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

Session Title: Farmer adaptations to climate and environmental change

Invited paper presented at the 2020 Annual Meeting of the Allied Social Sciences Association (ASSA), January 3-5, 2020 in San Diego, CA

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

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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 21-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.

Section 1: Introduction

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

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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 & Binswanger, 1992). Farmers adjust their crop choice and inputs in response to observed or forecast changes in seasonal rainfall (Rosenzweig & 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 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 decisions, significantly affecting both cropping and investment decisions (Feinerman & Tsur, 2014; Koundouri, Nauges, & Tzouvelekas, 2006; Marques, Lund, & 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 & 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, & Touma, 2015; Mallakpour, Sadegh, & AghaKouchak, 2018; Swain, Langenbrunner, Neelin, & Hall, 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, Wang, Carrillo, & Ault, 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, Cayan, Franco, Fisher, & Ziaja, 2018). 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 & 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 & Lund, 2012; Tanaka et al., 2006).

In the following section, we provide an overview of the climatological and agricultural setting for the study. We then introduce a similar theoretical model to provide insights into the role of drought risk in determining the relative value of annual and perennial crops. Section 4 introduces the data and empirical strategy, Section 5 gives results and Section 6 concludes.

Section 2: 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 (Fankhauser, 2019). Agricultural land is divided into 23 irrigation districts (Figure 1c), 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 and vegetable crops, toward perennial nut crops (Figure 1b). In 2000, annual crops, primarily cotton, alfalfa, and wheat made up 58% of crop land in Kern while perennial crops,
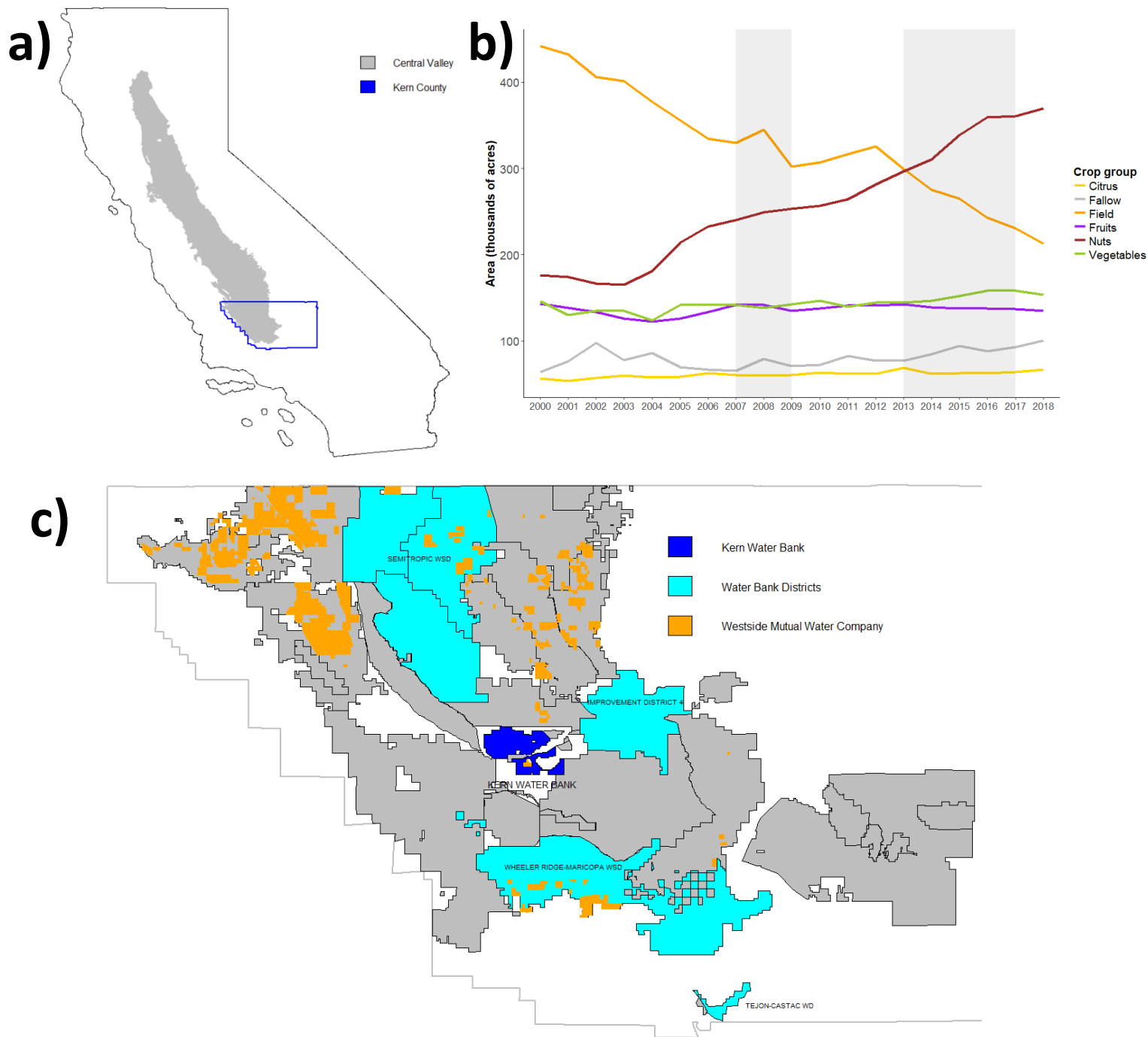
Figure 1: a) Location of Kern County and the Central Valley within California b) Evolution of agriculture in Kern county, 2000-2018. Shaded areas mark years classified as "critically dry" in the San Joaquin valley by the California Department of Water Resources (CDWR) c) Location of the Kern Water Bank, member irrigation districts, plots associated with the Westside Mutual Water Company, and other non-member irrigation districts within Kern County

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 1c). 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 and because they are typically grown with more efficient but capital-intensive irrigation systems (Zilberman et al., 2002). 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 serval 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. This dynamic induces large variation in the 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). A 2014 sale of water in Kern County, in the middle of an intense, multi-year drought, received almost 20 bids at $1,000 per acre-foot or higher (Henry, 2014).

This pattern would suggest the opportunity for intertemporal arbitrage of water, but 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, and therefore the world, is the Kern Water Bank (KWB). Since beginning operations in 1998, it has accounted for over 40% of the balances of all groundwater banks in California and over 80% of the agricultural water banking capacity in Kern County (Hanak & Stryjewski, 2012). It is located on 20,000 acres of sandy soil in the center of the agricultural area of Kern County (Figure 1c). 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.

Members of the KWB contribute some of their surface water allocations in wet years to the water bank in return for access to water at relatively low marginal cost during periods of scarcity. In other words, ownership of the KWB produces 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 unique 21-year dataset showing planting decisions of all landowners in Kern County.

Section 3: 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 farmer faces drought risk, d, assumed to follow a Bernoulli distribution parameterized with probability p and 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, since 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:

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

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 gestation 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:

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

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:

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

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 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 which is linear in p with an intercept of $\frac{\pi_a}{r}$ and a constant slope of $-\frac{p}{r}$ (green line). The expected NPV of perennial production is a decreasing and strictly convex function of p with an intercept of $\frac{1}{(1+r)^m}\frac{\pi_p}{r} - K$ (orange 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. $\frac{1}{(1+r)^m}\frac{\pi_p}{r} - K > \frac{\pi_a}{r}$).
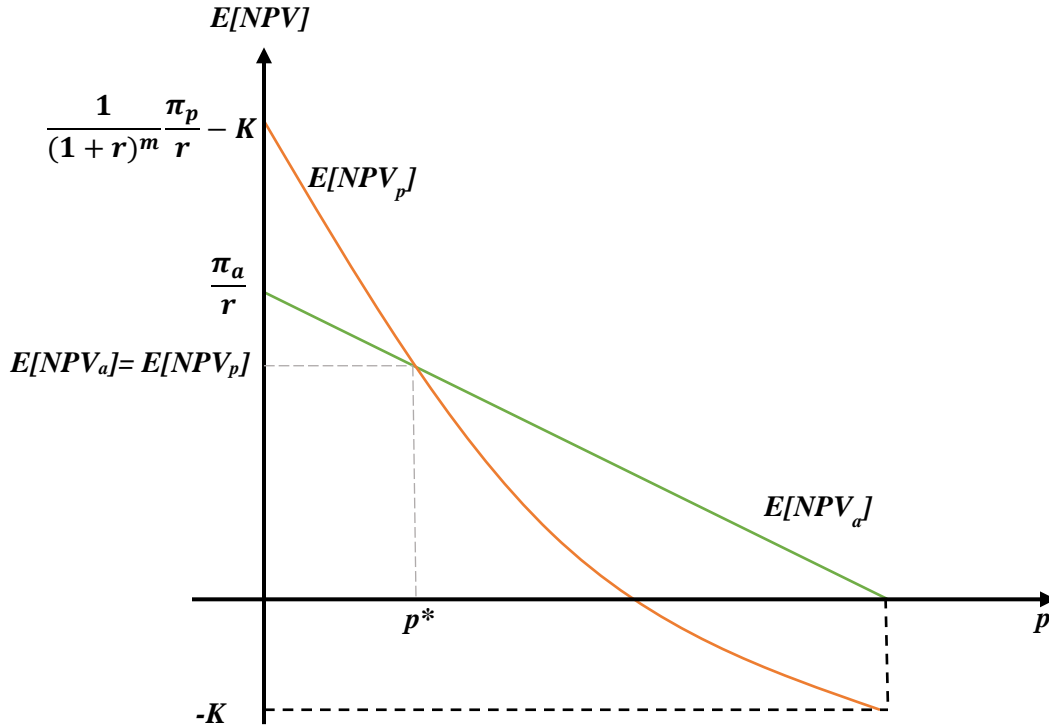
Figure 2. Expected NPV of annual (green) and perennial (orange) as a function of annual drought risk (*p*)

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. 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 the p, and should therefore be associated with expansion of perennial crops.

Section 4: Data and Empirical Strategy

We test this hypothesis using a 21-year panel giving the geographic boundaries, operator, and crop grown for all agricultural areas in Kern County (Kern County, 2019). Plot boundaries are available annually since 1997 (see Table A1). Maps of plot areas in 2000 and 2018 included in our working sample are shown in Figure A1. This shows the widespread switch from field crops to nut trees shown in Figure 1a, 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 can not 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 permit holders 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, 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 a classification given in Table A2.

With a long enough dataset, a natural empirical strategy would be a difference-in-difference examining change in the rate of perennial expansion after establishment of the KWB in member districts. Unfortunately, our data starts after establishment of the bank. Therefore, we first

present results of a long-differences estimation, comparing the change in perennial area for plots inside vs outside the KWB over the period of our data:

$$\Delta Crop_{ij} = KWB_j + \mu_i + \varepsilon_{ij}$$

Where $\Delta Crop_{ij}$ is the change in the share or the area of either annual or perennial crop between the end period (2014-2018) and the start period (1997-2001) for operator i in water district j, KWB is an indicator variable indicating whether that plot is 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 in levels between plots. The residuals are clustered at the operator and water-district level.

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 19 years in our sample were categorized as "critically dry" by the California Department of Natural Resources (namely 2007, 2008, 2013, 2014, and 2015).

$$Crop_{ijt} = Drought_t * KWB_j + \mu_i + \theta_t + \vartheta_j + \varepsilon_{ijt}$$

Where $Crop_{ijt}$ is the either the share or the area of either annual or perennial crops in land belonging to 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. θ_t and ϑ_j are fixed-effects that flexibly control for common time-varying shocks and time-invariant characteristics. In all regressions, residuals are clustered at the operator and water-district level.

In addition to these specifications, we also present results that include operator fixed-effects. These help alleviate concerns that certain characteristics of growers within irrigation districts that are part of the KWB made them more likely to switch into perennial crops. These fixed-effects control for all time-invariant differences between the individuals or companies farming in Kern County, but 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 A2. Thirty percent of operators farm in more than one irrigation district and 12% in 3 or more.

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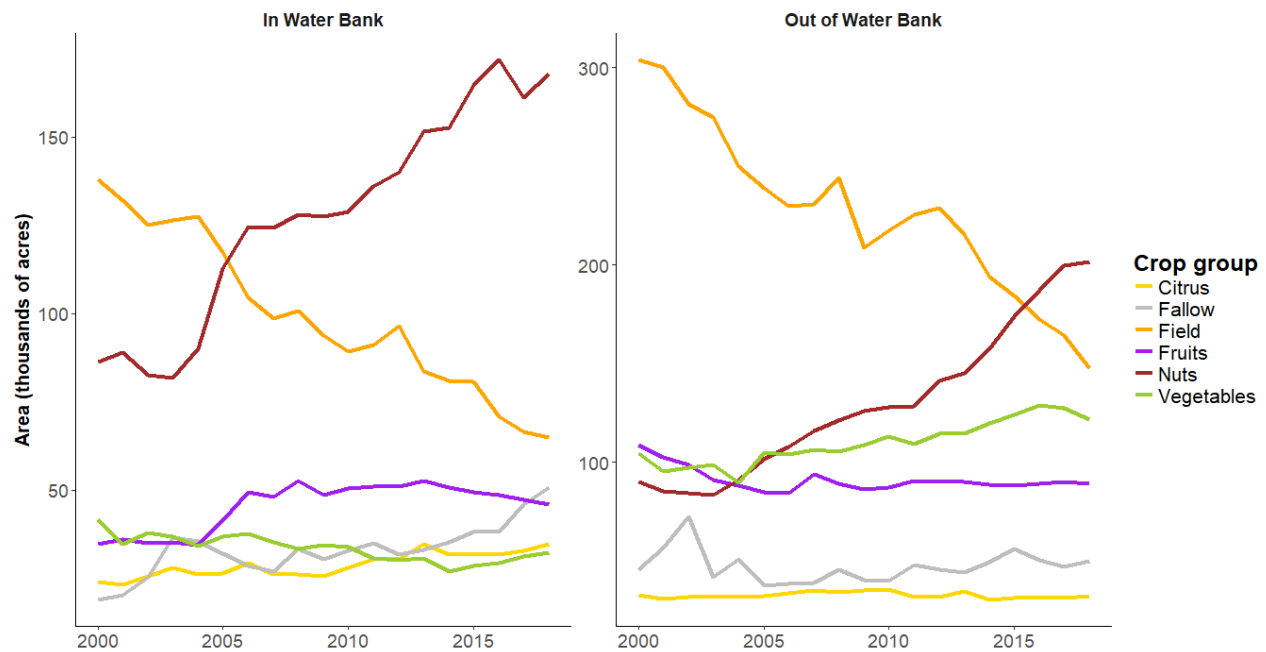
Figure 3: Change in cropping patterns in Kern County for land in vs outside of the KWB.

These observations are confirmed by results from the long-differences regression, shown in Table 1. Between the periods 1997-2001 and 2014-2018, we see evidence of a faster switch away from annual crops and into perennials within the KWB. The average area of perennial plots grew 52% faster for holdings within the KWB compared to outside of it, while the area of annuals shrank 67% faster. Controlling for operator fixed-effects, we see evidence that operators

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with plots both inside and outside the KWB chose to switch expand perennials faster in the plots within the KWB compared to outside it.

There are some water districts in the east side of Kern County which had a high fraction of perennial crops in the start of the period, mostly specializing in grape production. Water for these crops comes from the local Kern River, supplemented by groundwater pumping and produced water from the oil and gas industry during dry years (KCWA, 2011). Inclusion of these might change the interpretation of our findings, and so we also report result that exclude four water districts with average share of perennial crops greater that 85% in the first three years of the dataset. Results shown in Table A3 shows that excluding these districts does not change the size or sign of the estimated coefficients, but does substantially reduce power so that findings on perennial area are not significant. However, we still see evidence that the share of perennials increased more rapidly (and the share of annual crops decreased more rapidly) within the KWB compared to outside it.

Table 1: Long-difference estimates of the effect of water banking on cultivation decisions

	asinh(area)				Share			
	Perennials		Annuals		Perennials		Annuals	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Banking	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

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

Table 2 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).

Table 2: Panel estimates of the effect of water banking and droughts on cultivation decisions

	asinh(area)				Share			
	Perennials		Annuals		Perennials		Annuals	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
*Bank*Drought*	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

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

Finally, we 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 bank members, 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 (State of California 2016). 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. Table 3 shows results from a similar specification to that shown in Table 2, controlling for year and irrigation district fixed-effects, while estimating the effect on annual and perennial crop areas from being in Rosedale Rio-Bravo 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).

Table 3: Panel estimates of the effect of neighboring the KWB and droughts on cultivation decisions

	asinh(area)				Share			
	Perennials		Annuals		Perennials		Annuals	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Rosedale*Drought	-0.032	0.023	-0.283***	-0.230**	0.046***	0.035***	-0.040***	-0.031***
	(0.045)	(0.058)	(0.066)	(0.079)	(0.009)	(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	0.227	0.821	0.213	0.842	0.245	0.872	0.253	0.874
Observations	19308	18929	19308	18929	19308	18929	19308	18929

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

Section 6: 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. Given these findings, it is perhaps unsurprising that more recent years have seen an expansion of groundwater banking in Kern County, beyond the KWB (Hanak & Stryjewski, 2012). 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.

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Appendix

First and Second Derivatives of E[NPV$_a$] w.r.t. Drought Risk p

The first derivative of equation (3) with respect to p is given by:

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

which is negative for $0<p<1$.

The second derivative of equation (4) is positive (see Appendix) making $E[NPV_p]$ a convex function of p.

The second derivative of equation (3) is given by:

$$\frac{\partial^2 E[NPV_p]}{\partial p^2} = [(1-p)[2(1-p) + m(r+p)] + (r+p)[m(1-p) + m(m-1)(r+p)]]$$
$$* \frac{(1-p)^{m-2}}{(1+r)^m} * \frac{\pi_p}{(r+p)^3}$$

which is positive for $m>1$ making $E[NPV_p]$ a strictly convex function of p.

Year	Plots mapped	Plots permitted	% Mapped
1997	9,447	12,793	74
1998	10,311	13,309	77
1999	12,868	13,074	98
2000	13,483	13,483	100
2001	13,336	13,336	100
2002	13,217	13,217	100
2003	13,162	13,162	100
2004	12,946	12,946	100
2005	12,803	12,803	100
2006	12,923	12,923	100
2007	13,257	13,257	100
2008	13,477	13,477	100
2009	13,081	13,081	100
2010	13,150	13,150	100
2011	13,599	13,599	100
2012	13,942	13,942	100
2013	13,997	13,997	100
2014	13,906	13,906	100
2015	14,057	14,057	100
2016	14,017	14,017	100
2017	14,287	14,287	100
2018	14,437	14,437	100

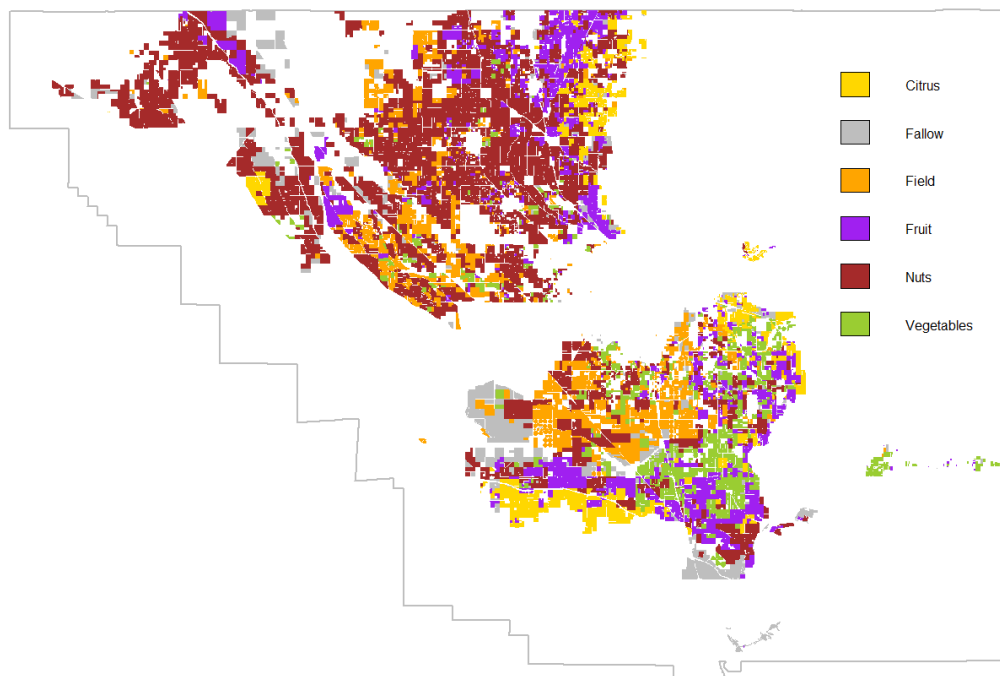Source: http://www.kernag.com/gis/gis-data.asp

Table A1: Number of plots contained in the Kern county crop boundaries, 1997-2018
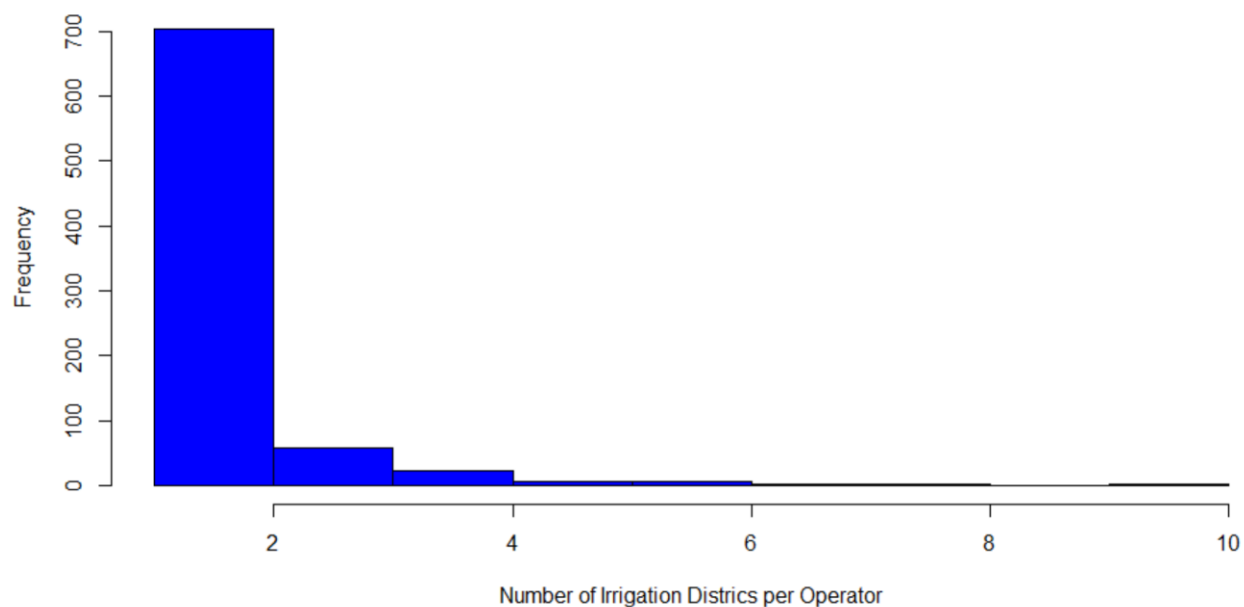
a) 2000
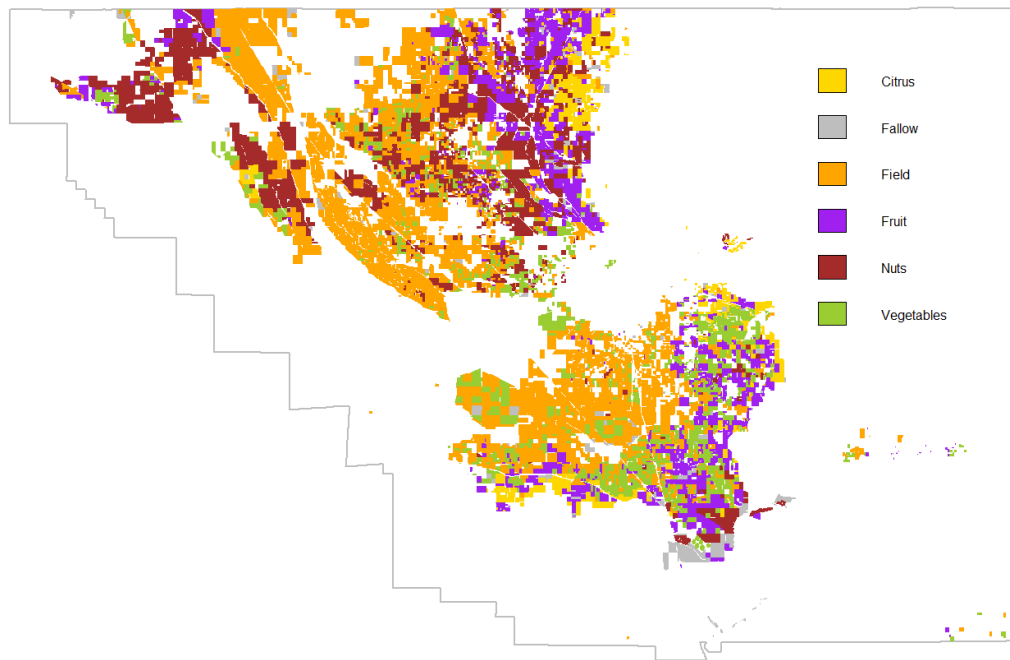
b) 2018

Figure A1. Plot boundaries of Kern county in 2000 and 2018 by major crop group.

Figure A2: Number of irrigation districts each operator has plots in for 2018.

Perennials			Annual		
Crop category	Crop	% of total acreage	Crop category	Crop	% of total acreage
Nuts	Almond	40.9	Field	Wheat	19.1
Nuts	Pistachio	23.7	Field	Alfalfa	12.1
Fruit	Grape	13.5	Vegetable	Carrot	10.6
Citrus	Orange	5.9	Field	Corn	8.3
Citrus	Tangerine	4.4	Vegetable	Potato	7.8
Fruit	Grape, Wine	4.1	Field	Cotton	7.5
Fruit	Pomegranate	1.5	Field	Sorghum	4.0
Fruit	Grape, Raisin	1.2	Vegetable	Tomatoes	2.4
Fruit	Grape, Organic	1.0	Vegetable	Onions	2.2
Fruit	Cherry	0.8	Field	Triticale	2.0
Other	Other	3.0	Other	Other	23.56

Table A2: Important perennial and annual crops in Kern County in 2018

	asinh(area)				Share			
	Perennials		Annuals		Perennials		Annuals	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Banking	0.476	0.146	-0.624	-0.545**	0.139*	0.106**	-0.146*	-0.121**
	(0.297)	(0.318)	(0.370)	(0.237)	(0.079)	(0.043)	(0.075)	(0.041)
Permittee FE	No	Yes	No	Yes	No	Yes	No	Yes
R-squared	0.009	0.661	0.012	0.613	0.033	0.679	0.039	0.702
Observations	559	271	559	271	559	271	559	271

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

Table A3: Results show the same regression reported in Table1 in the main text, but excluding water districts with where the average share of perennials by operator was greater than 85% in the 1997-1999 period (Cawelo WD, Delano Earlimart ID, Olcese WD, and Rag Gulch WD).

	asinh(area)				Share			
	Perennials		Annuals		Perennials		Annuals	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
*Bank*Drought*	0.576***	0.200*	-0.559***	-0.121	0.075***	0.029*	-0.081***	-0.027*
	(0.137)	(0.106)	(0.099)	(0.077)	(0.011)	(0.016)	(0.012)	(0.013)
Permittee 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	0.187	0.788	0.189	0.823	0.217	0.857	0.226	0.860
Observations	25463	25064	25463	25064	25463	25064	25463	25064

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

Table A4: Results show the same regression reported in Table2 in the main text, but excluding water districts with where the average share of perennials by operator was greater than 85% in the 1997-1999 period (Cawelo WD, Delano Earlimart ID, Olcese WD, and Rag Gulch WD).

	asinh(area)				Share			
	Perennials		Annuals		Perennials		Annuals	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Rosedale*Drought	-0.032	0.023	-0.283***	-0.230**	0.046***	0.035***	-0.040***	-0.031***
	(0.045)	(0.058)	(0.066)	(0.079)	(0.009)	(0.010)	(0.008)	(0.009)
Permittee 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	0.227	0.821	0.213	0.842	0.245	0.872	0.253	0.874
Observations	19308	18929	19308	18929	19308	18929	19308	18929

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

Table A5: Results show the same regression reported in Table 3 in the main text, but excluding water districts with where the average share of perennials by operator was greater than 85% in the 1997-1999 period (Cawelo WD, Delano Earlimart ID, Olcese WD, and Rag Gulch WD).