2 tend to have a greater share of land in barley and potatoes and less land area in corn and fallow compared to

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[24] The Cropland Data Layers are created using Landsat satellite imagery and a classification algorithm trained and validated using data from the Farm Service Agency Common Land Unit Program. Across the seven major crops in the study region, the accuracy of the classification algorithm varies by year and is on the order of 82–95% (measured using out–of–sample pixels correctly identified). For fallow land, the accuracy is on the order of 65–85%. Identifying fallowed land in this region is challenging because it is often difficult to distinguish from native vegetation.

No data is available for 2006, such that 10 years of data are available for the interval 2005-2015. For the years 2005, 2008, and 2010–2015 these data describe land allocation at a spatial resolution of 30m. In 2007 and 2009, the data are available at a slightly coarser resolution of 56m.This change in resolution followed a Scan Line problem in the Landsat 7 ETM sensor, which created missing data strips in the images. A substitute satellite, Resourcesat–1 was used to fill in the missing years of data after the satellite became usable in 2007 (Craig 2010). Data for 2006 is not available for Idaho.

[25] There is a negligible probability mass at the upper limit of one. The incidence of observations equal to one is on the order of 0.008-0.47 percent in our empirical dataset, which suggests that although farmers tend to specialize in a subset of the region's crops, it is rare that they allocate the entirety of their place of use to a single crop.

less senior rights. Quintiles 4 and 5 contain the greatest area planted to winter wheat (7.52 and 9.03% respectively) and the greatest amount of land fallowed (13.91 and 12.71%, respectively).

Land, Weather, Climate and Price Variables

Variables relevant to the land-allocation decisions undertaken by farmers at the beginning of the growing season include site-specific characteristics (soil quality, elevation, and slope), weather, climate norms, and expected crop prices.

Land quality at the place of use for each right is obtained from the NRCS SSURGO database (USDA NRCS 2016). The average elevation in the dataset is 1,281 m above sea level, with the most senior water rights located an average of 125 m higher than the least senior rights. In terms of slope, the most senior rights have an advantage over the least senior, with the former averaging 3.20% and the latter 5.52%. Soil productivity is captured using the dominant irrigated capability class rating within the place of use (*irrccd)*. A lower capability class rating indicates that soils have fewer limitations for crop growth. Irrigated capability class in the ESRP ranges from a low of 2 to a high of 7, with an average of 3.13.[26] Soils are more favorable at locations irrigated by senior water rights, on average.

Weather and climate data are obtained from land-based weather station measurements recorded in the Global Historical Climatology Network (GHCN) database (NOAA 2016). In total, we use 27 weather stations that spatially cover the ESRP, capturing significant cross-sectional and annual variation in weather and cross-sectional differences in long-term climate norms. Each water right place of use is paired with its closest weather station. To capture variability in weather conditions likely to influence land-allocation decisions at the time of planting, we create several variables summarizing temperature and precipitation. For

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[26] A lower number indicates soils that have fewer limitations for crop growth.

temperature, we summarize observed values in April, when planting decisions are made in the region for most crops. Specifically, we include the average maximum (*tmax*) and average minimum (*tmin*) temperatures at each location. Across all locations, the average April maximum temperature is 14.79^{o}C and the average minimum is 0.03^{o}C. Temperatures are similar across water right quintiles.

Winter precipitation is particularly important given the region's dry summer climate and reliance on winter precipitation as a supply of irrigation water. Because of the region's reliance on snowpack for surface water flows, the ideal metric for expected water availability is the depth of mountain snowpack. However, it is challenging hydrologically to link the snowpack in a distant mountain location with the amount of water available at any particular water right in the ESRP. Total winter precipitation falling at different locations across the ESRP is likely to be correlated with water stored in snowpack up-watershed from those locations and is used here as a proxy for natural water availability. At each weather station and for each year, we calculate total precipitation in the preceding winter (*wprcp*) as the sum total from October through March. The mean value across observations is 151.64 mm (5.97 inches), which is relatively similar across quintiles in Table 2, though with a slightly higher average among the least senior rights.

Climate norms for precipitation and temperature are represented by creating 30-year summary statistics spanning 1975-2004. Climate variables are created using data from the closest weather station to each water right that has a sufficiently long time series. For precipitation, we summarize winter and summer totals (*wprcpnorm*, *sprcpnorm*) and standard deviations (*wprcpsd*, *sprcpsd*). On average, water rights receive 155.96 mm of precipitation in the winter months and 116.84 mm in the summer (April through September). On an annual basis, winter precipitation varies significantly outside of the range of 30–year norms for the region. Given that winter precipitation is the primary source of surface water flows, this suggests significant inter-annual variability in the availability of surface water for irrigation., ranging from 2.54 to 492.76 mm with an average of 109.98 mm. A long-run measure of growing season temperatures is summarized as growing degree-days (*gddnorm*), which provide a nonlinear summary of the amount of time that temperatures fall between lower and upper bounds for crop growth. Though growing degree-days are not observed at the time of planting, long-run trends in biological growth time are expected to influence farmer crop choices. The mean value of growing degree-days across all locations is 4,860.67. Some crops (for example potatoes) are sensitive to weather variability and as such we also incorporate variability in growing degree-days (*gddsd*).

Prices for each crop by growing season are obtained from USDA NASS annual surveys (USDA NASS 2016a). A single price for each crop is available each year; there is no cross–sectional variation in the dataset within a year. Expected prices are captured by lagging prices by one year. All crop prices are normalized by the price received for alfalfa. Because prices for spring and winter wheat are highly collinear, we exclude the price of winter wheat from the analysis.

Results

We estimate the model in equation (8) to examine how land share varies with water right priority date and portfolio ownership. Initially, we estimate (8) with all surface water rights in the dataset ($N = 16,626$). The variables included in the vector of water right attributes ($\mathbf{w}$) are priority date (*pryr*), size of the place of use (*area*), a dummy variable indicating whether the right is part of a stack (*stack*), and a dummy variable indicating whether the right overlaps with a group water right (*group*).

Table 3 presents FMNL coefficient estimates for the seven crops in the analysis, where fallow is the excluded category. The estimated coefficient on priority date is statistically significant and negative for alfalfa, barley, corn, potatoes, and spring wheat; it is not statistically significant for sugarbeets or winter wheat. The estimated coefficient for the size of the place of use is positive and highly statistically significant for all crops save alfalfa. The presence of a water right stack or access to a group water right is also a significant predictor of the share of land allocated to the majority of crops. The coefficient for *stack* is positive and significant for the same crops as for priority date (alfalfa, barley, corn, potatoes, and spring wheat). The coefficient for *group* is positive and highly significant for all crops, indicating that less land is fallowed, on average, for parcels that have access to private surface water right and an irrigation district.

The site-specific variables for slope and irrigated capability class rating are significant predictors of land share for all crops. With the exception of potatoes, an increase in slope is associated with a decrease in the share of land allocated to crops relative to fallow. The coefficients for irrigated capability class rating are statistically significant and negative for all crops. This result, which is consistent with findings from prior studies in the economic literature, suggests that an increase in the index (a decrease in suitability for irrigated agriculture) is associated with an increase in the share of land allocated to fallow (Moore and Negri 1992; Mukherjee and Schwabe 2015). Of the weather variables included in the model, winter precipitation is positive and significant for six of the seven crops, as is the maximum temperature in April. A wet winter followed by a warm spring is associated with increased planting of crops relative to fallow.

The climate variables vary in sign and significance across crops, though the coefficients for the norm of growing degree-days are positive and significant in the majority of crops, with the exception of barley. These results make sense from an agronomic perspective: an increase in growing degree-days indicates a longer growing season that favors crop production. The lack of significance for barley corresponds to that found by Moore and Negri (1992) for the Pacific Northwest region. While growing degree-days are beneficial, an increase in the variability of growing degree-days creates a source of yield risk. In five of seven equations (alfalfa, barley, potatoes, spring wheat, and winter wheat), an increase in the standard deviation of growing degree-days is associated with a decrease in the share of land planted to crops relative to fallow.

The estimated own-price effects for corn and potato are negative and statistically significant. The own-price effect for sugarbeets is negative, but insignificant, and the own-price effects for barley, spring wheat, and winter wheat are positive and significant.[27] The poor performance of the price variables in the model is similar to the results of Moore and Negri (1992), and is most likely attributable to a lack of cross-sectional variation in prices across the study region. As long as crop prices are uncorrelated with water rights characteristics, this feature of the data does not compromise the properties of the estimated coefficients on the water rights variables, which are of primary interest in this analysis. Given that water rights attributes cannot, for institutional reasons, change from year to year in response to changes in crop prices or weather, we expect this requirement to hold.

Table 4 presents marginal effects for priority date based on the FMNL coefficient estimates in Table 3. Marginal effects are evaluated at the mean of each independent variable, with the exception of the dummy variables *stack* and *group*. We estimate marginal effects for the four possible combinations of stacked and group access portfolios. No portfolio captures the case

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[27] Sugarbeets are often grown under contract with processors, which may explain the insignificance of the own-price effect.

in which the land can only be irrigated under a single private surface water right (*stack* = 0, *group* = 0); for the group portfolio, land may be irrigated under a single private surface water right and water from a group right (*stack* = 0, *group* = 1); for the stacked portfolio, land may be irrigated under a stack of private surface water rights (*stack* = 1, *group* = 0); for the stacked, group portfolio, the land may be irrigated under a stack of private surface water rights and water from a group right (*stack* = 1, *group* = 1).

Across portfolio types, the marginal effect for priority date is positive and significant for fallow and sugarbeets, and negative and significant for barley, corn, and potatoes. The marginal effects for priority date are not significant in all cases for alfalfa and spring wheat. An increase in priority date (equivalent to a decrease in the probability that a right will be fulfilled) is associated with a land allocation that is more heavily weighted toward fallow and sugarbeets, and less heavily weighted toward barley, corn, and potatoes.[28] However, the magnitudes of the marginal effects differ across portfolio types. For fallow in particular, the marginal effect of priority date is substantially smaller for those water rights with group access than for those with no portfolio or those that are part of a stack. For spring wheat, the absolute value of the coefficient is smaller for those rights with group access. The marginal effects for sugarbeets and winter wheat also differ systematically between rights with or without group access.

Table 5 presents the expected land share for fallow and each crop by portfolio type, where the portfolios are as defined above. Expected shares are calculated by predicting the share of land in each crop for each water right-year and taking the mean across observations for each portfolio type. The expected share of land in each crop tracks closely with observed land shares

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[28] Sugarbeets are water-intensive, but are also among the more resilient crops in the region to a missed irrigation application (personal communication, Terrell Sorenson, June 16, 2016).

across portfolio types (presented in the Supplementary Appendix). For example, the observed mean share of land in barley by portfolio type is 7.72% for no portfolio, 17.16% for group access, 14.58% for stacked rights, and 27.39% for stacked rights with group access. The expected land shares in Table 5 are 6.46%, 17.10%, 14.00%, and 28.98% for each portfolio, respectively.

Rights with group access, regardless of whether they are part of a stack or not, fallow a smaller percentage of their land on average than those without group access. The expected share of land in fallow with no portfolio is 14.73% versus 4.28% for rights with group access. A portfolio of stacked water rights is associated with a slightly smaller share of land in fallow than in the no portfolio case (9.91%). A combination of stacked rights and group access is associated with the smallest average share of land in fallow (2.49%). Other land shares differ systematically across portfolio types as well. Barley features more prominently on land with group access and potatoes occupy a greater share of land under stacked water rights.

To summarize the differences in land allocation across the portfolio types, we also report in Table 5 an estimate of expected profit per hectare. Differences in expected profit across portfolios are driven solely by differences in the expected land allocation. To calculate expected profit, we use average crop prices and yields for the study period (2005-2015; USDA NASS 2016a) and data on operating costs from regional cost of production budgets published by state extension. Expected profit is greater for all portfolios than for the no portfolio case, but highest for portfolios that include access to group rights. Over the no portfolio case, the land allocation with stacked rights yields a 5.53% increase in annual profit, group rights yield a 15.60% increase in annual profit, and a combination of stacked rights and group access yields a 14.52% increase in annual profit.

In Table 5, we also evaluate how the expected land allocation and profit change with priority date. A change in priority date from 1869 to 2003 represents the maximum decrease in seniority possible in the dataset (equivalent to the greatest possible decrease in μ in the theoretical model). The resulting change in expected land shares in Table 5 represents an upper bound on the change in land allocation associated with a decrease in seniority. A decrease in seniority is associated with an increased share of land in fallow and alfalfa and a decrease in barley, corn, and potatoes, though the magnitudes of these effects differ across portfolio types. Examining the change in expected profit, the greatest change in expected profit from a loss in seniority occurs for the no portfolio and stacked portfolio cases. However, the loss from a decrease in seniority in these cases is small, no more than 2.66%. For portfolios with group access, the seniority effect is close to zero, which suggests that access to a group water right nearly completely offsets the estimated seniority effect.

We also estimate equation (8) separately for the subset of observations that are unstacked (*stack* = 0; N = 10,604) and stacked (*stack* = 1; N = 8,079). Both specifications are similar to that estimated for the full model, but they differ with respect to the vector of water rights attributes (**w**).[29] For unstacked water rights, the variables included in **w** are priority date (*pryr*), size of the place of use (*area*), and a dummy variable indicating whether the right overlaps with a group water right (*group*). For stacked water rights, the variables included in **w** are average priority date within the stack (*avgpr*), the number of water rights in the stack (*nrights*), size of the place of use (*area*), and a dummy variable indicating whether the right overlaps with a group water right (*group*). The use of *avgpr* and *nrights* in the specification for stacked observations allows

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[29] These specifications also exclude the lagged price variables, which created problems with collinearity in each subsample due to the lack of cross-sectional variation.

us to examine in greater detail the relationship between stacked portfolio characteristics and land shares. The FMNL coefficients, estimated separately for unstacked and stacked observations, are reported in the Supplementary Appendix.

Table 6 summarizes the marginal effects for priority date in each subsample. The marginal effect estimates for each subsample differ from those in the full sample, and from one another. Marginal effects from the full sample suggest that junior rights are more heavily planted to fallow and sugarbeets, and less heavily planted to barley, corn, and potatoes. Coefficient estimates for unstacked rights also indicate that junior rights are more heavily planted to fallow and sugarbeets, but the magnitude of the marginal effects is larger than in the full sample. Among unstacked rights, junior rights are less heavily planted to alfalfa and spring wheat. Coefficient estimates for stacked rights indicate that junior rights are more heavily planted to fallow and alfalfa, and less heavily planted to corn, potatoes, and winter wheat.

Table 7 summarizes expected land shares and profit across portfolios in each subsample. The expected land shares and profit for each portfolio are similar to those for the full sample (Table 5). Access to a stack increases expected profit over the no portfolio case by 4.57%. The increase in expected profit with group access is 14.08%, and that with a stack and group access is 15.68%. Though expected land shares and profit are similar to those in Table 5, the estimated upper bounds on the seniority effect exceed those in the full sample because of differences in the FMNL coefficient estimates for unstacked and stacked observations. For the no portfolio and stacked portfolio cases, the maximum potential loss in expected profit from a loss in seniority is capped at 5.05% and 5.51%, as opposed to 2.66% and 2.48% in the full sample. However, the general pattern across portfolios is much the same as that evident in the results in Table 5 in the sense that access to a group right, whether in combination with a stack or not, drives the effect of seniority toward zero.

Tables 6 and 7 also present results related to the number of rights within a stack for the sample of stacked observations. The marginal effects in Table 6 for stacked rights without group access suggest that stacks with a greater number of rights are more heavily allocated toward barley, potatoes, and sugarbeets, and less heavily allocated toward alfalfa, corn, and spring wheat. For stacked rights with group access, the magnitudes and signs of the marginal effects are similar to those for stacked rights with no group access. However, the marginal effect for fallow is smaller in magnitude with access to a group right than without. The same pattern bears out in Table 7, which presents the change in expected land share and profit with a one standard deviation increase in the number of rights in a stack, which is equivalent to 4.6 rights. An increase in the number of rights in the stack is associated with an increase in the share of land planted to barley and potatoes, and a decrease in land in fallow and alfalfa. On average, an increase in *nrights* of one standard deviation is associated with a 2.7% increase in profit for rights within a stack. As is the case for priority date, access to a group water right offsets this change in expected profit.

Conclusions

As priority year increases (or the probability of fulfillment declines), our results suggest an increase in fallow and a shift towards a less profitable crop mix. This result is consistent with the premise that owners of junior water rights may hedge against the risk of curtailment by planting a larger share of land to more drought-resilient and less remunerative land-allocation activities. In particular, fallowing emerges as a key difference in the land allocation between parcels irrigated by rights of differing seniority. Taking land out of production through fallow is one way to reduce irrigated production at the extensive margin in response to an anticipated curtailment. In contrast, senior water rights, which are relatively protected from the vicissitudes of annual water availability, are more heavily allocated toward more profitable, but drought-sensitive crops, such as potatoes and corn. Taken as a whole, systematic differences in land allocation across rights with differing priority dates generate a decrease in annual profit per unit land area of up to 5.51%.

We find that this seniority effect can be mitigated by ownership of a water rights portfolio, but that diversification across seniority alone is less salient than diversification across water right type. Specifically, access to a portfolio of stacked rights does little to offset the seniority effect, but access to a group right through an irrigation district drives the seniority effect toward zero. Within a stack, however, an increase in the number of water rights is a beneficial form of diversification, associated with a shift in land allocation away from fallow and toward crop production.

There are a number of benefits that may be associated with membership in an irrigation district. First, these groups tend to own a diverse set of water rights that span priority dates and water sources. Mukherjee and Schwabe (2014) demonstrate that this diversification across source provides a way to mitigate risk in water availability. Second, the way in which water is allocated within irrigation districts differs from the way in which prior appropriation is applied to private water rights. Members of a group own shares in total water deliveries to an irrigation district, so that a curtailment of any one right owned by the group is absorbed proportionally by all group members. As a result, no one irrigator is likely to suffer a complete loss of water during the growing season. This structure smooths the risk differential across irrigators within the district, potentially eliminating the inefficiency introduced by prior appropriation (Burness and Quirk

1979). An additional benefit of irrigation district membership is that many have established informal water trading systems, which also mitigate the inefficiencies that arise due to prior appropriation. It is outside of the scope of this analysis to disentangle which of these potential explanations (or others) is responsible for the decrease in seniority effect. However, the empirical results presented here confirm the benefits to district membership at the scale of the individual parcel, which is consistent with the results of prior studies that document the benefits to membership in an irrigation district (Brent 2016; Mukherjee and Schwabe 2014; Schlenker, Hanemann, and Fisher 2007).

The results of this analysis carry implications for the efficiency and distributional effects that may follow from climate-driven changes in the scarcity and variability of inflows a across the arid western U.S. (Melillo, Richmond, and Yohe 2014). Climate variability is predicted to increase water access uncertainty and conflicts over water between water users (Brent 2016; Cobourn 2015). As surface water scarcity increases, the risk differential, in terms of security of water provision, between farmers that hold senior versus junior surface water rights also grows, because junior water rights holders possess increasingly uncertain access to water (Burness and Quirk 1979, 1980). In relatively dry years with below-average precipitation, curtailments are deeper in the sense that even comparatively senior water rights are more likely to be curtailed. Our results suggest that welfare losses associated with deeper curtailments are likely to be borne most heavily by those producers with junior water rights who do not have access to an irrigation district. The acquisition of new water rights is often prohibitively costly, if not impossible due to administrative constraints and lags, and water markets outside of irrigation districts remain limited. Our results taken in combination with these institutional features suggest that the inefficiencies and distributional effects arising from risk heterogeneity under prior appropriation may persist, and perhaps worsen, under climate change.

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Table 1. Variable descriptions and summary statistics

Variable name[a]	Variable description	N	Mean	St. dev.
Land allocation variables (%)				
$alfalfa_{mt}$	Share of land in alfalfa	22,661	48.44	40.21
$barley_{mt}$	Share of land in barley	22,661	13.40	26.46
$corn_{mt}$	Share of land in corn	22,661	9.87	24.21
$fallow_{mt}$	Share of land fallowed	22,661	10.85	25.33
$potato_{mt}$	Share of land in potatoes	22,661	4.49	15.41
$swheat_{mt}$	Share of land in spring wheat	22,661	4.55	14.52
$sbeets_{mt}$	Share of land in sugarbeets	22,661	1.14	8.03
$wwheat_{mt}$	Share of land in winter wheat	22,661	7.25	19.08
Water right variables				
$pryr_{m}$	Year of surface water priority date[b,c]	26,040	1915	33.28
$area_{m}$	Area of place of use (ha)	26,050	45.57	95.05
$stack_{m}$	Dummy if part of surface water right stack	26,050	0.45	0.50
$nrights_{m}$	Number of rights within stack	11,800	4.22	4.40
$stackarea_{m}$	Area of place of use within stack (ha)	11,800	74.87	109.00
$avgpr_{m}$	Average priority year within stack[c]	11,800	1905	23.46
$group_{m}$	Dummy, overlap with group water right	26,050	0.22	0.41
Land, weather, and climate variables				
$elevrawm_{m}$	Area–weighted mean elevation (m)	23,980	1,281.54	250.88
$slopeawm_{m}$	Area–weighted mean slope (%)	23,980	4.40	5.95
$irrccd_{m}$	Dominant irrigated capability class	23,980	3.13	1.27
$wprcp_{mt}$	Total winter precipitation (mm)	26,018	151.64	77.62
$tmax_{mt}$	April average max. temperature (ºC)	24,987	14.79	2.47
$tmin_{mt}$	April average min. temperature (ºC)	24,987	0.03	2.11
$wprcpnorm_{m}$	Norm winter precip. (mm)	26,018	155.96	66.03
$wprcpsd_{m}$	Std. dev. winter precip. (mm)	26,018	58.67	17.61
$sprcpnorm_{m}$	Norm summer precip. (mm)	26,018	116.84	47.63
$sprcpsd_{m}$	Std. dev. summer precip. (mm)	26,018	48.51	16.72
$gddnorm_{m}$	Norm growing degree–days	26,018	4,860.67	265.23
$gdsd_{m}$	Std. dev. growing degree–days	26,018	438.96	256.54
Crop price variables				
$alfalfaprice_{t}$	Alfalfa price (USD/ton)	26,050	167.70	38.47
$barleyprice_{t}$	Barley price (USD/bu)	26,050	5.16	1.07
$cornprice_{t}$	Corn price (USD/bu)	26,050	4.93	1.25
$potatoprice_{t}$	Potato price (USD/cwt)	26,050	7.06	0.76
$swheatprice_{t}$	Spring wheat price (USD/bu)	26,050	6.33	1.23
$sbeetprice_{t}$	Sugarbeet price (USD/ton)	23,445	47.58	8.55
$wwheatprice_{t}$	Winter wheat price (USD/bu)	26,050	5.89	1.25

Notes: [a]$m = 1,\ldots,M$ indexes the cross section (the water right); $t = 1,\ldots,T$ indexes the time series (year, from 2005-2015, excluding 2006). [b]One water right is missing information for priority date, for a total of 2,604 cross sectional observations and a total of 26,040 over 10 years. [c]Mean priority year is rounded to the nearest year.

Table 2. Variable means by quintile based on seniority of water right

	Priority date of water right[a]				
Variable[b]	Quintile 1 (1869–1885)	Quintile 2 (1886–1892)	Quintile 3 (1893–1912)	Quintile 4 (1913–1951)	Quintile 5 (1952–2003)
Land allocation variables (%)					
$alfalfa_{mt}$	47.69	47.91	48.37	50.01	48.25
$barley_{mt}$	17.11	18.91	11.51	9.68	9.13
$corn_{mt}$	8.95	6.04	11.80	11.66	10.94
$fallow_{mt}$	9.82	6.10	11.75	13.91	12.71
$potato_{mt}$	4.89	6.31	3.98	3.17	4.15
$swheat_{mt}$	4.37	7.30	4.55	2.91	3.80
$sbeets_{mt}$	0.65	0.80	1.27	1.13	1.99
$wwheat_{mt}$	6.53	6.64	6.76	7.52	9.03
Water right variables					
$area_{m}$	45.14	50.68	58.55	34.54	39.90
$stack_{m}$	0.60	0.56	0.53	0.30	0.26
$nrights_{m}$	4.65	5.83	3.09	3.89	2.48
$stackarea_{m}$	62.37	65.92	87.72	79.97	94.67
$avgpr_{m}$	1890	1894	1903	1921	1951
$group_{m}$	0.24	0.31	0.21	0.15	0.19
Land, weather, and climate variables					
$elevrawm_{m}$	1,321.97	1,366.06	1,320.39	1,212.57	1,197.57
$slopeawm_{m}$	3.20	3.58	3.36	6.16	5.52
$irrccd_{m}$	2.76	2.89	3.04	3.60	3.33
$wprcp_{mt}$	148.08	141.73	144.27	159.26	164.59
$tmax_{mt}$	15.01	14.47	14.63	14.89	14.89
$tmin_{mt}$	–0.09	–0.48	–0.26	0.53	0.42
$wprcpnorm_{m}$	152.65	149.35	152.65	157.99	166.88
$wprcpsd_{m}$	56.90	58.42	57.91	59.44	59.94
$sprcpnorm_{m}$	112.78	125.98	120.90	111.51	114.05
$sprcpsd_{m}$	47.75	53.34	50.04	45.72	46.23
$gddnorm_{m}$	4,837.30	4,757.54	4,824.61	4,938.77	4,940.82
$gddsd_{m}$	410.63	391.24	396.36	521.40	473.82

Notes: [a]The priority date of a water right establishes its seniority in the regional hierarchy. The most senior water rights, in quintile 1, are those with the earliest priority dates (1869-1885); the least senior water rights, in quintile 5, are those with the latest priority dates (1952-2003). [b]$m = 1,\ldots,M$ indexes the cross section (the water right); $t = 1,\ldots,T$ indexes the time series (year, from 2005-2015, excluding 2006).

Table 3. Fractional multinomial logit (FMNL) coefficient estimates[a]

Log pseudo–likelihood = –21,977.80 Wald chi2(189) = 10,882.68
Number of obs = 16,626 Prob > chi2 = 0.0000

Variables	Alfalfa	Barley	Corn	Potatoes	Spring Wheat	Sugarbeets	Winter Wheat
pryr[b]	–0.199**	–0.325***	–0.503***	–0.490***	–0.246*	0.199	–0.189
area[b]	0.065	0.504***	0.641***	0.680***	0.644***	0.613***	0.677***
stack	0.165***	0.408***	0.149*	0.443***	0.458***	0.132	0.148
group	1.030***	1.394***	0.907***	1.027***	1.189***	1.418***	1.145***
elevrawm[b]	0.058**	0.105***	0.014	0.048	–0.011	–0.136***	0.032
slopeawm	–0.020***	–0.033***	–0.032***	0.023***	–0.178***	–0.144***	–0.047***
irrccd	–0.092***	–0.357***	–0.159***	–0.463***	–0.356***	–0.350***	–0.269***
wprcp	0.133***	0.090***	0.039	0.157***	0.106***	0.127**	0.145***
tmax	0.266***	0.162***	0.316***	0.207***	0.241***	0.029	0.200***
tmin	–0.169***	–0.170***	–0.098***	–0.230***	–0.103***	–0.458***	–0.138***
wprcpnorm	–0.447***	–0.808***	–0.213**	–0.341**	–0.554***	0.484**	–0.191
wprcpsd	1.768***	2.297***	2.200***	–0.095	0.881**	–2.027***	0.701
sprcpnorm	–0.017	1.256***	–0.113	–0.065	0.678***	–1.092***	–0.403*
sprcpsd	1.705***	–2.197***	1.346***	3.149***	1.033*	5.330***	4.055***
gddnorm[b]	0.265***	0.057	0.573***	0.485***	0.104*	0.985***	0.612***
gddsd[b]	–0.067***	–0.105***	–0.002	–0.114***	–0.142***	0.084	–0.081***
barleyNprice	65.826***	50.123***	22.679**	79.629***	54.916***	120.686***	42.201***
cornNprice	–317.860***	–229.538***	–362.625***	–301.824***	–379.782***	88.010	–289.720***
potatoNprice	–96.427***	–84.013***	–104.601***	–114.752***	–178.122***	74.754	–107.665***
sbeetNprice	15.776***	13.051***	20.024***	20.640***	25.697***	–0.690	17.353***
swheatNprice	320.757***	199.274***	423.275***	223.638***	463.278***	–376.448***	288.607***
constant	–28.375***	–5.723	–47.614***	–26.664***	–22.955***	–37.829***	–45.104***

Note: [a]Asterisks denote statistical significance at the 0.1% level (***), the 1% level (**), and the 5% level (*). The excluded land allocation category is fallow. [b] Estimated coefficients multiplied by 10^2.

Table 4. Marginal effects for priority date by portfolio[a]

Sample:	All observations			
Portfolio:[b]	None	Group	Stacked	Stacked, group
Fallow	2.4e–04	9.3e–05	2.0e–04	7.8e–05
	(7.2e–05)	(2.8e–05)	(6.3e–05)	(2.4e–05)
Alfalfa	1.2e–04	2.3e–04	1.7e–04	2.6e–04
	(1.1e–04)	(1.1e–04)	(1.1e–04)	(1.2e–04)
Barley	–9.0e–05	–1.1e–04	–1.0e–04	–1.3e–04
	(5.4e–05)	(7.6e–05)	(6.5e–05)	(8.9e–05)
Corn	–2.0e–04	–1.7e–04	–1.9e–04	–1.6e–04
	(5.5e–05)	(5.0e–05)	(5.2e–05)	(4.7e–05)
Potatoes	–9.6e–05	–9.3e–05	–1.2e–04	–1.1e–04
	(3.7e–05)	(3.7e–05)	(4.5e–05)	(4.5e–05)
Spring wheat	–5.9e–06	–3.0e–06	–5.3e–06	–1.5e–06
	(2.0e–05)	(2.4e–05)	(2.5e–05)	(3.0e–05)
Sugarbeets	2.3e–05	3.7e–05	2.3e–05	3.5e–05
	(9.7e–06)	(1.6e–05)	(9.4e–06)	(1.5e–05)
Winter wheat	1.3e–05	2.4e–05	1.6e–05	2.6e–05
	(4.4e–05)	(5.0e–05)	(4.3e–05)	(4.8e–05)

Notes: [a]Marginal effects for priority date (*pryr*) are evaluated at the mean for each independent variable with the exception of the dummy variables *stack* and *group*. [b]No portfolio marginal effects are calculated for *stack* = 0, *group* = 0; group portfolio marginal effects are calculated for *stack* = 0, *group* = 1; stacked portfolio marginal effects are calculated for *stack* = 1, *group* = 0; stacked, group access portfolio marginal effects are calculated for *stack* = 1, *group* = 1. Standard errors are in parentheses.

Table 5. Expected land share and profit by portfolio

Sample:	All observations			
Portfolio:	None	Group	Stacked	Stacked, group
Expected land shares (%) and profit[a]				
Fallow	14.73	4.28	9.91	2.49
Alfalfa	55.15	53.69	50.79	38.22
Barley	6.46	17.10	14.00	28.98
Corn	14.29	4.28	11.55	3.22
Potatoes	2.57	5.91	4.69	9.72
Spring wheat	1.73	8.14	3.99	12.05
Sugarbeets	1.23	1.39	1.04	0.84
Winter wheat	3.85	5.20	4.03	4.48
Profit (USD/ha)	1,039.23	1,201.31	1,096.75	1,190.11
Change (%) with maximum increase in priority date[b]				
Fallow	3.25	1.29	2.81	1.08
Alfalfa	1.34	2.84	2.05	3.32
Barley	–1.21	–1.53	–1.39	–1.73
Corn	–2.56	–2.21	–2.39	–2.02
Potatoes	–1.23	–1.19	–1.53	–1.46
Spring wheat	–0.09	–0.05	–0.08	–0.03
Sugarbeets	0.34	0.54	0.33	0.51
Winter wheat	0.16	0.30	0.20	0.33
Profit	–2.66	–0.33	–2.48	–0.44

Notes: [a]Expected land shares are calculated as the mean of the predicted shares across observations within each portfolio type. Expected profit is calculated based on predicted land shares using the average price per unit yield for each crop over the duration of the study period (2005-2015) and yield and operating costs per hectare from regional cost of production budgets. [b]The maximum increase in priority date is from 1869 to 2003. Change in land share and profit with the maximum increase in priority date is the percentage difference in land share and profit for the least senior water right relative to the most senior water right.

Table 6. Marginal effects for priority date and number of rights by portfolio

Sample:	*stack* = 0		*stack* = 1	
Portfolio:	None	Group	Stacked	Stacked, group
Marginal effects, priority date[a]				
Fallow	3.6e–04	1.7e–04	4.1e–04	1.3e–04
	(1.0e–04)	(4.9e–05)	(1.5e–04)	(4.8e–05)
Alfalfa	–4.5e–04	–3.7e–04	9.0e–04	9.5e–04
	(1.3e–04)	(1.3e–04)	(2.9e–04)	(2.9e–04)
Barley	8.0e–06	2.5e–05	–1.2e–04	–1.7e–04
	(5.3e–05)	(7.3e–05)	(2.0e–04)	(2.4e–04)
Corn	–4.1e–05	–3.1e–05	–3.3e–04	–2.4e–04
	(6.6e–05)	(7.0e–05)	(7.9e–05)	(5.7e–05)
Potatoes	2.6e–05	3.9e–05	–4.8e–04	–2.9e–04
	(3.4e–05)	(4.3e–05)	(1.8e–04)	(1.1e–04)
Spring wheat	–3.6e–05	–4.4e–05	3.9e–05	4.1e–05
	(1.6e–05)	(2.0e–05)	(9.3e–05)	(1.1e–04)
Sugarbeets	6.9e–05	1.3e–04	–3.5e–05	–3.8e–05
	(1.4e–05)	(3.3e–05)	(4.1e–05)	(4.0e–05)
Winter wheat	5.6e–05	8.1e–05	–3.8e–04	–3.9e–04
	(6.7e–05)	(7.9e–05)	(1.6e–04)	(1.6e–04)
Marginal effects, number of rights				
Fallow	–	–	–2.7e–03	–9.2e–04
			(1.6e–03)	(5.2e–04)
Alfalfa	–	–	–1.4e–02	–1.7e–02
			(1.7e–03)	(1.5e–03)
Barley	–	–	1.3e–02	1.7e–02
			(7.6e–04)	(9.0e–04)
Corn	–	–	–1.2e–03	–9.3e–04
			(6.1e–04)	(4.6e–04)
Potatoes	–	–	6.2e–03	3.6e–03
			(5.4e–04)	(3.0e–04)
Spring wheat	–	–	–1.1e–03	–1.4e–03
			(4.4e–04)	(5.1e–04)
Sugarbeets	–	–	4.2e–04	4.4e–04
			(1.8e–04)	(1.9e–04)
Winter wheat	–	–	–8.9e–04	–1.1e–03
			(7.8e–04)	(8.0e–04)

Notes: [a] For the sample *stack* = 0, the priority date variable is *pryr* (which is identical to *avgpr*) and *nrights* = 1 for all observations. For the sample *stack* = 1, the priority date variable is *avgpr*.

Table 7. Predicted land share and profit by portfolio, stacked and unstacked samples

Sample:	*stack* = 0		*stack* = 1	
Portfolio:	None	Group	Stacked	Stacked, group
Expected land shares (%) and profit				
Fallow	14.61	5.77	11.28	2.48
Alfalfa	52.74	49.77	48.37	38.46
Barley	6.66	16.31	13.22	27.03
Corn	13.08	4.27	11.08	2.71
Potatoes	2.57	5.98	4.71	9.60
Spring wheat	1.68	7.60	3.55	11.76
Sugarbeets	1.02	1.73	1.11	0.66
Winter wheat	7.64	8.56	6.69	7.31
Profit (USD/ha)	1,027.61	1,172.32	1,074.58	1,188.75
Change (%) with maximum increase in priority date[a]				
Fallow	4.93	2.30	4.32	1.41
Alfalfa	–6.13	–5.25	7.91	8.73
Barley	0.07	0.28	–1.51	–1.93
Corn	–0.57	–0.46	–2.80	–1.98
Potatoes	0.34	0.50	–4.23	–2.50
Spring wheat	–0.47	–0.57	0.27	0.32
Sugarbeets	1.13	2.19	–0.32	–0.35
Winter wheat	0.71	1.02	–3.65	–3.69
Profit	–5.05	–0.98	–5.51	–0.48
Change (%) with one standard deviation increase in number of rights[b]				
Fallow	–	–	–1.23	–0.42
Alfalfa	–	–	–6.48	–7.61
Barley	–	–	6.14	7.75
Corn	–	–	–0.57	–0.43
Potatoes	–	–	2.86	1.65
Spring wheat	–	–	–0.51	–0.63
Sugarbeets	–	–	0.19	0.20
Winter wheat	–	–	–0.42	–0.51
Profit	–	–	2.70	–0.25

Notes: [a] The maximum increase in priority date is 1870 to 2003 when *stack* = 0 and 1877 to 1977 when *stack* = 1. The change in land share and profit with the maximum increase in priority date is the percentage difference in land share and profit for the least senior portfolio relative to the most senior portfolio. [b] One standard deviation change in the number of rights is 4.6 rights when *stack* = 1 (when *stack* = 0, *nrights* = 1 for all observations). The change in land share and profit with one standard deviation increase in the number of rights is the change relative to the land share and profit earned with a portfolio that has 4.6 fewer water rights.

Supplementary Appendix

Table A1. Summary statistics by portfolio type

Portfolio:	None		Group		Stack		Stack, group	
Statistic:	N	Mean	N	Mean	N	Mean	N	Mean
Land allocation variables (%)								
$\mathit{alfalfa}_{mt}$	9,207	52.13	2,194	49.00	6,673	49.00	2,916	37.97
barley_{mt}	9,207	7.72	2,194	17.16	6,673	14.58	2,916	27.39
corn_{mt}	9,207	12.82	2,194	4.25	6,673	9.34	2,916	2.79
fallow_{mt}	9,207	14.13	2,194	5.78	6,673	11.42	2,916	2.83
potato_{mt}	9,207	2.58	2,194	6.01	6,673	4.30	2,916	9.51
swheat_{mt}	9,207	1.94	2,194	7.81	6,673	4.10	2,916	11.68
sbeets_{mt}	9,207	1.07	2,194	1.70	6,673	1.00	2,916	0.66
wwheat_{mt}	9,207	7.62	2,194	8.29	6,673	6.27	2,916	7.18
Water right variables								
pryr_{m}	11,810	1,923.61	2,430	1,920.11	7,140	1,903.45	2,930	1,898.26
area_{m}	11,820	17.30	2,430	40.81	7,140	64.87	2,930	74.48
Land, weather, and climate variables								
$\mathit{elevrawm}_{m}$	11,330	1,192.27	2,420	1,387.72	5,830	1,325.62	2,890	1,465.45
$\mathit{slopeawm}_{m}$	11,330	5.84	2,420	2.22	5,830	3.87	2,890	2.32
irrccd_{m}	11,330	3.48	2,420	2.67	5,830	3.10	2,890	2.42
wprcp_{mt}	11,790	6.57	2,430	5.17	7,138	5.83	2,930	4.87
tmax_{mt}	11,268	59.57	2,367	57.26	6,862	58.17	2,870	57.12
tmin_{mt}	11,268	32.92	2,367	31.28	6,862	31.44	2,870	30.95
$\mathit{wprcpnorm}_{m}$	11,790	6.64	2,430	5.22	7,138	6.17	2,930	5.08
$\mathit{wprcpsd}_{m}$	11,790	2.41	2,430	2.19	7,138	2.32	2,930	2.06
$\mathit{sprcpnorm}_{m}$	11,790	4.13	2,430	5.20	7,138	4.90	2,930	5.40
$\mathit{sprcpsd}_{m}$	11,790	1.71	2,430	2.26	7,138	2.00	2,930	2.24
$\mathit{gddnorm}_{m}$	11,790	4,948.68	2,430	4,718.37	7,138	4,828.79	2,930	4,716.44
gddsd_{m}	11,790	488.57	2,430	451.60	7,138	381.24	2,930	374.04

Table A2. Fractional multinomial logit (FMNL) coefficient estimates, unstacked observations[a]

Log pseudo–likelihood = –14,932.59 Wald chi2(189) = 3,641.58

Number of obs = 10,604 Prob > chi2 = 0.0000

Variables	Alfalfa	Barley	Corn	Potatoes	Spring Wheat	Sugarbeets	Winter Wheat
pryr[b]	–0.322***	–0.233*	–0.298**	–0.151	–0.511***	0.804***	–0.176
area[b]	0.188*	0.555***	0.695***	0.629***	0.541***	0.609***	0.518***
group	0.851***	1.168***	0.882***	1.060***	1.075***	1.471***	0.993***
elevrawm[b]	0.071***	0.041	0.041	0.016	–0.010	–0.021	0.063*
slopeawm	–0.019***	–0.018	–0.041***	–0.001	–0.078***	–0.100***	–0.016*
irrccd	–0.097***	–0.292***	–0.109***	–0.341***	–0.346***	–0.476***	–0.151***
wprcp	0.006	–0.034	0.041*	0.034	–0.013	0.068	–0.048*
tmax	0.060***	0.006	0.113***	0.044*	–0.041	0.098**	–0.015
tmin	–0.114***	–0.056**	–0.148***	–0.065*	–0.106***	–0.113**	0.020
wprcpnorm	–0.029	–0.367***	0.043	0.050	0.050	0.312*	0.048
wprcpsd	0.613***	1.113***	1.233***	–0.588	–0.981***	–0.907*	0.377*
sprcpnorm	–0.189*	0.954***	–0.240	–0.403*	0.046	–0.725**	–0.087
sprcpsd	0.688**	–2.606***	–0.172	2.361***	1.532***	3.202***	0.949**
gddnorm[b]	0.184***	–0.108***	0.469***	0.250***	0.143***	0.495***	0.291***
gddsd[b]	0.005	–0.056**	0.095***	–0.114***	–0.107***	–0.079	–0.075***
constant	–3.575	11.692***	–22.436***	–11.824**	7.493*	–45.300***	–13.469***

Note: [a]Unstacked observations are those for which *stack* = 0. Asterisks denote statistical significance at the 0.1% level (***), the 1% level (**), and the 5% level (*). The excluded land allocation category is fallow. [b]Estimated coefficients multiplied by 10^2.

Table A3. Fractional multinomial logit (FMNL) coefficient estimates, stacked observations[a]

Log pseudo–likelihood = –11,228.66 Wald chi2(189) = 7,318.85
Number of obs = 8,079 Prob > chi2 = 0.0000

Variables	Alfalfa	Barley	Corn	Potatoes	Spring Wheat	Sugarbeets	Winter Wheat
avgpr[b]	–0.299	–0.556*	–1.376***	–1.163***	–0.388	–0.976	–0.901***
nrights[b]	0.384	12.442***	–0.290	12.021***	0.712	9.139*	2.070
area[b]	–0.253***	0.053	0.268***	0.742***	0.629***	0.391**	0.481***
group	1.213***	1.379***	0.775***	0.598***	1.254***	1.207***	1.136***
elevrawm[b]	0.085	0.157**	–0.039	0.003	0.022	–0.248***	0.038
slopeawm	–0.017*	–0.167***	–0.008	–0.014	–0.126**	–0.344***	–0.018
irrccd	–0.064	–0.172***	–0.266***	–0.468***	–0.459***	–0.115	–0.237***
wprcp	0.024	–0.002	0.032	0.055	0.040	–0.023	0.154***
tmax	0.039**	0.035*	0.047*	0.068***	–0.067***	0.098*	0.099***
tmin	–0.084***	–0.090***	–0.124***	–0.062*	–0.002	–0.179***	–0.126***
wprcpnorm	–0.012	–0.130	0.635**	0.111	–0.612*	–0.185	–0.051
wprcpsd	0.903	0.782	–1.124	–1.303	1.094	1.468	0.198
sprcpnorm	0.295	1.123***	–0.528**	0.266	1.688***	1.113*	0.243
sprcpsd	0.666	–2.295***	2.971***	2.005*	–2.344**	–0.389	1.543*
gddnorm[b]	0.391***	0.124*	0.877***	0.468***	0.161*	0.840***	0.533***
gddsd[b]	–0.075***	–0.082***	–0.024	–0.059	–0.064	0.095	–0.036
constant	–16.354**	2.649	–19.216**	–5.472	1.427	–27.361*	–15.688*

Note: [a] Stacked observations are those for which *stack* = 1. Asterisks denote statistical significance at the 0.1% level (***), the 1% level (**), and the 5% level (*). The excluded land allocation category is fallow. [b] Estimated coefficients multiplied by 10^2.