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Intertemporal Arbitrage of Water and Long-Term Agricultural Investments: Drought, Groundwater Banking, and Perennial Cropping Decisions in California

Jesus Arellano-Gonzalez and Frances C. Moore

Abstract

In arid areas, irrigation water is an essential input into agricultural production. However, rainfall and, correspondingly, surface water supplies, are often highly variable, creating uncertainty over the value of long-term, water-dependent investments in these cropping systems. Moreover, climate change is expected to increase both crop water requirements and the variability of seasonal rainfall, meaning the constraints imposed by variable water supplies are likely to grow in cost as climate change progresses. In this setting, storing water in wet years for use in dry years is valuable. In particular, it would be expected to increase the value of perennial crops, which require large up-front investments that pay off gradually over the life of the tree. We first show, in a simple theoretical model, that given the timing of returns to investments in perennial crops, there is always some level of drought risk above which annual crops will be preferred to perennials. We then demonstrate this effect empirically using a unique institutional setting in which access to a relatively new form of water storage, groundwater banking, effectively created spatial variation drought risk between irrigation districts in Kern County, California. Using a 22-year dataset of individual cropping decisions, we provide evidence that access to a large groundwater banking project, the Kern Water Bank, increased the rate at which farmers switched from lower-value annual crops such as wheat and alfalfa, into high-value perennial nut crops, primarily almonds and pistachio.

Key words: California, crop switching, drought, groundwater, irrigation, perennials,
JEL codes: Q150, Q250, Q540

Running Head: Groundwater banking and agricultural investments

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Water is an essential input into agricultural production, but the natural supply of water is not equally distributed either across space or across time. Agricultural systems have developed a variety of approaches to deal with the uneven supply of rain: locating in places where precipitation is generally adequate for rainfed production, timing planting to coincide with the wet season, accessing alternative supplies of water by pumping groundwater, or moving and storing rainwater in surface irrigation systems. In many agricultural systems, natural variability in this essential input creates costly uncertainty in annual production, optimal management strategies, and the value of investment decisions. The value of irrigation investments therefore comes not only from expanding but from smoothing the available water supply, thereby reducing the risk associated with rainfall fluctuations, something particularly important in arid areas where water supply imposes a binding constraint on production.

The costs of rainfall variability have been widely documented, particularly in developing country contexts. In arid areas reliant on seasonal rainfall, variability in the timing and amount of rainfall has large effects on output (Rosenzweig and Binswanger 1992). Farmers adjust their crop choice and inputs in response to observed or forecast changes in seasonal rainfall (Rosenzweig and Udry 2014; Taraz 2017). In the absence of insurance, farmers have been shown to adopt risk-averse strategies, rejecting higher value but risky options in favor of lower but less variable returns. For instance, Karlan et al. (2014) find that rainfall risk is a binding constraint on the investment decisions of farmers in northern Ghana. Relieving that constraint through the provision of index insurance leads to substantial on-farm investments that increase productivity.

The role of rainfall risk in developed countries has been less widely studied, likely for two reasons. Firstly, in most temperate cropping systems, temperature rather than rainfall is the binding meteorological constraint on production (Schlenker and Roberts 2009). Secondly, in drier areas, large investments in irrigation infrastructure (Edwards and Smith 2018) as well as the widespread use of crop insurance, have reduced the exposure of farmers to local rainfall variability and decreased risk in many regions. However, in arid areas, water supply risk may still be an important determinant of production, significantly affecting both cropping and investment decisions (Feinerman and Tsur 2014; Koundouri, Nauges, and Tzouvelekas 2006; Marques, Lund, and Howitt 2005).

Perennial crops such as fruit and nut trees are long-term investments because they have high establishment costs and are unproductive in the first 3-4 years of the tree's life. These costs are paid back over the lifetime of the tree (Feinerman and Tsur 2014). If farmers are unable to access water in any year, the tree dies and they lose all future production. Perennial crops are thus inherently more exposed to drought risk than annual crops because fallowing land is very costly. Zilberman et al. (2002) document that fallowing land in annual crops was a significant margin of adjustment to the serious California drought of 1987-1991. In years with severe water deficits, farmers of perennial crops however face a choice between losing the trees and securing water at high price on the market (Qin et al. 2019). Therefore, drought risk is an important determinant of the returns to perennial crops and investments to reduce variability in water supplies will be correspondingly valuable in these systems.

Climate change is expected to increase the variability of rainfall in the future creating more intense, heavy rainfall events with longer dry spells in between (Diffenbaugh, Swain, and Touma 2015; Mallakpour, Sadegh, and AghaKouchak 2018; Swain et al. 2018). In addition, warmer temperatures will increase crop water demand, making any deficit in rainfall more damaging to agriculture (Lobell et al. 2013; Ortiz-Bobea et al. 2019). This means understanding how water supply variability constrains agricultural production will be important for quantifying the impacts of climate change and identifying promising adaptation options. In California in particular, in addition to increasing inter- and intra-annual variability, climate change is expected to shift runoff to earlier in the year as less snow falls in the Sierra Nevada and the snowpack melts earlier in the year (Bedsworth et al. 2018; Qin et al. 2020). This creates a disconnect in the timing of peak water availability in the spring and peak irrigation demand in mid-summer, increasing the importance of water storage for managing water supply availability throughout the year.

Here we show that the ability to smooth interannual water supplies is important in the uptake of high-value perennial crops. Specifically, access to a major groundwater banking project, which allows members to store some portion of their surface water endowment as groundwater in wet years for future use in dry years, accelerated adoption of perennial nut crops in southern California. There are two main contributions. Firstly, while a number of papers have addressed the spatial inefficiencies in California water allocations associated with a limited water market, fewer have directly estimated the effect of temporal inefficiencies and, conversely, the value of water storage (Bruno and Jessoe 2019; Hagerty 2019). Here we provide empirical evidence that reducing drought risk through access to large scale water storage enables higher-value but riskier production.

Secondly, we provide evidence on the effectiveness of a relatively new form of water storage technology, groundwater banking. Given the increasingly variable flows expected with climate change, as well as new regulatory constraints on unsustainable groundwater extraction in California and the difficulty of permitting new reservoir storage, groundwater banking is increasingly seen as essential for managing water supply variability in the future (Hanak et al. 2019; Hanak and Lund 2012; Tanaka et al. 2006). Moreover, because surface water must be given up ("deposited") in wet years in order to be recovered in dry years, benefits to farmers are purely from reducing the variability of supply, not from increasing the aggregate amount of water available for irrigation, making it distinct from general groundwater irrigation that has been studied previously (Merril and Guilfoos 2018).

Agriculture in Kern County and the Kern County Water Bank

The Central Valley of California is one of the most productive agricultural areas in the world, producing about two-thirds of US fruit and nuts, including essentially all the country's peaches, plums, figs, raisins, olives, almonds, walnuts, and dates (CDFA 2018). This is despite the fact that local rainfall is highly seasonal – during the summer essentially no rain falls in the Central Valley. Production relies on transporting water both across space, from water rich northern California to growing areas in the southern Central Valley, and across time, from winter to summer via natural storage as snowpack in the Sierra Nevada and artificial storage in reservoirs (Schlenker, Hanemann, and Fisher 2007). Although irrigation using groundwater expanded in response to the 2013-2016 drought, it still makes up only about one third of total irrigation water (CDWR 2015).

Kern County is the very southern end of the Central Valley, in the Tulare Basin (Figure 1a). Local precipitation is extremely low, but the county has over 1 million acres of agricultural land, producing $7.4 billion in 2018 (KCDAMS 2019). Agricultural land is divided into 23 irrigation districts (Figure 1c and Figure A3), which supply water to members from a variety of sources including deliveries from the two large aqueduct systems that transport water from northern California (the Central Valley Project (CVP) and the State Water Project (SWP)), the local Kern River, groundwater extraction, and recycled water from the oil and gas industry.

Since the early 2000s, Kern County has seen a pronounced shift in cropping patterns, away from annual field crops, toward perennial nut crops (Figure 1b). In 2000, annual crops, primarily cotton, alfalfa[1], and wheat made up 58% of crop land in Kern while perennial crops, primarily almond, pistachios and grapes made up 36%. By 2018, that ratio had switched so that annual crops were just 36% while perennials were 55%. This trend continued over 2 major, multi-year droughts (Figure 1b). The driver of perennial expansion has been the planting of nut crops, primarily almond, pistachio, and walnut. These crops have seen an expanding market and rising prices in the last 20 years. From 2000 to 2018 the prices of almonds and pistachios more than doubled (USDA 2018).

In an area with seasonal rainfall like Kern County, tree crops tend to use less irrigation than annuals both because the trees are inherently less thirsty than annuals (Allen et al. 1998, see also Table A2) and because they are typically grown with more efficient but capital-intensive irrigation systems (Zilberman et al. 2002; Tindula et al. 2013; Taylor and Zilberman 2017). However, despite reducing average water use, perennials can increase exposure to drought risk. This is because, in addition to initial planting costs, they require a maturation period of several years, during which they are unproductive. These upfront investments, that must be taken on ex-ante, before rainfall is realized, mean that fallowing – an important margin of adjustment to drought for annual crops – is unavailable to perennial farmers. In years when water is scarce, perennial farmers must either pay high prices to secure water or lose their investments.

This makes perennial investments potentially risky in southern California, where annual winter precipitation, and thus the volume of surface water available for irrigation is extremely variable. In wet years there is more than enough water to meet the needs of existing water rights holders while in dry years some rights are ‘curtailed’, meaning owners are not able to use the water they are usually entitled to. For example, between 2014 and 2015, in the middle of an intense multi-year drought, irrigators in the San Joaquin valley were assigned 0% of their total CVP contracted volumes (Sugg 2018). Deliveries from the SWP were also affected throughout the drought (Howitt et al. 2014 and 2015; Medellin-Azuara et al. 2016). This dynamic induces large variation in the marginal value of irrigation water, from close to zero in wet years to an estimated $900 per acre-foot in the southern San Joaquin to avoid fallowing highly valuable cropland (Hanak et al., 2019).

This pattern would suggest the opportunity for intertemporal arbitrage of water, mitigating the negative consequences of lower precipitation and severe curtailments during dry years particularly in highly exposed areas such as Kern County. However, storing water is difficult and expensive. Historically, reservoirs have been the only technology available for large-scale, interannual water storage, but reservoir operations are determined by multiple, sometimes conflicting objectives including flood control and power generation. Moreover, further expansion of reservoir storage in California is unlikely given concerns over ecological disruption. A relatively new technology for the intertemporal arbitrage of water is groundwater banking. This involves deliberately allowing surface water in wet years to infiltrate into aquifers and storing it as groundwater for use in dry years, when it is pumped out and returned to surface irrigation systems.

The capacity for groundwater banking has been growing rapidly in California since the late 1990s. The largest groundwater bank in California is the Kern Water Bank (KWB) which is located on 20,000 acres of sandy soil in the center of the agricultural area of Kern County (Figure 1c). Since beginning operations in 1995, it has accounted for about 40% of the balances of all groundwater banks in Kern County and about 80% of its water banking balances come from agricultural participants (Hanak and Stryjewski 2012; Jezdimirovic, Sencan, and Hanak 2019; Hanak et al., 2019). The KWB is owned by a coalition of three Kern County irrigation districts, one irrigation district in neighboring Kings County, Improvement District 4 which supplies water to the City of Bakersfield, and the Westside Mutual Water Company (Figure 1c). Westside Mutual has large land-holdings throughout the southern Central Valley, primarily associated with production of almonds, pistachios, and citrus.

Establishment of the KWB in its current form was tied to a renegotiation of SWP contracts in 1994, termed the “Monterey Amendments”, in which contractors paid in kind for the land and permission to operate the bank by permanently retiring 45,000 acre-feet of SWP entitlements (KWBA 2020). Accordingly, members of the bank are made up of SWP contractors, rather than those relying on the CVP or the Kern River (Table 1). On average, 58.5% of the water banked in the KWB comes from contracts with the SWP. Water from Kern River and the CVP represent 27% and 14.5% respectively (KWBA 2018).

Members of the KWB are responsible both for the up-front capital investments necessary to deliver water to the bank, to recharge into groundwater, and to recover via pumping when required (approximately $50 million, KCWA 2020) and the variable cost of storing water in wet years and recovering it in dry years. KWB members pay a cost to bank water of $9.5-16.0 per acre-foot for recharge, depending on the location, in addition to the forgone benefits of using that surface water contemporaneously. The vast majority of “deposits” into the bank (95%) happen during wet and above normal water years, when the marginal benefit of irrigation water is low (KWBA 2018). The recovery cost for withdrawal is $98-153 per acre-foot depending on the season (CLEE 2019).

Benefits to bank members come in the form of secure access to water supplies during dry years, when surface water deliveries are curtailed. In these years, farmers would otherwise face a choice of forgoing irrigation and fallowing fields, pumping local groundwater (which has become expensive due to a falling groundwater table in the region and is increasingly regulated in California), or paying high prices for scarce surface water: A 2014 sale of water in Kern County, at the height of an intense, multi-year drought, received almost 20 bids at $1,000 per acre-foot or higher (Henry 2014). In other words, because membership of the bank reduces the economic costs of a dry year, it effectively introduces institutional variation in exposure to drought risk across growers. In the following section, we develop theoretical intuition for how this affects the value of perennial crops, and therefore the likelihood of switching from annuals into perennials. We then test this using a 22-year dataset showing planting decisions of all landowners in Kern County.

Theoretical Model

We model the decision of a simple, profit-maximizing farmer considering adopting a perennial crop or continuing an annual crop, adapting the model of drought risk for perennial crops given in Feineman and Tsur (2014). The occurrence of a drought is random variable d, assumed to follow a Bernoulli distribution parameterized with probability p and assumed to be i.i.d across years.

For the annual crop, farmers are able to observe water availability before planting. This captures the California case where summer irrigation water availability is determined by winter snowfall and is known before spring planting. Profits from the annual crop are given by π_a if d=0 and by 0 if d=1. If irrigation water is not available due to drought, farmers can chose to fallow and avoid losing planting costs. Therefore, the net present value (NPV) of annual cropping over an infinite horizon is given by:

$$(1) \qquad E[NPV_a] = \sum_{t=1}^{\infty} \frac{\pi_a}{(1+r)^t} * P[d=0] = \frac{(1-p)\pi_a}{r}$$

For perennial crops however, farmers must decide on planting before the realization of drought, incurring an upfront planting cost *K*. In addition, perennial crops require a maturation period *m* years before producing. Starting in year *m+1,* the perennial crop produces profits π_p and continues to do so indefinitely until a drought occurs. Once a drought occurs, the tree dies and the farmer loses all future production.

Given that drought is assumed to be Bernoulli distributed, the number of years before a drought occurs (given by τ) follows a geometric distribution. The NPV of the perennial crop is given by:

$$NPV_p = -K + \frac{1}{(1+r)^m} \sum_{t=1}^{\tau} \frac{\pi_p}{(1+r)^t} * P[t > m] = -K + \frac{(1-p)^m}{(1+r)^m} * \frac{\pi_p}{r} * \left[1 - \frac{1}{(1+r)^\tau}\right]$$

Where -K gives the fixed planting costs, and the second term gives the discounted value of future production starting in year m+1, given that there is no drought before the tree reaches maturity.

Since the timing of drought, and therefore the number of years of production, is uncertain, NPV_p is also uncertain. Its expected value is given by:

$$(2) \qquad E[NPV_p] = -K + \frac{(1-p)^m}{(1+r)^m} * \frac{\pi_p}{r} * \left[1 - E\left(\frac{1}{(1+r)^\tau}\right)\right]$$

where,

$$E\left(\frac{1}{(1+r)^\tau}\right) = \sum_{t=1}^{\infty} \frac{(1-p)^{t-1}}{(1+r)^t} p = \frac{p}{1-p} \sum_{t=1}^{\infty} \left(\frac{1-p}{1+r}\right)^t = \frac{p}{1-p} * \frac{1-p}{r+p} = \frac{p}{r+p}$$

Substituting in (2), we get:

$$(3) \qquad E[NPV_p] = -K + \frac{(1-p)^m}{(1+r)^m} * \frac{\pi_p}{r+p}$$

Equation (3) is an intuitive expression demonstrating the expected value of a perennial crop will depend on the fixed planting costs, the number of years until maturity, the annual profits and drought risk, and the discount rate. The Appendix gives the first and second derivatives of $E[NPV_p]$ with respect to p and shows that this is a downward sloping and convex function.

Figure 2 shows how the expected NPV of annual and perennial crops change with annual drought risk. The expected NPV of annual production is linear in p with an intercept of $\frac{\boldsymbol{\pi_a}}{\boldsymbol{r}}$ and a constant slope of $-\frac{\boldsymbol{p}}{\boldsymbol{r}}$ (solid line). The expected NPV of perennial production is a decreasing and strictly convex function of p with an intercept of $\frac{1}{(1+r)^m}\frac{\pi_p}{r} - K$ (dashed line). The graph depicts the interesting case in which, in the absence of drought risk, the expected value of perennials is higher than the expected value of annuals (i.e. $\frac{1}{(1+r)^m}\frac{\pi_p}{r} - K > \frac{\boldsymbol{\pi_a}}{\boldsymbol{r}}$).

It is clearly apparent that there will always be some level of drought risk, p*, beyond which the expected value of annuals will exceed that of perennials, irrespective of the relative annual profits of the two crops in the absence of drought. For areas close to this critical value, we would expect lower drought risk to result in expansion of area in perennial crops. Large-scale groundwater banking allows farmers to smooth water supplies and therefore lower the risk of extreme water shortages, effectively lowering p, and increasing the expected value of perennial crops.

Our model assumes that once a drought occurs, the tree dies and the farmer loses all future production. In that sense, the definition of a drought is not based strictly on rainfall, but on the agricultural availability of water. If farmers are able to draw on stored water such as from reservoirs, then a single year of drought may not result in a critical absolute scarcity of water. In that sense, p^* could instead be interpreted as the probability of a given year triggering a critical drought event. Though this probability will be lower than the probability of a single dry year, the qualitative insights from the model still hold.

Data and Empirical Strategy

We test this hypothesis using a 22-year panel containing the geographic boundaries of all agricultural plots in Kern County collected and made available by the Kern County Department of Agriculture and Measurement Standards (KCDAMS 2019). The panel identifies the operator, the plot boundaries, and the agricultural commodity grown within it annually since 1997 (see Table A1) and comes from data collected by the county as part of their permitting processes. Maps of plot areas in 2000 and 2018 included in our working sample are shown in Figures A1 and A2. These shows the widespread switch from field crops to nut trees shown in Figure 1b, but also shows the spatial heterogeneity in perennial uptake: by 2018 some areas had switched fully into nuts or fruit crops while in others field crops are still significant.

We classify each plot as perennial, annual or fallow and, because individual plots cannot be uniquely tracked from year to year (since boundaries change slightly and plots do not have unique identifiers), we aggregate the area of annual and perennial crops to the operator-by-irrigation district-by-year level. On average across the sample, each operator has 9.7 plots within each irrigation district. There are 2,298 operators over 23 irrigation districts and a total 27,686 observations. The period saw a gradual consolidation of land, with total agricultural area staying relatively constant but the number of operators decreasing by 15%, and average land holdings per operator increasing from 1.1 to 1.3 thousand acres.

We identify plots of land within the KWB as those either within one of the member irrigation districts (i.e. Wheeler Ridge-Maricopa, Semitropic, Tejon-Castac and Improvement District 4) or plots identified as belonging to the Westside Mutual Water Company (i.e. land operated by The Wonderful Company or Paramount Farms, which merged over the relevant time period and which own Westside Mutual). Crops are classified as either annual or perennial based on the classification given in Table A2.

Table 1 gives a comparison between land within and outside of the KWB for a number of important variables including soil quality, rainfall, groundwater access, and cropping mix at the beginning of the period of analysis (the year 2000). It shows no evidence of systematic differences between plots in vs out of the KWB on these dimensions. We note however that irrigation districts members of the KWB are entirely contractors of the SWP, whereas other irrigation districts in Kern also receive water from the CVP and Kern River. This results from the historical connection between the establishment of the KWB and the renegotiations of entitlements under the SWP previously. However, many irrigation districts outside of the KWB also receive SWP water, meaning any unobservable factors associated with being a SWP contractor are unlikely to confound our estimate of the effect of the KWB.

In addition, we examine whether other groundwater management across districts might explain differences in perennial expansion inside and outside the KWB. Figure A3 shows the boundaries of the irrigation districts and the boundaries of the Groundwater Sustainability Agencies (GSAs) in Kern County. Notably, the members of the KWB fall into four different GSAs. GSAs are a relatively recent institution, formed in a bottom-up process by water users as part of the

Sustainable Groundwater Management Act of 2014. However, to the extent their boundaries reflect a longer history of cooperation on groundwater management, this appears to be largely orthogonal to treatment as part of KWB membership.

With a long enough dataset, a natural empirical strategy would be a difference-in-difference examining the expansion (or contraction) of areas farmed with perennial and annuals crops after the establishment of the KWB in member districts. Unfortunately, our data starts shortly after the establishment of the bank. Therefore, we first present results of a long-differences estimation, comparing the change in areas inside vs outside the KWB over the period of our data:

$$\Delta Crop_{ij} = KWB_j + \mu_i + \varepsilon_{ij} \quad (4)$$

Where $\Delta Crop_{ij}$ is the change in the area (transformed using the inverse hyperbolic sine function[2]) or the share of the area of either annual or perennial crops between the end period (average for 2014-2018) and the start period (average for 1997-2001) for operator i in water district j.

Plot areas are aggregated at the operator-by-irrigation district level. If the dependent variable is the area (share), it should be interpreted as the change in the amount (proportion) of land of operator *i* in water district *j* cultivated with perennials or annual crops over the long difference period. *KWB* is an indicator variable indicating whether that plot is operated by a member of the Kern Water Bank, μ_i, is an operator fixed-effect controlling for all time-invariant differences between companies or individuals farming over this period in Kern County. Differencing controls for any time-invariant differences at the operator-by-district level. The identifying assumption is therefore that there is no time-varying unobserved factor affecting the value of perennials, relative to annuals, that affects plots within the KWB differently from plots outside of it, for a particular operator.

Our second identification strategy uses the fact that the value of water banking is highest during times of scarcity and the fact that five out of 22 years in our sample were categorized as “critically dry” by the California Department of Natural Resources (namely 2007, 2008, 2013, 2014, and 2015) (CDWR 2019). We rely on the following fixed effects estimation:

$$Crop_{ijt} = Drought_t * KWB_j + \mu_i + \vartheta_j + \theta_t + \varepsilon_{ijt} \quad (5)$$

Where $Crop_{ijt}$ is the area (its arcsinh transformation) or the share of the area of either annual or perennial crops of operator *i* in irrigation district *j* in year *t*. *Drought* is an indicator variable indicating whether the water year for that irrigation season (i.e. from fall of the previous year through spring of the current year) was critically dry. μ_i, is again an operator fixed-effect. ϑ_j and θ_t are irrigation-district and year fixed-effects that flexibly control for time-invariant and time-variant differences respectively. The identifying assumption for this specification is that no variable other than bank membership affects the change in the relative value of perennials (or annuals) during a dry year compared to a wet year differently for plots within vs outside of the KWB, for a particular operator.

In both regressions, the inclusion of μ_i alleviates concerns about unobserved characteristics of growers making them more likely to switch into perennial crops. However, this strategy limits the estimating variation to operators with holdings in more than one irrigation district. The distribution of the number of irrigation districts by operator is given in Figure A4. Thirty percent of operators farm in more than one irrigation district and 12% in 3 or more. However, since these may be an unrepresentative subset of farmers within Kern County, we also present results omitting the operator fixed-effect and find results are largely robust to this change. In both regressions residuals are clustered at both the operator and water-district level.

Finally, we also look for evidence of spillovers to neighboring water districts from the KWB. Part of the problem of groundwater banking is that, if groundwater withdrawals are unregulated and aquifers extend beyond the boundaries of the bank, then excluding non-members from accessing stored water is challenging. This has been the situation in Kern County until recently, although recent legislation in California will more strictly regulate groundwater withdrawals (Kiparsky et al. 2017). Evidence that actors within Kern County perceive spillover effects comes from a lawsuit filed by the Rosedale Rio-Bravo Water Storage District following the first major withdrawals from the KWB during the 2007-2008 drought, claiming water bank operations negatively affected the water table in the district (Barringer 2011). Rosedale Rio-Bravo is the only district with a significant direct border with the KWB and so we test for evidence of spillover effects of the bank by comparing the evolution of perennial crops in Rosedale Rio-Bravo compared to other districts that are also outside the KWB using the specification in equation (5).

Results

A simple visualization of changes in cropping patterns inside vs outside the KWB is shown in Figure 3. Changes between 2000 and 2018 are dominated by a switch away from field crops, primarily wheat, alfalfa and cotton, and into tree nuts, primarily almonds and pistachios. Although nut expansion has occurred throughout Kern County, the switch away from field crops occurred far earlier in areas with access to the water bank. Total area classified as inside the water bank has increased somewhat due to expansion of area associated with Westside Mutual Water Company.

These observations are confirmed by results from the long-differences regression, shown in Table 2. Between the periods 1997-2001 and 2014-2018, we see evidence of a larger switch away from annual crops and into perennials within the KWB. The increase in perennial area is 52% larger for plots within the KWB compared to outside of it, while the decrease in the area of annuals is 67% larger (columns 1 and 3). Controlling for operator fixed-effects, we still see evidence that operators, on average, increased perennial area and decreased annual area more quickly on their plots within the KWB than on plots outside of it (columns 2 and 4). Results hold when the dependent variable is expressed in shares. For example, column 6 (8) indicates that the average change in the share of land cultivated with perennial (annuals) is 11 percentage points (pp) larger (12 pp more negative) for plots within the KWB, compared to those outside.

In Table A3, we also report results that exclude five water districts where the average share of perennial crops is greater than 85% in the first three years of the dataset. A few irrigation districts on the east side of Kern County were already invested in citrus and grape production, prior to the start of our dataset (Figure A1), meaning the potential for perennial expansion in these areas is small. Limiting the analysis only to those places with substantial area in annuals at the start of the period provides a check on the interpretation that access to the KWB enabled the expansion of perennials. We still find evidence that the share of perennials crops increased (and the share of annual crops decreased) more within the KWB than outside it.

Table 3 shows the results using annual data. Because of the water district and year fixed-effects, we are only able to estimate the interaction between being in the KWB and experiencing a critically dry year. But we are able to control for all time-invariant differences between water districts and for all common time-varying factors, such as increasing nut prices over time. We see evidence, both within and between operators, that the ability to smooth water supply encourages perennial adoption during drought. The area of perennials is 63% larger for operators within the KWB during a drought year, compared to operators outside of the KWB during a non-drought year while the estimated effect on annuals is almost equal and opposite. Effects are substantially smaller, but still statistically significant when controlling for operator fixed-effects. Excluding the eastern water districts with widespread perennial adoption at the beginning of the period does not change these findings (Table A4).

Finally, Table 4 shows the results from the test for spillovers using a specification identical to that in Table 3, but estimating the effect of being in the Rosedale Rio-Bravo district, rather than the KWB, during a drought. We find some suggestive evidence for positive spillovers from the water bank – compared to other non-KWB areas during a drought, farmers in Rosedale Rio-Bravo maintained a higher fraction of land in perennial crops and a lower fraction in annuals. These results hold if irrigation districts with a large share of land in perennials initially are excluded from the analysis (Table A5).

Conclusions

This paper has provided evidence on the importance of water supply risk in constraining the uptake of long-term investments that are sensitive to drought and, conversely, the value of water storage in reducing water supply risk. Perennial crops can provide high returns, but they substantially reduce the flexibility of farmers to respond to adverse water supply shocks. If the probability of drought is too high, the risk associated with this lost flexibility will be large enough to offset even large gains in profitability. Evidence from the Kern Water Bank setting confirms this intuition: areas with access to large-scale groundwater storage, which effectively reduced their exposure to water supply shocks, adopted perennials faster than areas without access to this infrastructure. These findings are supported by the seasonal pattern observed in groundwater bank balances which have tended to decrease during dry episodes as farmers rely on stored water to offset surface water curtailments (Hanak and Stryjewski 2012; Jezdimirovic, Sencan, and Hanak 2019).

The smoothing of water supply translates into higher agricultural returns. Between 2000 and 2018 the total value of agriculture in Kern County increased by 240% mostly explained by an increased production of perennial crops (KCDAMS 2001 and 2019). A back-of-the-envelope calculation suggests that the KWB increased the gross value of agriculture in Kern County by 4.6% (based on observed prices and assuming that perennial cultivation would have grown at the same rate for KWB members as it did in non-KWB members and that land not used for perennials was used for annuals instead). As climate change increases both the inter- and intra-annual variability in hydrologic flows, storing water as groundwater will likely be an important tool for managing this risk.

Footnotes

[1] Alfalfa can be harvested repeatedly for several years. However, drought risk to alfalfa farmers looks more similar to that associated with annual crops than with that of perennials in that it does not require the same upfront costs as fruit or nut perennials and does not necessitate a long maturation period to start producing. In Mediterranean and desert zones, such as California, irrigated alfalfa is typically harvested in short intervals (Putnam, Summers, and Orloff 2007). As a result, key aspects of its cultivation practices are closer to those of an annual crop and we have categorized it as an annual for the purposes of this study.

[2] The inverse hyperbolic sine (or arcsinh) transformation has gained popularity in applied economics because its similarities with the logarithmic transformation and because it retains observations with values equal to zero. The transformed variable $\tilde{x}$ takes the form $\tilde{x} = \ln(x + \sqrt{(x^2 + 1)})$. As in a logarithmic

transformation, estimated coefficients could be interpreted as elasticities or semi elasticities (Burbidge et al. 1988; MacKinnon and Magee 1990).

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Figure titles

Figure 1**:** a) Location of Kern County and the Central Valley within California, b) Evolution of agriculture in Kern County, 2000-2018. Shaded areas mark years classified as “critically dry” in the San Joaquin valley by the California Department of Water Resources (CDWR 2019), c) Location of the Kern Water Bank, member irrigation districts, plots associated with the Westside Mutual Water Company in 2018, and other non-member irrigation districts within Kern County.

Figure 2**.** Expected NPV of annual (solid line) and perennial (dashed line) as a function of annual drought risk (*p*)

Figure 3: Change in cropping patterns in Kern County for land in vs outside of the KWB.

Tables

Table 1: Balance Test[a] Between Land Areas In and Out of the Kern Water Bank

(1)	(2)	(3)	(4)	(5)
Variable	**N**	**Out of KWB**	**In KWB**	**Diff. (Std. Err.)**
1) Plot farmed with Annuals (1=Yes, 0=No)[b]	12,226 plots	0.606	0.668	0.061
				(0.107)
2) Plot farmed with Perennials (1=Yes, 0=No)[b]	12,226 plots	0.355	0.286	-0.068
				(0.095)
3) Mean annual precipitation (mm) (normal for 2000)[c]	6,181 grid cells	244.147	220.542	-23.605
				(22.637)
4) Mean seasonal precipitation (mm) (normal for 2000)[c]	6,181 grid cells	93.981	87.165	-6.817
				(6.799)
5) Grid cell overlaps with underlying groundwater aquifer (1=Yes, 0=No)[d]	6,323 grid cells	0.831	0.995	0.164
				(0.112)
6) Grid cell classified as[e]:				
Excellent soil (1=Yes, 0=No)		0.138	0.100	-0.037
				(0.058)
Good soil (1=Yes, 0=No)		0.362	0.336	-0.025
				(0.089)
Fair soil (1=Yes, 0=No)	6,316 grid cells	0.124	0.088	-0.036
				(0.038)
Poor soil (1=Yes, 0=No)		0.179	0.153	-0.027
				(0.105)
Very poor soil (1=Yes, 0=No)		0.067	0.097	0.030
				(0.069)
7) Number of districts receiving water from[f]:				
State Water Project		11	4	
Central Valley Project		6	0	
Kern River		7	0	

Note: [a]The balance test was constructed by regressing the variable noted in column (1) on a dummy variable identifying plots (variables 1 and 2) or grid cells (variables 3 to 6) associated with members of the KWB. The intercept of this regression represents the mean for non-KWB areas and is reported in column (3). The mean for KWB areas, reported in column (4), is obtained by adding to the intercept the coefficient on the dummy for KWB membership. Column (5) reports the mean difference with standard errors (in parentheses) clustered at the water district level. [b]Plot boundaries, crops and operator information is obtained from KCDAMS (2019). [c]Annual and seasonal precipitation normals (average of 20 years) at the grid cell level were constructed using DAYMET (Thornton et al. 2018). [d]The geographic boundaries of the underlying groundwater basins in the sample area (obtained from https://data.cnra.ca.gov/dataset/ca-bulletin-118-groundwater-basins) were rasterized using a resolution of 1km x 1km. Membership to the KWB for the resulting grid cells was determined based on location. [e]Kern County soil properties were obtained from https://databasin.org. The grid cells that resulted from rasterizing soil polygones at a 1km x 1km resolution where assigned to membership of the KWB based on location. [f]Information on water sources was gathered from the websites of each water district and from KCWA (2011).

Table 2: Long-difference Estimates of the Effect of Water Banking on Cultivation Decisions

	Δarcsinh (area)				Δshare			
	Perennials		Annuals		Perennials		Annuals	
Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
KWB	0.517*	0.150	-0.669*	-0.535**	0.146*	0.106**	-0.152*	-0.119***
	(0.291)	(0.305)	(0.370)	(0.229)	(0.079)	(0.041)	(0.076)	(0.040)
Operator FE	No	Yes	No	Yes	No	Yes	No	Yes
R-squared	0.010	0.661	0.014	0.571	0.036	0.649	0.042	0.677
Observations	607	320	607	320	607	320	607	320

Note: Standard errors (in parenthesis) clustered at Operator and Water District level. * p<0.10, ** p<0.05, *** p<0.01

Table 3: Panel Estimates of the Effect of Water Banking and Droughts on Cultivation Decisions

	Δarcsinh (area)				Δshare			
	Perennials		Annuals		Perennials		Annuals	
Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Drought KWB*	0.628***	0.207*	-0.571***	-0.131*	0.078***	0.029*	-0.083***	-0.028**
	(0.154)	(0.105)	(0.094)	(0.074)	(0.011)	(0.015)	(0.011)	(0.013)
Operator FE	No	Yes	No	Yes	No	Yes	No	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
WD FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.201	0.788	0.220	0.824	0.240	0.858	0.252	0.862
Observations	27686	27308	27686	27308	27686	27308	27686	27308

Note: Standard errors (in parenthesis) clustered at the Operator and Water District level. * $p<0.10$, ** $p<0.05$, *** $p<0.01$

Table 4: Panel Estimates of the Effect of Neighboring the KWB and Droughts on Cultivation Decisions

	Δarcsinh (area)				Δshare			
	Perennials		Annuals		Perennials		Annuals	
Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Drought Rosedale*	-0.002	0.034	-0.297***	-0.243***	0.050***	0.037***	-0.042***	-0.032***
	(0.044)	(0.062)	(0.059)	(0.074)	(0.008)	(0.010)	(0.008)	(0.009)
Operator FE	No	Yes	No	Yes	No	Yes	No	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
WD FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.242	0.817	0.244	0.839	0.265	0.871	0.279	0.874
Observations	21481	21115	21481	21115	21481	21115	21481	21115

Note: Standard errors (in parenthesis) clustered at the Permittee and Water District level. * p<0.10, ** p<0.05, *** p<0.01