Solving the Common-Pool Resource Problem Using Markets?

– A Study of the Surface Water Trading and Groundwater Depletion in California*

Hao Zhao

Caltech

Abstract

This paper examines how a surface water market affects the performance of a groundwater basin that is in open access. The market only solves the groundwater over-extraction problem when pumping costs are high, while market failure arises when the common pool resource (CPR) problem is severe. I build a theoretical model to analyze the agricultural water use in California Central Valley. The model establishes the link between the efficacy of surface water market and the farmers' crop choices in response to water supply changes. I use a micro level crop choice data to test the theory and find that the farmers rarely react to short-term water supply variations. In particular, crop acreage does not fall during droughts. This implies that pumping costs are low and sellers replace whatever amount they sell with groundwater. Therefore, surface water trade is inefficient when taking into account the depletion of groundwater resource and should be curtailed until the CPR problem is addressed.

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1 Introduction

Economists have long argued that markets allocate resources efficiently [Smith (1937); Walras (1874); Marshall (1895); Coase (1960)]. For example, water markets have been established in many places around the world to cope with water scarcity [Bjornlund (2003); Bithas (2008)]. In California, the property rights that allowed private capture of water from streams to support mining and farming, laid the foundation of water trade [Libecap (2007)]. Moreover, a surface water market should help address the mismatch of historical water rights allocation and current demand within and beyond agriculture. Yet there remain strong reservations in the agricultural community, principally because of fears that water will be "stolen" by urban communities [Libecap (2008)]. Meanwhile there are also concerns that trading surface water accelerates aquifer depletion since surface water is a substitute for groundwater [Hanak (2005)]. These are the focus of this paper.

How can the surface water market affect the performance of groundwater basins? The answer depends on the severity of common-pool resource (CPR) problem confronting the groundwater system. This paper investigates this issue using data from agricultural output and water supply in the Central Valley of California. I build a model to establish the implications of surface water trade in a variety of property rights settings for groundwater. I then test which of these conditions apply to California. The empirical study shows that the evolution of crop patterns over space and time are consistent with the assumptions that surface and ground water are perfect substitutes in the economy and the groundwater basin is in open access. I then demonstrate that the private trade between agricultural water districts leads to both lower overall social efficiency and unsustainability of the groundwater basin.

For most aquifers, scholars and policy makers only have access to data on surface water consumption at the district level. In particular, all estimates of groundwater consumption are obtained as a residual difference between expected water consumption by activity and realized surface water application. One reason for this is that, as is the case in the Central

Valley, most wells are unmetered. To offset this lack of data, I develop a theoretical model that details how crops respond to different property rights regimes. I evaluate the social welfare change when the agricultural economy moves from autarky to water markets, and compare the two regimes with the social planer's optimal allocation. The efficacy of market depends on the marginal cost of groundwater use.

With a high enough pumping cost, the marginal cost of using groundwater equals its marginal return in the economy (henceforth this case will be referred to as the water constraint binds). In this case, if only the high-value users pump groundwater, the surface water market reduces overall reliance on groundwater because low-value farmers will sell their surface water to high-value users and will not pump groundwater to replace the surface water they sold. If the low-value farmers also use groundwater, as long as the water constraint binds, the overall extraction in the economy remains unchanged after reallocating surface water from low-value to high-value users. Under both circumstances, the surface water market is efficient in reallocating resource while not causing extra depletion of the aquifer.

With a low enough pumping cost, the low-value farmers find it still profitable to use groundwater until all their land has been farmed (henceforth this case will be referred to as the land constraint binds). With a surface water market, farmers who have access to groundwater will sell their surface water to farmers who do not and then pump the amount sold off to continue their low-value farming. The rise of a surface water market thus speeds up the depletion of groundwater aquifer and is not necessarily efficient.

The theoretical model establishes the link between market efficiency and the underlying condition of the economy. It is important to note that in this paper the effectiveness of market solution, or the "social welfare", only depends on whether the water or land constraint binds in the economy. A recent law in California [SGMA (2014)] defines the "social optimum" as maintaining the sustainability of the basin (average extraction equals recharge). My model is consistent with the legislation as it accounts for the difference of groundwater depletion rate under different institutions. When a market is inefficient in allocating resources, it leads to lower social welfare because it accelerates the depletion of the aquifer.

I use a micro-level crop choice data published by Kern County Department of Agriculture to test the hypotheses derived from the theoretical model. The dataset includes geocoded crop choice for each plot of farmland in Kern County from 1999 to 2016. Combining the crop choices with water supply data that I collected from various sources allows me to estimate the reaction of individual crop choice to changes of water supply, hence identifying whether the water or land constraint binds in the Central Valley.

The key empirical finding is that fallowing[1] is invariant to surface water supply. It does not change with annual surface water delivery or the extent of water sales. This fundamental invariance implies that whenever the low-value users sell more surface water to high-value users without access to groundwater, they pump more groundwater to satisfy the water demand of their crops. This is consistent with the theoretical predictions of the model only when the land constraint binds and is not consistent with its prediction when the water constraint binds. Therefore, the surface water market in the Central Valley is not efficient in reallocating resource and it has a negative impact for the sustainability of the basin.

This paper offers a telling example of the classical theory of the second best [Lipsey and Lancaster (1956)]: Without an integrated market for surface and ground water upon the cap-and-trade practice, it would be better to postpone the implementation of a surface water market if the groundwater basin is unregulated. This conceptual framework can extend to any situation where a market is put in place for a private resource that is a substitute to a CPR. For example in fishery, a transferable quota system out of the regulation in certain species will cause less efficient fishermen to sell their quota and transit to technologies that help to catch the non-targeted species, leading to depletion of those species that remain in

[1]There are other reasons why farmers fallow their land. Sometimes a farmer fallows her land for a period as part of crop rotation in order to restore fertility. This paper concerns fallowing that results from water scarcity. As will shown by the plot-level data, most of the fallowing in the data persists over time, implying that the farmland is no longer actively farmed.

open access [Squires et al. (1998)]. The emission trading system also has an unintended substitute effect that exacerbates air pollution. As documented by Martin et al. (2014), firms tend to sell their emission quota and reallocate to regions with less strict environmental restrictions after the implementation of the European Union Emissions Trading System. This results a severer pollution in those unregulated regions and a potential higher global leakage.

The paper is structured as follows. Section 2 reviews the literature on the subject. Section 3 provides some necessary background of water markets in the Central Valley of California. Section 4 presents the model that illustrates how a surface water market affects the depletion of a groundwater basin. Section 5 presents the empirical analysis including the tests on the model implications. The final section concludes.

2 Literature Review

This paper contributes to the literature on water market by revealing the unintended consequence of a surface water market on an open access groundwater system. Brozovic et al. (2002), Chong and Sunding (2006), Grafton et al. (2012) and many others have written about the efficiency gain from surface water market without considering its consequences on aquifers. Srivastava et al. (2009) examined groundwater market in India, noting that it leads to depletion of groundwater tables although it helps small and marginal farmers realize better yields. In response to the 2014 legislation, scholars have been evaluating the cap-and-trade regime of groundwater [Nylen et al. (2017); Bruno (2017), (2018); Duym (2018)]. Culp et al. (2014) expressed the same concern on restricting groundwater pumping when implementing a water market.

Findings in this paper echoes Ostrom's exploration of common property management institutions [Ostrom (1990); Ostrom, Gardner and Walker (1994); Ostrom and Walker (2000); Ostrom (2002)]. According to Ostrom, managing a commons requires defining clear group boundaries, which is also necessary for a market solution to work.

The two closest papers to this one are probably Howitt (1994) and Knapp et al. (2003). Those studies focused on California's first public water market in 1990s and reached a similar conclusion that a surface water market accelerates the decline of the water table and the source region only benefits from the market if the groundwater basin is depleted at an efficient rate. This early work mostly depended on county or district level data, and calculated aggregate water demand elasticity to estimate the difference of groundwater extraction under different regimes. My empirical analysis based on micro level crop choice data shows that such estimation is inaccurate as the calculation of aggregate elasticity does not condition on other factors. Instead, I find that crop acreage is actually not sensitive to water supply changes and the transition of crops is mainly driven by price and spatial influences.

Moreover, previous work generally relied on the accounting model to calculate groundwater extraction (residual of aggregate crop demand minus surface water supply), and requires a strict bathtub assumption for estimation of groundwater depletion rate. My work is based on a theoretical model that lays out how an individual farmer reacts as water supply conditions change and my empirical analysis examines the individual groundwater use decision without relying on the accounting model and the bathtub condition, both of which have been criticized for their inaccuracy.

3 Background: Water market in the Central Valley of California

In 2012, California produced nearly $45 billion in agricultural products, or about one-tenth of the total for the entire nation [Pacific Institute and Natural Resources Defense Council (2014)]. The Central Valley is the center of the state's agricultural production. It consumes around 70% of the state's total water use. How institutions manage that water is critical for the state's future. It also forms a valuable laboratory to understand the interaction between surface and ground water. The marginal value of water use varies dramatically across regions with different types of crops, as well as between agricultural and urban users. Given agriculture's share in total water use and frequent water shortage in the state, economists are promoting water markets to allocate water in a more efficient manner [Murphy et al. (2000); Culp et al. (2014)].

California's first public water market took off in the early 1990s as an outcome of the prolonged drought. The state's Department of Water Resource (DWR) and the federal Bureau of Reclamation (USBR) conducted a series of dry-year water trade programs, including the California Drought Water Bank examined in Howitt (1994). According to that paper, about 17% of water purchased by the Bank came from north of the state where surface water was in excess of water demand, about a half came from farmers who fallowed their low-value crops and a third came from farmers who then increased their groundwater extraction.

Despite the increased overall income and employment documented by Howitt, communities in the source regions have raised concerns about the potential adverse effect of the water market on local economy and groundwater aquifer [Hanak (2005)]. By 2002, 22 of the state's 58 counties had issued ordinances that required a permit to export groundwater or to extract groundwater used in substitution for exported surface water [Hanak (2003)]. As a result trade in water across counties may be coming to a standstill.

The resistance to the large-scale water market by the agricultural communities continues to this day. California water authorities have still not established a statewide water exchange. However, as the sources of most surface water supply, the state water project (SWP) and central valley project (CVP) actually allow water transfer between their contractors. Local surface water rights owners, for example the City of Bakersfield who owns the primary Kern River water rights, have also been involved in transfer contracts to supply surplus water to their neighbors. Brewer et al. (2008) and Howitt and Hanak (2005) report consistent water transfers in California from 1980s to 2000s.

Under the *de facto* loose control, a private water market has emerged as a natural adaptation to water supply imbalance across agricultural water districts. Private water transfers between agricultural districts have increased in response to the decline in surface water delivery. On one hand, districts without groundwater have larger a import demand for irrigation water; on the other hand, faced with high prices, districts with groundwater are now willing to sell their surface water entitlement and turn to the alternative water source. The water sold off could be temporary surface water delivery from SWP or CVP, or storage of water that the districts put in the water bank during water surplus period[2].

Water districts with access to groundwater sell tens of thousands of acre feet of surface water to districts without groundwater every year and, as I will show, farmers then extract additional groundwater to replace what they sold off. As a result, the overall farming acreage in the Central Valley has not changed in the last twenty years despite frequent droughts and a large drop in surface water delivery. The overall demand for irrigation water has grown and become less flexible due to a rapid rise in permanent crop acreage. Permanent crops are more water intensive and require irrigation every year. Not surprisingly, the groundwater basins are in critical overdraft across the Central Valley.

In next section, I derive the theoretical framework of how a surface water market affects the groundwater basin depletion and social welfare. A market can lead to higher social welfare or not, depending on whether it successfully reallocates resource from low-value to high-value users without speeding up the depletion of CPR system. The model is designed to analyze agricultural water use in California Central Valley, and it is easily to be applied to the case including both agricultural and urban users, as well as other situations where a market is put in place for a private resource that is a perfect substitute to a common pool resource.

[2]According to the board meeting memo of Berrenda Mesa Water District in November 5, 2015, its neighboring district, Buena Vista Water Storage District (BVWSD) has offered to sell its 21,000 AF of banked water through a co-managed water bank. Based on an interview with the engineer in BVWSD, it has also sold surface water supply to its neighboring districts in 2014 and pumped water that year to replace the water sold off.

4 Theoretical Model: Depletion of groundwater basin with surface water market

The decision marker is called a "farmer". It refers to whomever (owner-operator, tenant or landlord) makes the key decisions. In the Valley, due to frequent drought and upstream environmental concerns in recent decades, surface water supplies are highly uncertain. Farmers' residual demands for irrigation water are satisfied by pumping from the valley's aquifer. The model examines how farmers choose what crops to grow and how much water to pump based on water supply conditions and the suitability of their land to different crops. I use the analysis to compare aggregate extraction under different institutional regimes.

Water supply

I consider a two-period, no-discounting, agricultural economy where water is the key input in production. For simplicity, all farms are of equal size, D[3], and both annual and permanent crops require 1 unit of water. Therefore, every farmer demands D units of water to fully irrigate her land. A farmer may use water from up to two sources: surface and ground water. The two are perfect substitutes to each other. I assume a farmer always has unsatisfied water demand after using up her own surface water supply.

I assume that surface water (W^s) is delivered each period by an outside agency in equal quantity to each farm[4]. That amount depends on the realized state s. $s \in \{H, L\}$ where H denotes a wet year and L denotes a dry year. The realized state in each period is i.i.d. from

[3]The model ignores any effect of the size of farm or identity of farmer. Tests of the theory are also robust at farm, plot or acre level despite different degrees of measurement error. Although big farms might enjoy an advantage in capital investments or in moving water around, the organization of water districts mitigates this advantage to a large extent. In particular surface water allocation is per acre based so that farms of various sizes have equal rights to water. See the empirical analysis later for more evidence.

[4]Surface water delivery per acre actually varies across water districts as their water rights per acre differ. As I will show in the model results, the spatial variation of surface water supply does not affect the equilibrium outcome in the regime with a social planner or a surface water market since surface water will always be

a binary distribution: $\Pr(W^s = W^L) = q$ and $\Pr(W^s = W^H) = 1 - q$. As surface water is generally cheaper than groundwater, I normalize the cost of surface water to 0.

Groundwater is pumped from the aquifer at a per unit cost $c^g > 0$[5]. It is a CPR so in the absence of regulation, everyone with access to groundwater can extract as much as they want up to their well's capacity (we assume that well capacity does not bind). Because of the externalities of CPR use, extraction has a social cost as well. The social cost includes future increased pumping lift and associated energy consumption due to a lower water table. It also includes the cost of drilling deeper wells as groundwater may become unreachable with current wells. There are also important environmental impacts from rapid depletion of the aquifer like land subsidence and increased water salinity. For now, I model all these costs in a reduced form. I assume the social cost is paid each period as a function of that period's aggregate extraction and is shared equally per acre. The overall extraction E produces a social cost $g(E)$ with $g'(E) \geq 0$ and $g''(E) \geq 0$. As $g(.)$ is a monotonic function of E, I make no specific assumption about $g(.)$. Instead, I use E to measure the social cost.

Farmers (and farms) can be divided into two subgroups: those who only use surface water as F^s and those who have access to groundwater as F^g.

Crop choice

At each period, each farmer decides between an annual crop (a) and a permanent crop (p). The permanent crop requires a one-time fixed cost c^o to plant, which captures the investment needed before a harvest can be brought in[6], and pays back $r^p \in (\frac{1}{2}c^o, c^o)$ every period. The

reallocated to high-value farmers. In the autarky equilibrium, farmer with more surface water rights can plant more permanents. Both model implications are further confirmed by the empirical tests.

[5]Pumping depth varies across the basin, so does the pumping cost. I leave this aside because how the individual pumping cost varies only affects the identify of the marginal groundwater user. It has no influences on the comparison of different regimes in the model.

[6]It takes 7-10 years for pistachio trees to reach significant production; almonds start to bear in the third year and reach full production after 5-6 years.

annual crop requires no fixed cost to grow and pays back r^a each period. The permanent crop needs to be irrigated in both periods to have a return in the second period (otherwise the crop dies and must be replanted).

The return of annuals (r^a) and the fixed cost of planting permanent crops (c^o) do not vary across space or time, while the return of permanent crops differs over space. r_i^p reflects the heterogeneity of land quality across farms. I relabel the agents such that $r_i^p > r_j^p$ if $i < j$ (famer i has a farm that is more productive in permanent crops than farmer j if $i < j$). I assume that there is a farmer i^*, such that for all $i > i^*$, the average two-period return of permanent crops is lower than the return of annuals: $r_i^p - \frac{1}{2}c^o < r^a$ and for all $i \leq i^*$: $r_i^p - \frac{1}{2}c^o > r^a$. I also assume $c^g < r^a$, therefore it is profitable for all farmers to use groundwater[7].

I denote those with index $i > i^*$ as group F^a since they always prefer annual to permanent crops. For those $i \leq i^*$, they belong to group F^p since they prefer permanents to annuals if they receive enough water supply.

Recall that the farmers also differ by their access to groundwater. The land quaility and water supply conditions produce four types of farmers (by slightly abuse of the notation, F also denote the farmland by the farmers):

1. F^{sa}: annual crop farmers restricted to surface water. $F^{sa} = F^s \cap F^a$;
2. F^{sp}: permanent crop farmers restricted to surface water. $F^{sp} = F^s \cap F^p$;
3. F^{ga}: annual crop farmers with access to groundwater. $F^{ga} = F^g \cap F^a$;
4. F^{gp}: permanent crop farmers with access to groundwater. $F^{gp} = F^g \cap F^p$.

[7]A farm with land quality low enough ($\max\{r^a, r_i^p - \frac{1}{2}c^o\} < c^g$) can only operate in the autarky regime. With an opportunity to trade, the farm should sell its surface water rights and exit since overall surface water is in shortage. To keep a consistent count of farmland, my model only considers active farmland with high enough quality that using groundwater is profitable in some situation. Adding low quality land in my model will increase the efficiency gain from a surface water market.

There are m^{sa}, m^{sp}, m^{ga} and m^{gp} farmers in each group. I assume the number of groundwater users $m^g = m^{ga} + m^{gp}$ is large, so the classic CPR problem arises.

Surface water market

The surface water market allows agents to exchange surface water. As there is no product differentiation, I assume the sellers are involved in Bertrand competition, and water's transfer price thus equals the opportunity cost for sellers. If the sellers only use surface water, the price of water equals the return of using water on their own land. If the sellers pump groundwater, the price equals the pumping cost c^g plus whatever social cost they individually have to bear.

Timing

In each period, events unfold as follows: First, every farmer observes the realized state of surface water supply. Each farmer then decides what to plant. For permanent crops, in period 1, she decides what acreage to plant and in period 2, she determines the fraction of existing crops to irrigate. For annual crops, she decides what acreage to plant for the current period. Second, if there is a water market, farmers can trade for surface water. Third, farmers may pump groundwater to irrigate her crops after using up their surface water supply. Finally, every groundwater user pays an equal share of the social cost.

I examine three regimes in this model. In the first regime, a social planner runs all the farmland together. He decides the overall extraction and crop choice to maximize the total social welfare. The second regime is autarky. Each farmer has her own water supply and water trade is prohibited. In the third regime, I introduce a market where farmers can trade their surface water. Groundwater remains open access in all cases.

I start with the social planner:

4.1 Social Planner

The social planner (SP) runs all farmland together. He can allocate the surface water wherever he wants although the groundwater can only be applied locally[8]. His endowment is therefore $\mathbf{D} = mD$ of farmland and surface water supply $\mathbf{W}^s = mW^s$.

Social welfare in this model is defined as the total profit from the crops minus the cost of extraction. At period t, it is:

$$R_t = r_t^p N_t^p + r^a N_t^a - g(E_t) - c^g E_t \tag{1}$$

where r_t^p is the average return on permanent crop land that sums up to N_t^p. In each period t, SP chooses a portfolio (N_t^a, N_t^p) of annual and permanent crops subject to the land constraint $N_t^a + N_t^p \leq \mathbf{D}$. Because it is lower cost, SP will always use all the surface water before pumping groundwater. Extraction of groundwater equals the residual demand for water: $E_t = N_t^a + N_t^p - \mathbf{W}_t^s$.

I solve the SP's problem backward. In period 2, SP maximizes social welfare by choosing N_2^a and N_2^p:

$$\text{Period 2:} \quad \max_{N_2^a, N_2^p} R_2 = r_2^p N_2^p + r^a N_2^a - g(E_2) - c^g E_2 \tag{2}$$

with $E_2 = N_2^a + N_2^p - \mathbf{W}_2^s$.

Since it does not pay to grow new permanent crops in period 2 ($r_i^p < c^o$), period 2's permanent crop is subject to a resource constraint: $N_2^p \leq N_1^p$. Meanwhile, since permanent crop land F^p yields higher return than annual crop land F^a, SP always irrigates the existing permanent crops first: $N_2^P = N_1^P$ whenever $N_2^a > 0$.

[8] In a world where the supply of surface water is higher than the demand from regions without access to groundwater, optimality achieves if the social planner moves water to irrigate all high-quality land. This is not necessarily true when surface water supply is low relative to the demand of farmland without groundwater. Some high-quality land might remain fallowed even when all surface water is supplied to no groundwater area (efficiency will require moving some groundwater as well). The Central Valley is the former case.

SP's crop choice problem is equivalent to an optimal extraction problem. He faces two sets of constraints when choosing how much groundwater to extract. Extraction has an upper bound from the land constraint:

$$\text{Land Constraint:} \quad E_2 \leq \mathbf{D}^s = \mathbf{D} - \mathbf{W}_2^s \tag{3}$$

There is also a water constraint that SP will not pump at a higher cost than the return to groundwater. Depending on the marginal use of water, it needs to either satisfy a water constraint (4) or equalize marginal cost and marginal return (5):

$$c^g + g'(E_2) \leq r^a \qquad \text{when} \quad N_2^a > 0 \tag{4}$$

$$\textit{or} \quad c^g + g'(E_2) = r_2^p > r^a \quad \text{when} \quad N_2^a = 0 \tag{5}$$

Three cases arise in period 2:

1. If surface water satisfies the demand from permanent crops, SP will pump to irrigate annuals.

2. If surface water is not enough for all permanents but c^g is low enough that it pays to plant annuals with groundwater, SP will irrigate all permanents first and then apply groundwater on the annuals.

3. If surface water is not enough for all permanents and c^g is large enough that it does not pay to plant annuals with groundwater, SP will irrigate permanent crops with groundwater until the marginal cost equals the marginal return.

For the first two cases, the marginal crop is annuals. The water constraint (4) matters so that the marginal cost of using groundwater is equal to or below the marginal return of annuals. For the third case, the marginal crop is permanents. Constraint (5) matters: the marginal cost of using groundwater equals the marginal return on farmland i after all land with quality higher than i is irrigated.

The model also has implications for the SP's decisions given that surface water supply varies. Indeed if groundwater is cheap SP grows annuals in both wet and dry years. But if groundwater is expensive to pump SP may decide to grow annuals only in wet years or even to never grow annuals. As we will see in the empirical section, in the Central Valley, substantial vegetables and field crops are harvested every year. That implies that annuals are always the marginal crop and henceforth I focus on that case.

When annual crops are at the margin ($N_2^a > 0$), either the land (equation 3) or water constraint (equation 4) binds in equilibrium. When groundwater is cheap, the land constraint binds. In other words, the social planner farms all land because the basin's sustainability is not a concern. In a water deficit state like California, fallowing is observed constantly in the Valley. Therefore I consider the solution with a binding water constraint and leave the land constraint case to further discussion.

In period 2, as the water constraint always binds, groundwater extraction is the same in dry and wet years: $E_2 = g'^{-1}(r^a - c^g)$. All permanent crops are irrigated and therefore the size of permanent crops remains unchanged: $N_2^p = N_1^p$. Any residual water goes to annuals: $N_2^a = W_2^s + E_2 - N_2^p$. For a given acreage of farmland, marginal cost of pumping is higher in dry years than wet years because of lower surface water supply. As a result, some annual crop land that is actively farmed in wet years will turn to fallowing in dry years.

In period 1, SP expects to irrigate all permanent crops in period 2. He chooses N_1^p and N_2^p to maximize the expected two-period sum of social welfare:

$$\text{Period 1:} \quad \max_{N_1^a, N_1^p} R_1 + \mathbb{E}(R_2) = (2r_1^p - c^o)N_1^p + r^a(N_1^a + \mathbb{E}(N_2^a)) - 2g(E) - 2c^g E \tag{6}$$

Given that all permanent crops will be irrigated in period 2, SP grows permanents on all F^p land since the average return is higher than annuals ($r_1^p - \frac{1}{2}c^o > r^a$): $N_1^p = m^g D$. Water constraint always binds so pumping is constant: $E = E_1 = E_2 = g'^{-1}(r^a - c^g)$. Residual water after satisfying demand of permanents goes to annual crops: $N_1^a = W_1^s + E - N_1^p$.

Only annual crop land is fallowed in either period. Since permanent crops are more valuable than annual crops, the social planner reallocates some surface water from F^a to F^{sp} to ensure irrigation of the high-value crops. F^{sa} land is fallowed, some of the F^{ga} land is also fallowed because the marginal cost of pumping has already reached the marginal return of annual crops (water constraint binds).

In summary, the overall extraction, crop acreage and social welfare in the social planner's case are:

$$
\begin{aligned}
E^{SP} &= g'^{-1}(r^a - c^g) && (7)\\
N_t^{p,SP} &= m^p D && (8)\\
N_t^{a,SP} &= W_t^s + E^{SP} - N_t^p && (9)\\
R_t^{SP} &= \sum_{i \in F^p} r_i^p D + r^a N_t^{a,SP} - c^o N_t^{p,SP} \mathbb{1}\{t=1\} - g(E^{SP}) - c^g E^{SP} && (10)
\end{aligned}
$$

4.2 Autarky

Under autarky, farmers choose a crop depending on their water supply and land quality. Therefore, I characterize the strategy of the four types of farmers separately.

Surface water only annual crop farmer: F^{sa}

F^{sa} only uses surface water and prefers annual crops. For annuals the farmer's decision is independent in each period. As the return of the annual crop is positive, F^{sa} grows annual crops up to her surface water supply each period:

$$
\text{For farmer } \; i \in F^{sa}: \quad n_{ti}^{p,A} = 0; \quad n_{ti}^{a,A} = W_t^s \tag{11}
$$

Surface water only permanent crop farmer: F^{sp}

F^{sp} prefers permanent crops over annuals if there is enough water to secure the second period irrigation. Since she has no access to groundwater and the surface water supply varies over time, the farmer has to choose a portfolio of crops that deals with the supply risk of irrigation water.

There is a risk-free acreage of permanent crops, W^L, that the farmer can always irrigate. If $W_1^s = W^L$, she can plant at most W^L permanents, and there is no irrigation water risk because $W_2^s \geq W^L$. If $W_1^s = W^H$, she chooses the amount of permanents crops $n_{1i}^p \in [W^L, W^H]$ to maximize her expected two-period payoff:

$$\max_{n_{1i}^p} n_{1i}^p(r_i^p - c^o) + (W^H - n_{1i}^p)r^a + qW^L r_i^p + (1-q)[n_{1i}^p r_i^p + (W^H - n_{1i}^p)r^a] \tag{12}$$

Note that, the maximal amount of permanent crops the farmer can irrigate in period 2 when the state is low is W^L.

The problem takes one of the two corner solutions:

$$n_{1i}^p = \quad W^H \quad \text{if} \;\; (2-q)(r_i^p - r^a) - c^o > 0 \tag{13}$$

$$n_{1i}^p = \quad W^L \quad \text{if} \;\; (2-q)(r_i^p - r^a) - c^o < 0 \tag{14}$$

When the chance of low water supply, q, is large enough: $q > 2 - \frac{c^o}{r_i^p - r^a}$, the expected future return is so low that the farmer prefers the risk-free solution $n_{1i}^p = W^L$. When $q < 2 - \frac{c^o}{r_i^p - r^a}$, the expected future return is large enough that she is willing to bear the risk $n_{1i}^p = W^H$.

It is reasonable to assume $q > 2 - \frac{c^o}{r_1^p - r^a}$ in this model – at least for California where droughts hit frequently. More generally, if we consider the second period as a longer horizon representing the lifetime of a real permanent crop, it is likely that q has a high value. As a result, every permanent crop farmer i^{sp} chooses to grow W^L acreage of permanents in period 1 and uses extra water to grow annuals whenever it is available:

$$\text{For farmer } \; i \in F^{sp}: \quad n_{ti}^{p,A} = W^L; \quad n_{ti}^{a,A} = W_t^s - W^L \tag{15}$$

Groundwater users: F^{ga} ***and*** F^{gp}

Groundwater users are considered together since they affect each other through the negative externality of extraction. As the cost of pumping c^g is uniform for all pumpers and every groundwater user takes the same fraction $\frac{1}{m^g}$ of the social cost, the marginal cost of using groundwater is the same across all agents. In equilibrium, the aggregate extraction E_t^A in period t is where the lowest marginal return of the pumpers equals the marginal cost of using groundwater at that level.

The farmer's extraction decision depends on the social cost. Three cases arise:

If the social cost shared by each farmer is negligible: $\frac{1}{m^g} g'(m^g(D - W^s)) < r^a - c^g$, every groundwater user pumps. The land constraint binds for all groundwater users and the equilibrium outcome in the economy is that:

$$\text{For farmer } i \in F^{gp}: \quad n_{ti}^p = D; \;\; n_{ti}^a = 0; \;\; e_{ti} = D - W_t^s \tag{16}$$

$$\text{For farmer } i \in F^{ga}: \quad n_{ti}^p = 0; \;\; n_{ti}^a = D; \;\; e_{ti} = D - W_t^s \tag{17}$$

If the social cost taken by each individual is moderate: $\frac{1}{m^g} g'(m^{gp}(D - W^L)) < r^a - c^g < \frac{1}{m^g} g'(m^g(D - W^s))$, it is profitable for all permanent crop farmers to use groundwater but only a fraction of annual crop farmers find it worth pumping. The water constraint binds. The marginal groundwater user is always an annual crop farmer, therefore the equilibrium aggregate extraction in the economy is constant: $E^A = g'(m^g(r^a - c^g))$. Permanent crop farmers F^{gp} pump to irrigate all their land and annual crop farmers F^{ga} pump extra water as well. Without loss of generality, I assume smaller i pumps first if several agents have the same marginal return[9]. Then there are two marginal annual crop farmers i^L and i^H that $c^g + \frac{1}{m^g} g'(\sum_{i \in F^g, i \leq i^L}(D - W^L)) = r^a$ and $c^g + \frac{1}{m^g} g'(\sum_{i \in F^g, i \leq i^H}(D - W^H)) = r^a$, who correspond to the highest i who pumps in dry and wet years respectively. The equilibrium

[9]Since annual crop farmers are assumed to have the same marginal return, it could also be the situation that they all use some groundwater and fallow a fraction of crops. How groundwater extraction is allocated among the annual crop farmers does not affect the outcome of the model as we only care about the aggregate volume.

outcome of the economy is that:

$$\text{For farmer } i \in F^{gp}: \quad n^p_{ti} = D; \quad n^a_{ti} = 0; \quad e_{ti} = D - W^s_t \tag{18}$$

$$\text{For farmer } i \in F^{ga} \quad n^p_{ti} = 0 \ \text{ and for} \tag{19}$$

$$i \leq i^L: \quad n^a_{ti} = D; \quad e_{ti} = D - W^s_t \tag{20}$$

$$i^L < i \leq i^H: \quad \begin{cases} n^a_{ti} = D; \ e_{ti} = D - W^H_t & \text{if } \ W^s_t = W^H_t \\ n^a_{ti} = W^s_t; \quad e_{ti} = 0 & \text{if } \ W^s_t = W^L_t \end{cases} \tag{21}$$

$$i > i^H: \quad n^a_{ti} = W^s_t; \quad e_{ti} = 0 \tag{22}$$

In this case the marginal groundwater user farms annual crops. But which farmer is marginal changes due to the variation in surface water supply. Given the acreage to irrigate, the marginal cost of using groundwater is lower in wet years than dry years thanks to more surface water supply. Therefore, more annual crop farmers can use groundwater in wet years: $i^H > i^L$ and less need to fallow their land.

If the social cost is sufficiently large: $\frac{1}{m^g} g'(m^{gp}(D - W^L)) > r^a - c^g$, only permanent crop farmers use groundwater. Similar to when the marginal pumper is an annual crop farmer, there will be a marginal groundwater user who always grow permanents on all her land and farmers with lower quality land fallow part of their land just like the surface water only farmers. I will discuss this case in detail when introducing the surface water market.

I mainly consider the first two cases when the marginal groundwater user is an annual crop farmer because, for the last half centuray at least, in the Central Valley a large fraction of annual crops are irrigated using groundwater.

The extent of fallowing in the autarky case depends on each farmer's water supply condition. For F^s, $D - W^H$ acres of land are never used due to lack of water. They grow $W^H - W^L$ more acres of annuals in wet years and fallow that land in dry years. F^{gp} farmers never fallow because the permanent crops make pumping worthwhile. If the social cost is negligible, F^{ga} farmers do not fallow since the pumping cost c^g is smaller than the return of annuals r^a. When the social cost is large enough, some F^{ga} farmers find using groundwater too expensive. They only use surface water to irrigate their crops and fallow their surplus land as the surface water only farmers.

When the social cost is negligible (land constraint binds), the overall extraction, crop acreage and social welfare in the economy are:

$$\begin{aligned}
E_t^A &= m^g(D - W_t^s) && (23)\\
N_t^{p,A} &= m^{sp}W^L + m^{gp}D && (24)\\
N_t^{a,A} &= m^{sa}W_t^s + m^{sp}(W_t^s - W^L) + m^{ga}D && (25)\\
R_t^A &= \sum_{i\in F^{sp}} r_i^p W^L + \sum_{i\in F^{gp}} r_i^p D - c^o N_t^{p,A}\mathbb{1}\{t=1\} + r^a N_t^{a,A} - g(E_t^A) - c^g E_t^A && (26)
\end{aligned}$$

When the marginal groundwater user is always an annual crop farmer (water constraint binds), the overall extraction, crop acreage and social welfare in the economy are:

$$\begin{aligned}
E^A &= g'^{-1}(m^g(r^a - c^g)) && (27)\\
N_t^{p,A} &= m^{sp}W^L + m^{gp}D && (28)\\
N_t^{a,A} &= m^a W_t^s + m^{sp}(W_t^s - W^L) + E^A - m^{gp}(D - W_t^s) && (29)\\
R_t^A &= \sum_{i\in F^{sp}} r_i^p W^L + \sum_{i\in F^{gp}} r_i^p D - c^o N_t^{p,A}\mathbb{1}\{t=1\} + r^a N_t^{a,A} - g(E^A) - c^g E^A && (30)
\end{aligned}$$

We now compare the autarky and the social planner's outcomes to see where the inefficiency comes from.

Autarky vs. Social planner

The social optimal extraction is[10] $E^{SP} = g'^{-1}(r^a - c^g)$. Most farmers in the Central Valley have access to groundwater, so the overall extraction under autarky exceeds the social optimum ($E^A > E^{SP}$) when either the land or water constraint binds[11]. Under both situations, all permanent crop farmers with access to groundwater F^{gp} will pump and fully irrigate their land and annual crop farmers F^{ga} pump the extra water until the corresponding constraint binds.

The acreage of permanents under autarky is $N_t^{p,A} = m^{sp}W^L + m^{gp}D$, which is smaller than the social planner's case: $N_t^{p,SP} = m^pD$. On the other hand, the acreage of annuals is larger than in the social planner's case since the overall water use is higher: $N_t^{a,A} = E^A + W_t^s - N_t^{p,A} > E^{SP} + W_t^s - N_t^{p,SP} = N_t^{a,SP}$.

The overall crop choice and groundwater extraction under autarky both deviate from the social optimum. Autarky's inefficiency has two sources. One is the CPR problem: groundwater users only bear a fraction of social cost, leading to a higher level of extraction than the social optimum. The other comes from the resource misallocation in the economy: some farmers with low productivity r^a are able to produce using surface water while some farmers with high productivity $r_i^p > r^a$ can not fully utilize their land because they have no

[10] Recall section 4.1. This is the outcome when the water constraint binds in the social planner's case. If the social planner's land constraint binds, the socially optimal extraction will be larger than groundwater demanded by all groundwater users in the autarky regime: $E^{SP} > m^g(D - W^s) = E^A$. Thus sustainability of the basin is not a concern and inefficiency of the autarky regime comes from the rigidity to move water around.

[11] When the water constraint binds, the overall extraction under autarky satisfies: $c^g + \frac{1}{m^g}g'(E^A) = r^a$. The overall extraction with the social planner satisfies: $c^g + g'(E^{SP}) = r^a$. Since $g''(.) > 0$ and $m^g \gg 1$, we have $E^A > E^{SP}$. As for the case when land constraint binds, it is possible that $E^{SP} > E^A$ if the social cost is low and the size of land without access to groundwater is large. Neither is true in the Central Valley.

access to groundwater. I calculate the inefficiency of autarky in this case:

$$
\begin{aligned}
R^{SP} - R^{A} = \quad & g(E^{A}) - g(E^{SP}) - (E^{A} - E^{SP})(r^{a} - c^{g}) + \\
& \sum_{i \in F^{s} \cap F^{p}} (D - W^{L})(r_i^{p} - r^{a})
\end{aligned} \tag{31}
$$

The first line in the RHS measures the distortion from the common pool (the increased social cost minus the return of using the extra water to grow annuals). The second line in the RHS measures the distortion from resource misallocation, which is the gain that would arise if water in the annual crop land was used to grow more permanents. Next I introduce a surface market in the autarky model and examine how it affects social welfare.

4.3 A market in surface water

With the market, farmers can trade in surface water. The opportunity cost of selling one's surface water allocation is the return from farmland or the cost of pumping groundwater. The market's efficiency depends on the identity of marginal groundwater user.

If the marginal groundwater user is a permanent crop farmer, annual crop farmers do not pump and are willing to sell their surface water. Indeed, permanent crop farmers are willing to pay more than the return of annuals: $p^{w} > r^{a}$. Moreover, permanent crop farmers with lower return than the marginal farmer will also sell their surface water since their marginal return from water is lower than the marginal cost of using groundwater. Permanent crop farmers with high value are potential buyers of the surface water. In equilibrium, the price for surface water equals to the marginal cost of using groundwater, and the marginal permanent crop farmer's return is such that: $r_i^{p} = c^{g} + \frac{1}{m^{g}} g'(iD - W^{s})$.

In this case, the water market leads to less groundwater extraction than autarky. Under autarky F^{gp} farmers can only use their own surface water and must pump groundwater, while with a market they buy the cheaper surface water and pump less. When the cost of using groundwater is high enough, the surface water market is both efficient and preserves sustainability of the common-pool system. Unfortunately it does not seem this case has ever held in California. Instead the Central Valley suggests that the marginal groundwater user is always an annual crop farmer.

Water constraint binds

If the water constraint binds, the opportunity cost of using groundwater equals the return to planting annuals (r^a). At a price of r^a, F^{sp} farmers will use the market to make up for any deficiency in surface water. The sellers are all annual crop farmers (both F^{sa} and F^{ga}). Because the water constraint binds, the cost of pumping water is higher than r^a, thus annual crop farmers will not pump groundwater to replace surface water they sell. Instead they will fallow.

In equilibrium, extraction E^M remains the same as under autarky. Buyers of water now have a secured water supply, so they will grow permanents on all their land. The overall extraction and crop acreage in the economy are:

$$\begin{aligned} E^M &= {g'}^{-1}(m^g(r^a - c^g)) \qquad (32) \\ N_t^{p,M} &= m^p D \qquad (33) \\ N_t^{a,M} &= mW_t^s + E^M - m^p D \qquad (34) \end{aligned}$$

I calculate the welfare gain with surface water market at period 2 (period 1 is similar except for an extra term of the fixed cost in planting permanent crops):

$$R^M - R^A = \sum_{i \in F^{sp}} (D - W^L)(r_i^p - r^a) > 0 \qquad (35)$$

As a result, the surface water market improves social welfare since it reallocates water from low to high value users. If I compare the market with the social planner's case, the acreage of permanent crops is the same but more groundwater is used on annual crop land. In this case, the market solves the reallocation problem but it does nothing to attack the CPR problem if it arises under autarky.

The size of fallowing in the economy changes with surface water delivery in this case:

$$N_t^{f,M} = mD - mW_t^s - E^M \tag{36}$$

Permanent crop farmers purchase surface water to irrigate their crops, therefore the size of permanent crop land is not sensitive to the realized surface water supply. However, annual crop farmers who sell water to the permanent crop farmers fallow more land in dry years since they receive less surface water supply and sell more water.

Land constraint binds

If the land constraint binds under autarky, the marginal cost of using groundwater water is $c^g + \frac{1}{m^g}g'(E^A) < r^a$. The cost of pumping is less than the opportunity cost of surface water users who plant annual crops. F^g farmers who sell their surface water, pump extra water to replace it. Without loss of generality, I assume the land constraint still binds after the water trade. Therefore water is only sold out by groundwater users and the price out of a Bertrand competition is below r^a.

Farmers without groundwater have an opportunity cost equal to or above r^a and are unwilling to sell at the prevailing price. In fact, all surface water only farmers are potential buyers of water. Since water price $p^w < r^a$, F^{sp} farmers purchase water to secure irrigation of their permanent crops and F^{sa} farmers purchase water to grow annuals.

The surface water market leads to higher extraction since more farmland will receive irrigation. The overall extraction and crop acreage in the economy are:

$$E_t^M = m(D - W_t^s) \tag{37}$$

$$N_t^{p,M} = m^p D \tag{38}$$

$$N_t^{a,M} = m^a D \tag{39}$$

Without loss of generality, I calculate the welfare change with surface water market at period 2 when a drought hits:

$$R^M - R^A = g(E^A) - g(E^M) + \sum_{i \in F^{sp}} (D - W^L)(r_i^p - c^g) + \sum_{i \in F^{sa}} (D - W^L)(r^a - c^g) \quad (40)$$

Although the surface water market does induce trade from low cost pumpers to high value users, the efficiency gain from water reallocation is not realized since the sellers just pump more groundwater. If the increased social cost with a surface water market $|g(E^A) - g(E^M)|$ is larger than the return of extra crops grown by the surface water only farmers (the last two terms in equation (40)), the distortion from CPR problem dominates and the market produces an outcome worse than autarky.

By assumption the marginal social cost of extraction is higher than the net return of annuals: $g'(E^M) > g'(E^A) > g'(E^{SP}) = r^a - c^g$. Unless the return to permanent crops is so high that irrigating more permanent crops using groundwater is socially beneficial, equation (40) will be negative since the increased social cost is more than the value of the extra acreage of permanents. In this case, although the surface water market has solved the resource misallocation problem (as all F^p land is irrigated), it exaggerates the CPR problem by inducing a lager extraction than the autarky case.

No fallowing occurs in this case:

$$N_t^{f,M} = 0 \quad (41)$$

In summary, when the marginal groundwater user is an annual crop farmer, the efficiency of surface water market depends on the condition of the groundwater basin and the severity of the CPR problem[12]. If the social cost of extraction borne by individual pumper is large enough, overall extraction from the basin is limited by the marginal return of annuals.

[12]Note that discussion in this section is based on the assumption that land constraint does not bind in the social planner's case. If the land constraint binds, there is no CPR problem. Overall extraction from the basin is below the social optimum even when all land is farmed. Extraction under autarky is at an

Introducing a surface water market will not result more extraction but only reallocate water efficiently. However, if the social cost borne by each farmer is small, the surface water market lets F^s farmers irrigate their crops using groundwater through the nominal surface water trade, leading to a higher level of extraction from the aquifer.

4.4 Hypotheses

The theoretical model generates two sets of hypotheses. One set summarizes how crop choices react to water supply changes. The other set describes how the underlying condition of the economy and the effectiveness of surface water market affect fallowing decisions.

Hypothesis 1. *In area with frequent drought, the size of permanent crops does not respond to changes in surface water delivery.*

Hypothesis 2. *In surface water only districts, without surface water trade, the size of annual crops increases with surface water delivery.*

Whether the water or land constriant binds in the economy has different implications on the efficacy of water market. Although I lack direct observation on the cost and payoff structure of each farmer, and cannot directly decide which constraint binds, the model makes different predictions at the fallow decisions of water sellers under the two situations:

Hypothesis 3. *If the surface water market is efficient, annual crop farmers fallow less land when surface water supply is high.*

Hypothesis 4. *If the surface water market is inefficient, fallow acreage is not correlated with surface water supply.*

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inefficient level since some farmers have no access to groundwater and have to fallow part of their land, while surface water market will lead to the same level of efficiency as the social planner since it grants all farmland irrigation water through surface water reallocation.

5 Empirical analysis

To test the hypotheses, I focus on Kern County in the Central Valley because its Department of Agriculture has published crop choice data for each plot of farmland since 1997. I match the crop data to local water supply conditions.

In Kern County, surface irrigation water is supplied by 21 water districts who hold contracts for delivery of surface water from the State Water Project (SWP), Central Valley Project (CVP) and Kern River. Some water districts also drill wells and deliver groundwater to their clients together with surface water. Most districts charge a uniform basic price for the water they deliver. The on-site price may include a varying surcharge based on the distance between the water user and the water delivery facilities.

There are also some farms in the county that do not belong to any water districts and rely on private wells for irrigation. Within the water districts, many farmers have also drilled private wells and pump groundwater to supplement what they receive from the district. Because private wells are not metered, the actual water used by individual farmers is unknown. In most water districts every acre has an equal and proportional right to surface water so I assume each acre receives the total district water supply divided by acres farmed.

Table 1 reports the summary statistics for each water district over the period 1999-2016. There are four districts without access to groundwater (henceforth referred as surface-water-only–SWO–districts). They cover 13% of the farmland in Kern County. The SWO districts use 22% of all surface water delivered to the county, implying that they hold more long-term surface water rights than the water districts with groundwater (henceforth referred as groundwater–G–districts). Nevertheless, surface water supply for these four districts only accounts for 60% of their total water demand, and they also purchase short-term water delivery from other agencies.

These SWO districts choose different crops than the rest of the valley. They grow 19% of the permanents in the whole county but only 6% of the annuals. They fallow more farmland

(26%) than G districts (18%). The large fraction of fallowing in SWO districts reflects water scarcity due to lack of groundwater access. Surprisingly those districts are devoting a larger fraction of farmland to permanent crops than the G districts. For farmers in SWO areas, surface water imports are thus essential.

In Table 2, I report the history of crop change by water district type and surface water delivery. The major crop in Kern County has moved from annuals to permanents over the sample period. Surface water delivery for all the water districts has been very variable, which is not surprising given that California has multi-year wet-dry cycles. Moreover, there is a general declining trend due to delivery reductions associated with increasingly stringent environmental regulations.

In G districts, acreage of annuals has dropped by 20%. Fallowed acres have also fallen despite the reduction in surface water supply. Permanent crop acreage has grown rapidly, driving up total agricultural water demand. The water demand unsatisfied by surface water is met by groundwater extraction. As a result, the changing crop pattern is accelerating the basin's depletion.

In SWO districts, the acreage of annual crops has dropped dramatically (85%). Half of the decline goes to fallowing and half of the land transits to permanent crops. Depletion of the basin has also increased because of SWO districts' increasing demand for water import. It peaked at 2014 when nearly 90% of irrigation water had to be imported from outside the districts. In 2016, SWO districts still purchased about 130,000 acre-feed of extra water. That accounts for 40% of water consumption within those districts.

The theoretical model predicts that the water transferred from G districts to SWO districts has two possible implications: (1) more fallowing or (2) more groundwater pumping. That overall the number of fallowed acres does not increase over time rules out the first possibility. Moreover the change of relative product price that favors permanent crops seems to push against fallowing land and instead toward pumping groundwater. To confirm the aggregate crop pattern, we examine the farmland transition matrix using plot-level crop choice data.

These data help clarify how much of the transition is caused by water sales and how much is due to a price effect that favors permanents.

5.1 Crop transition at plot level

To start, we must construct a plot-crop data set from the Kern County Spatial Database. In practice plots vary in shape over time, making it difficult to track the evolution of crops. Instead of plots, I study the observed crop at 12102 fixed points on the map over time. Doing so creates a spatially consistent data set where each dot stands for a square of 61.8 acres. The number of dots with active farming information is similar to the number of registered plots in the original data.

Table 3 reports summary statistics of the reconstructed dot-level crop choice data. On average, 35% of dots are used for annual crops, 39% are used for permanents and 26% are fallowed. The number is close to the acreage data in Table 1 although the size of annuals is reported larger in acreage because there might be multiple harvest of annual crops within a year. In addition, the dot-level data picks up more fallowed land due to the ability to track changes in consistent locations while in the acreage data sometimes the fallowed land is not reported. The trends of declining annuals and rising permanents persist at the dot level. While for fallowing, the dot data shows that it stabilized at around 28% after 2003 both in SWO and G districts. This implies that neither the water market nor the price effect plays an important role on fallowing in the recent decade and crop transition mainly happened between annual and permanent crops.

SWO and G districts have different dynamics. In SWO districts, fallowing increases by 150%, compared with a 30% increase in G districts. Fallowing mainly comes from a reduction in annual crops. In SWO districts, only 7% of annuals in 1999 remain annual crop in 2016 and more than half are fallowed. While in G districts, over 50% of annuals remain and only a quarter are fallowed. The large fraction of fallowing in SWO districts confirms that they are water scarce.

Despite that scarcity, the number of dots with permanent crops in SWO districts grows over time. Permanent crops' share increases from 40% in 1999 to more than 50% in 2016, even larger than the fraction in G districts. This is due to a substantial fraction of annual acreage transitioning to permanents.

The big increase in permanent crops is consistent with a transition from autarky equilibrium to market equilibrium in the model due to the introduction of private water trade. Under autarky, SWO farmers could not expand permanents acreage in wet years since they would not have enough water in the next drought. Instead, they grew some annuals and fallowed annual crop land in dry years to water their permanent crops[13]. When it became feasible to buy surface water, SWO farmers expanded their permanent acreage. The decline of annual acreage is also predicted by the model.

5.2 Empirical methods

The crop transition at dot level show that the water market influenced crop choice in those water districts without groundwater. Permanent crop acreage increased as a result of water trade, which is consistent with the model prediction that water market reallocates surface water from groundwater users to high-value users who have no access to groundwater. At the same time, efficiency of water market is challenged by the fact that fallowing does not rise in SWO districts as an outcome of water transfer from SWO to G districts. To confirm those implications, I estimate crop choice at the plot level.

According to the hypotheses (3 and 4) developed in section 4.4, the main outcome of interest is how much annual crops are fallowed. Since annual crops are the marginal crops that may be sensitive to water supply variations, I infer the underlying state of the economy from the impact of water supply changes on the farmers' fallowing decision. I also test the impact of surface water supply to permanent crops (hypothesis 1) and to annual crops

[13] In fact, Berrenda Mesa Water District has water allocation rule that permanent crop land is served first whenever there is shortage in water supply.

in surface water only districts (hypothesis 2) to check the model predictions on permanent crops and crop pattern in autarky equilibrium. The outcome variables could be binary choice whether or not a type of crop is planted on a certain dot or continuous measure of the fraction of a certain type of crops within a certain area.

Water supply is the main influence on crop choice as discussed in the model. Three different variables are used to measure variation in water supply across space and time. *SWP allocation* is a percentage of the full entitlement of SWP water the water district receives in a given year. It is the main explanatory variable of interest as it measures the change of surface water supply for the same land over time. It is highly correlated with a drought index [Zhao (2017)]. *Surface water rights* is the ratio of long-term surface water supply over total crop water demand. It captures the spatial variation between different water districts due to their different endowment of surface water. *Groundwater access* captures the difference between surface water only and groundwater districts. It varies over space but not time.

Additional control variables include:

Land quality: I acquire a cropland suitability index (CSI) for vegetables (*CSI Potato*) and field crops (*CSI wheat*) from Food and Agriculture Organization (FAO) of the United Nations. I do not include FAO's land suitability index for permanent crops because it does not vary across the region examined.

Relative crop price: I compute the *price ratio* of permanent to field crops each year. A common view on the cause of transition from annual to permanent crops is that price changes favor permanent crops. Figure 1 shows that it is not always the case. In fact, the price of vegetables has been rising even faster than the price of permanent crops, reflecting the increase in labor cost because vegetables are much more labor-intensive than the tree crops. Nevertheless, as the acreage of vegetables is relatively stable and the transition mainly happens from field crops to permanent crops, I use the relative price of permanent to field crops to control the price effect on crop decisions.

Agriculture capacity: Local density of agriculture matters as it affects the local investment of infrastructure or knowledge spillover. I measure the local *agriculture capacity* as the number of dots that are actively farmed within one mile circle of the observation point.

Lagged crop choice: The *lagged crop choice* measures the influence of crop decision in the past. Serial correlation arises for different reasons. For permanent crops, it is mainly due to the fixed cost on planting trees. For annuals, it could be the special knowledge the farmers gained before growing the crop, or special tools they purchased, or some unobserved factors of the land that make growing a certain type of crops more profitable.

Network influence: The *network influence* measures how a farmer's crop choice is affected by the decisions of her neighbors. For each observation point, network influence is calculated as the density of the same type of crops within its one mile circle (number of dots with the same type of crops divided by total number of dots). I use the lagged value of the density to avoid simultaneous influences between farmers' crop decisions.

In spatial analysis, individual observations usually correlate with each other based on their geological closeness. Beyond the network influence, which is a special form of spatial interdependence, spatial econometricians have developed econometric models dealing with the issue of spatial autocorrelation between control variables or error terms. I take one of the model that is appropriate to the water market context and the spatial autocorrelation in my data.

5.2.1 Evidence of spatial autocorrelation

To evaluate spatial autocorrelation, I divide the dot sample into those dots with permanent crops and those with other uses. If there is no spatial autocorrelation among the observations, the crop choice should be random across locations, and the distributions of neighboring density of permanent crops in the two subsamples should be similar. If there is positive spatial autocorrelation neighboring areas around the dots with permanent crops should also have higher density of permanents.

Figure 2 displays the cumulative density distribution of the permanent density in the neighboring area of the two subsamples. In the upper panel, I calculate the density of permanent crops in 1999 and the results for 2016 is presented in the lower panel.

Difference in distribution of permanent crop density between the two subsamples are striking both in 1999 and 2016. Taking the one mile circle (solid line) around the dots as an example, at the 50% threshold, the density in the permanent crop dot subsample is around 0.7 while in the other subsample is about 0.1.

Spatial autocorrelation generally decreases with distance. The cumulative density distribution line approaches to the 45 degree line (dot line) when it moves from one mile circle to one-to-two mile ring (dash line) and then to two-to-five mile ring (dash& dot line) around the dots.

I also check the difference over time. Due to the increase of relative price of permanents a large fraction of farmland transits to permanent crops through the sample period, thus I expect the distribution of permanent crop density to increase over time and the distributions of the two sample to become more similar. Comparison between the left and right panel confirms my expectation. In fact, in the two-to-five-mile ring area, the two distributions are quite similar in 2016 as both of them become close to the 45 degree line.

Moran (1950) developed a formal measure of spatial dependence called Moran's I, which is defined as:

$$I = \frac{N}{\mathbb{W}} \frac{\sum_i \sum_j w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_i (x_i - \bar{x})^2} \tag{42}$$

where N is the number of observations, x is the variable of interest, w_{ij} is the spatial weight between observation i and j and $\mathbb{W}$ is the sum of w_{ij}.

If there is no spatial autocorrelation, the expectation of I is $E(I) = \frac{-1}{N-1}$ which converges to 0 in a large sample. On the other hand, if there is spatial autocorrelation, the value of I varies from -1 to $+1$ with negative value implying negative spatial autocorrelation and positive value corresponding to positive spatial autocorrelation.

I calculate the Moran'I for water districts without groundwater. As presented by table 5, the value is positive and statistically significantly different from $E(I)$ in both 1999 and 2016. It confirms that there is spatial autocorrelation in the data and the specification of econometric model should account for it. Moreover, comparison between the two years is consistent with our observation from the figure that due to the increased popularity of permanent crops, the distribution of crops around different dots becomes close. Therefore the Moran's I is smaller in 2016 than in the first year of the sample period.

5.2.2 The econometric model

Outcome variables in the empirical analysis could be either a binary crop choice $d \in \{0, 1\}$ that $d = 1$ if a certain type of crop is planted at a given plot and $d = 0$ otherwise, or a continuous variable $d \in [0, 1]$ that d measures the density of a certain type of crop within a certain area. Without loss of generality, I derive the econometric model based on the binary crop choice of planting a permanent crop. The models for other binary choices follow directly. Estimation using the continuous outcome variables are conducted as robustness check. The estimation technique is less complicated and standard in literature [Reference].

Whether to grow a permanent crop at dot i in year t is determined by the latent profit y_{it}. The farmer compares y_{it} with other options including growing annuals and fallowing in current period. I pool other options as an outside option and normalize the value of the outside option to 0. Therefore the relationship between the normalized profit and crop choice is:

$$d_{it} = \begin{cases} 1, & \text{if } y_{it} > 0; \\ 0, & \text{otherwise} \end{cases} \tag{43}$$

Farmer of dot i chooses $d_{it} = 1$ if and only if the latent profit $y_{it} > 0$.

In a standard discrete choice model, the latent profit function can be written as:

$$y_{it} = x_{it}\beta + \varepsilon_{it} \tag{44}$$

where x_{it} is a vector of explanatory variables and ε_{it} is individual-time specific error term. In the absence of spatial autocorrelation (or more accurately ε_{it} is i.i.d.), probit or logit regression could be applied to estimate the vector of coefficients β. However, because of spatial interdependence, the standard probit/logit estimation results are no longer efficient and may not be consistent.

There is a rich literature discussing the spatial autocorrelation in the land use problem [Li et al. (2013)]. The issue becomes complicated with a discrete choice model since the usual differencing method can not be applied here. In addition, due to the heteroskedasticity among the error terms, the standard maximum likelihood estimation is infeasible as it requires n-dimensional integration where n is the size of the sample. Below I discuss specific forms of spatial autocorrelation that may exist in my data and provide solutions to each.

In general, the crop choice data features two sorts of spatial autocorrelation. Factors that are fixed over time but correlated over space cause permanent spatial interdependence. Most geological features such as access to groundwater and surface water river or land quality belong to this category. For this type of spatial autocorrelation, it is included in the explanatory vector x_{it} if it is observed, for example, the land suitability to specific crops [Holmes and Lee (2012)]. Otherwise, it contributes to an intercorrelated component in the error term. Below is the vector of individual errors at period t:

$$\varepsilon_t = e + u_t \tag{45}$$

where e is the vector of unobserved individual feature. $e = \rho We + v$ due to spatial interdependence where W is the weight matrix depending on the distance between observations, ρ measures the level of spatial autocorrelation and v is a time-invariant individual shock.

Note that, if the dependent variable is continuous, the fixed spatial autocorrelation could be easily resolved by taking difference across time:

$$y_t - y_{t-1} = (x_t - x_{t-1})\beta + (u_t - u_{t-1}) \tag{46}$$

Although we can not estimate the scale of spatial autocorrelation ρ, the estimator for explanatory variables β is unbiased, efficient and consistent.

For the discrete choice model, Pinkse and Slade (1998) provide a GMM method to estimate the discrete choice model with spatial dependent error terms.

A second type of spatial autocorrelation arises when the dependence between farmers' crop choices evolves over time. Different economic explanations could be applied to explain the transitory spatial interdependence.

The first channel I consider is when a farmer's crop choice is affected directly by others' choices. For example, the economies of scale arises from having other land nearby planted with the same crop, which may help lower costs by adding to the pool of labor with special skill or allowing share of special tools [Holmes and Lee (2012)]. Higher crop density may also encourage local government/agency to invest in infrastructure that is more helpful for that crop. For instance, agglomeration of water-intensive crops may encourage local water suppliers to dig more wells. Finally, there are knowledge spillover from neighbors' crop choices [Munshi (2004)]. Since the crop choices are observable, the latent profit function includes the choices on other dots as in Mohammadian and Kanaroglou (2003):

$$y_t = x_t\beta + \rho W d_t + \varepsilon_t \tag{47}$$

Standard profit/logit estimation could be applied to estimate the model parameters.

When profitability is locally correlated, the second channel of transitory spatial autocorrelation arises. This differs from the first channel as it involves forward looking behavior where farmers are influenced by the additional value created by increasing a particular crop's local density. In this situation, farmers expect that high value of the latent variable will lead to growing permanent crops by other farmers, which in turn lowers costs and introduces network effects. The specification of latent profit function in this channel is:

$$y_t = \rho W y_t + x_t\beta + \varepsilon_t \tag{48}$$

In the literature, such specification is often referred to as a spatial lag model. The latent profit can be written as:

$$y_t = (I - \rho W)^{-1} x_t\beta + (I - \rho W)^{-1}\varepsilon_t \tag{49}$$

Smirnov (2010) proposes a Pseudo maximum likelihood estimator to estimate the above model with an additional assumption that individuals disregard shocks on others. Klier and McMillen (2008) extend the Pinkse and Slade (1998) GMM method to this setting.

The last channel of time-variant spatial autocorrelation involves situations when farmers' decision are driven by unobservables that are correlated over space. The transitory case of interdependent error term is an extension of the permanent spatial autocorrelation we examined before, except that the error term now is written as:

$$\varepsilon_t = \rho W \varepsilon_t + u_t = (I - \rho W)^{-1} u_t \tag{50}$$

This model is often referred to as spatial error model. In the literature, econometricians rarely distinguish the transitory and permanent cases since the GMM estimator could be applied in both situations. The latent profit function can be written as:

$$y_t = x_t \beta + (I - \rho W)^{-1} \varepsilon_t \tag{51}$$

As shown in Anselin and Florax (2012), the spatial lag model and spatial error model are special case of each other with additional assumption on the parameters. Influence from both channels exist in the farming decision. A farmer grows a certain type of crop on a given dot based on her expectation of her neighbors' choices. At the same time, neighboring farmers profits are affected by similar local geological and water conditions.

In the Central Valley, the major factor that drives the crop pattern change over the sample period is the relative price of permanent to field crops. Since crop price affects the farmers' choice through their profit function, I consider the influence from latent profits of neighboring land as the main channel through which farmland correlates with each other. At the same time, most of local unobserved geological connections should be captured when we include land quality, water supply and agriculture capacity in the latent profit function. Therefore, I adopt the spatial lag model and conduct the pseudo maximum likelihood (PML) estimation to examine the crop choice with spatial autocorrelation.

5.2.3 Derivation of PML estimator

The pseudo maximum likelihood estimator I use is a simplification of Smirnov (2010) that facilitates computation with a large dataset. For the spatial lag specification, the latent profit function is (the subscript for time is ignored):

$$y = Ax\beta + A\varepsilon \tag{52}$$

where $A = (I - \rho W)^{-1}$ is the spatial multiplier matrix. A could be expanded as the limit form:

$$A = \lim_{n \to \infty} I + \rho W + \rho^2 W^2 + ... + \rho^n W^n \tag{53}$$

Denote by D the $n \times n$ matrix composed of the diagonal elements of the matrix A. D indicates private effects of random shocks on the individual profits. As shown by equation 53, these effects are the sum of direct non-spatial effects and aggregate spatial effects.

The conditional choice probability for the individual i to plant permanent crops is:

$$P_i = \Pr(d_i = 1 | \{\varepsilon_j, j \neq i\}, \beta) \tag{54}$$

Rewrite the latent profit function as:

$$y = Ax\beta + (A - D)\varepsilon + D\varepsilon \tag{55}$$

Note that the diagonal elements in the matrix $A - D$ are zero, thus the conditional choice probability is:

$$P = \Pr(\varepsilon < \frac{Ax\beta + (A - D)\varepsilon}{D}) \tag{56}$$

Therefore the individual conditional probability is:

$$P_i = \frac{1}{1 + \exp(-\frac{g_i}{d_{ii}})} \tag{57}$$

where $g_i = \sum_{j=1}^{n} a_{ij} x_j \beta + \sum_{j=1}^{n} (a_{ij} - d_{ij}) \varepsilon_j$.

Notice that the random components ε_j in g_i are i.i.d. with mean 0, therefore they have no systematic effect on the conditional choice probability P_i. Suppose individuals focus only on spatial effects that systematically affect their conditional choice probability and disregard all other effects. Then private shock $a_{ii} = d_{ii}$ always affects the conditional choice probability while a_{ij} with $j \neq i$ has no expected effect. The simplified closed form for the conditional probability is:

$$\hat{P}_i = \frac{1}{1 + \exp(-\frac{\sum_{j=1}^{n} a_{ij} x_j \beta}{d_{ii}})} \tag{58}$$

Estimation for such specification is equivalent to the spatial discrete choice model with spatial random profit:

$$\tilde{y}_i = Ax\beta + D\varepsilon_i \tag{59}$$

The pseudo maximum likelihood estimator for the original model is the maximum likelihood of this model. As the computation involves inversion of the spatial weight matrix A, which is difficult with a sample size n over $10,000$, I simplify the spatial weight matrix by assuming away the spatial effects of order larger than three:

$$A \approx \tilde{A} = I + \rho W + \rho^2 W^2 \tag{60}$$

and denote the matrix of diagonal elements of $\tilde{A}$ as $\tilde{D}$. In the end, it is easy to find the maximum likelihood estimator for:

$$\tilde{y}_i = \tilde{A}x\beta + \tilde{D}\varepsilon_i \tag{61}$$

This is the PML estimator I will present in the estimation results.

5.3 Estimation results

Table 6 reports the tests of hypothesis 1: permanent crops are not correlated with water supply changes over time. The coefficient of SWP allocation is negative and statistically significant in column (1), implying that in years with less surface water supply, there is more transition to permanent crops. This is consistent with the introduction of water trade in later periods when the surface water supply was low. Such effect disappears in the other three columns where lagged crop choice or time trend is added to control for long run changes in crop choice. That SWP allocation does not matter is consistent with hypothesis 1 that permanent crops are not subjected to water supply variations.

Variation of surface water rights has no influence on the likelihood of growing permanents. This is consistent with the idea that water scarcity is mitigated by surface water trade. The positive coefficient of groundwater access implies that SWO districts grow more permanents than G districts. This is also supported by water trade.

FAO measures of land quality have no impact on the permanent crop decisions. The price effect is as expected (except for column (3) where the time trend that absorbs the price effect) that higher relative price of permanent to field crops leads to more transition to the permanents.

Influences from related agricultural decisions all have expected sign. A plot in a region with denser agriculture, planted with permanent crops in the past, or in a neighborhood with larger density of permanent crops is more likely to have a permanent crop. The spatial correlation parameter estimated in PML estimation (column (4)) is also positive and statistically significant, confirming the existence of spatial interdependence of crop choices.

Table 7 presents tests of hypothesis 2. Although private water trade was always allowed during the sample period, in the early years water districts without groundwater had not transited to permanent crops in large scale and surface water delivery was high, so there was no need for private water trade and the economy was in the autarky equilibrium. The year 2004 is chosen as the cutoff because in surface water only districts the acreage of permanent crop suddenly jumped 20% from 2004 to 2005 after a long period of slow growth.

To confirm the model's autarky predictions, I estimate the correlation between annual crop decision and water supply conditions in water districts without groundwater before 2004. Coefficients for SWP allocation are positive across all specifications and statistically significant in the subsample with high fallow density (column (4) and (6)). This implies that on farmland with relatively low quality, the annual crop farmers pay attention to surface water supply and fallow the land if water supply is low, consistent with the autarky equilibrium that annual crops are sensitive to short-term surface water supply variation.

As for other control variables, the effect of surface water rights is mixed. Districts with more surface water allocation may grow more annuals or transit to more permanents. Land quality has a negative sign, implying that high quality land is more likely to be planted with permanents when there is water scarcity. Other variables all have expected sign. The price effect and spatial autocorrelation are both consistent with findings in Table 6.

The main results of this paper are shown in Table 8. The two competing hypotheses 3 and 4 provide different predictions about water market efficiency and fallowing decision. I look at whether the likelihood of fallowing is affected by surface water supply conditions or not. Column (1) and (2) report the logit regression results using all G districts, column (3) reports logit regression results using only the regions with high density of fallowing, column (4) reports logit regression results using only farmland that is never planted with permanent crops and the last two columns report the PML estimation results based on all water districts.

The key variable of interest is SWP allocation. None of the estimated coefficients for SWP allocation are statistically significant, suggesting that fallowing is not sensitive to surface water supply. Therefore, when a low-value farmer sells her surface water to high-value users, she does not fallow her land. Instead, the farmer likely pumps more groundwater to supplement irrigation water for her crops. This contradicts hypothesis 3 and is consistent with hypothesis 4 that the market does not efficiently reallocate water from low to high value users, instead it just provides high-value users with water.

Surface water rights have a positive and statistically significant influence on fallowing decision. Such effect goes away when lagged crop choice is not controlled, implying that places with less surface water rights fallow earlier than area with more surface water rights. This is consistent with the lack of pumping capacity in early years of the sample period.

Land quality has a negative effect on fallowing as expected, although the coefficient is only statistically significant under some specifications. The relative price of permanent crops to fields reduces fallowing. But the effect becomes smaller and even goes away when we restrict the sample size or control for spatial autocorrelation, consistent with the findings at aggregate level that price effect is not a main driver for fallowing.

The lagged crop choice and network influence have the expected sign. As the two are usually highly correlated, the effect of network influence is absorbed by the lagged crop choice (column (1)). This is confirmed by the coefficient of spatial correlation term in the column (5) and (6). When I include the lagged crop choice in the regression with spatial autocorrelation under control, the estimated measure of spatial correlation is negative. This is because the lagged crop choice has already captured most of what determines whether a plot will be fallowed or not. In fact, in column (6) where I do not include lagged crop choice in the regression, the measure of spatial autocorrelation is positive and statistically significant, suggesting that dots where neighborhood fallow rate is high are also more likely to be fallowed.

Robustness check

To booster confidence in the earlier results I conduct a robustness check by replacing the binary outcome variable with a continuous variable that measures the density of different types of crops. I first divide the Kern County into blocks of 1914 acres, which is the average size of farms in the data. Then I calculate the fraction of fallowing, permanent crop and annual crop within each block as the continuous outcome variables.

I rerun the previous three tests using both OLS and MLE estimation of the SAR specification. The results are shown in Table 9. Column (1) - (4) test the permanent crop decisions. Column (5) and (6) explore the influencing factors for annual crop decision in SWO districts before 2004. Column (7) and (8) evaluate fallowing decisions in G districts.

The estimated coefficients are consistent with the former results. For permanent crop decisions, a negative and statistically significant coefficient for SWP allocation is found in column (1) and (3) and such effect goes away when lagged crop choice is put in control. This is consistent with the results in table 6.

Column (5) and (6) imply a positive although not statistically significant effect of SWP allocation on annual crop planting decisions in SWO districts before 2004. This is consistent with the findings in table 7. We are not able to restrict the sample into a subsample with only high fallow density since the sample size shrinks dramatically. Nevertheless, having not found a significant effect at farm level implies that fallowing annuals in dry years is not a common action in response to drought. Instead large farms can maintain production and only small farms with low profitability fallow.

Column (7) and (8) are test results of our main focus. Consistent with Table 8, the coefficient of SWP allocation on fallow decisions is not statistically significant. It implies that farmers do not fallow land when surface water supply is low, confirming hypothesis 4 that the surface water market is inefficient.

6 Conclusion

Water sales from groundwater districts to surface water only districts are likely to continue in the Central Valley over next few years. These sales are driven both by droughts and by the increased demand for permanent crops. Beyond California, markets are likely to become popular in the era of global warming and the increasing shortage of surface water supply. The consequence of establishing a surface water market varies depending on the underlying economic and hydrological condition of the region. This paper shows that a surface water market can cause harm when groundwater extraction is unregulated. Since the marginal cost of pumping groundwater is low, farmers simply replace any water they have sold by pumping more groundwater. The overall impact of the water market is to grant more farmers access to groundwater, making the CPR problem even worse.

In the Central Valley the surface water market neither reallocates resources nor sustains the aquifer. The scale of increased extraction to replace the surface water sold off is large. On average, the import demand from surface water only districts is about 140,000 AF per year. If all import comes from the groundwater districts, extra groundwater extraction to replace the surface water sold off accounts for 8% of all groundwater use by all the water districts. What's worse, the surface water only districts are at the boundary or out of the groundwater aquifer, therefore the water transfered to that area eventually run off instead of percolating back to the groundwater system as a source of natural recharge.

According to the USGS report (2009)[14], the long-term average groundwater pumpage in the Central Valley as a whole is about 8.6 million acre-feet (MAF) per year while the annual recharge is only 7.7 MAF. Kern County agriculture alone consumes 20% of total groundwater extraction in the Valley. Moreover, if we apply the same ratio of extraction to safe yield in the whole Valley to Kern County, over-extraction above the safe yield in Kern County is about 174,000 AF per year, more than 80% of which could be blamed to the surface water trade!

This paper's conclusions have implications for all aquifers in arid or semi-arid regions – places where the land constraint rather than the water constraint binds in agricultural activity. Some argue that depletion of aquifer is caused by excessive transition from annual to permanent crops which increase water demand and makes more inelastic. Other argue that a water market reallocates water efficiently so that the overall reliance on groundwater basin will decline. Findings of this study suggest that neither the transition to permanents or lack of water market are to blame for depletion. Rather it's the common pool. As long as the groundwater basin is unregulated, low-value farmers have no incentive to stop growing annual crops or to halt their surface water sales and their extraction from the groundwater

[14]Groundwater Availability of the Central Valley Aquifer, California.

aquifer will not stop. Therefore, the very first step to solve the sustainability and efficiency problem of water use is to define groundwater rights and stop unlimited pumping. It is only after closing the common pool that a water market can work as expected to reallocate resource toward higher efficiency.

The argument presented here is not specific to water. The effectiveness of market is rarely guaranteed when it involves a common property. As the CPR problem origins from the users' unlimited use of the resource, market sometimes introduces demand that leads to even higher depletion of the common pool. Fur bearing animals went nearly extinct in the early nineteenth century as an outcome of the North American fur trade [Berkes et al. (1989)]. Today, the water users in the Central Valley of California are risking the future of the valley on excessive pumping caused by private water trade. The market cannot be assumed to be helpful to solving the resource depletion problem. If we want a market to work efficiently while not depleting the resource that is traded, we must define the boundary of the resource system properly.

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Tables and figures

TABLE 1

WATER DISTRICT SUMMARY STATISTICS

Water District	Farmland	Annuals	Permanents	Fallowing	Water Demand	Surface Water Delivery
Without access to groundwater						
Belridge Water Storage District	52,110	12,003	32,111	7,997	132,761	74,187
Berrenda Mesa Water District	37,720	6,427	23,814	7,478	92,274	56,537
Lost Hills Water District	62,664	11,859	28,059	22,747	119,436	72,723
Tejon - Castac Water District	2,005	-	10	1,995	33	1,926
Total	154,500	30,289	83,994	40,217	344,504	205,374
With access to groundwater						
Arvin - Edison Water Storage District	157,854	78,472	49,463	29,919	354,461	86,879
Buena Vista Water Storage District	48,351	37,377	5,313	5,661	110,444	13,005
Cawelo Water District	42,158	1,911	35,809	4,439	119,365	23,323
Delano - Earlimart Irrigation District	8,191	150	7,358	683	23,921	112,141
Henry Miller Water District	39,668	19,233	158	20,276	48,590	21,675
Kern - Tulare Water District	15,484	1,551	11,064	2,869	39,282	43,697
Kern County Water Agency	7,123	4,149	16	2,957	10,425	24,752
Kern Delta Water District	160,409	115,395	10,444	34,570	321,908	15,671
North Kern Water Storage District	75,596	20,313	46,984	8,300	201,129	7,854
Rag Gulch Water District	450	5	124	321	409	4,138
Rosedale - Rio Bravo Water Storage District	40,102	24,090	11,048	4,964	95,578	27,411
Semitropic Water Service District	160,289	86,825	55,509	17,956	394,689	95,916
Shafter - Wasco Irrigation District	35,519	13,071	19,754	2,694	95,890	47,993
Southern San Joaquin Municipal Utility District	50,968	8,359	39,727	2,882	148,024	87,719
Tehachapi - Cummings County Water District	17,292	7,268	317	9,707	19,184	2,625
West Kern Water District	4,114	1,541	829	1,743	6,508	3,969
Wheeler Ridge - Maricopa Water Storage District	128,970	44,158	57,724	27,089	295,111	120,333
Unserved area	65,576	38,634	10,195	16,747	129,209	-
Total	1,058,115	502,502	361,835	193,778	2,414,127	739,100

Summary statistics for the Kern County water districts, averaged over the period 1999-2016. The crop data is from Kern County Spatial Data. The water supply data is from SWP and CVP websites. The units on land are acres and the units on water are acre-feets.

TABLE 2

HISTORY OF CROP CHANGE

	Surface water only districts						
Year	Fallowing	Annuals	Permanents	Annual Crop Water Demand	Permanent Crop Water Demand	Total Water demand	Surface Water Delivery
1999	6,406	80,973	61,889	202,433	198,044	400,477	333,218
2000	8,233	73,892	67,143	184,731	214,857	399,588	302,846
2001	9,650	70,991	68,627	177,476	219,607	397,084	131,233
2002	35,457	48,135	65,676	120,336	210,164	330,500	235,547
2003	30,498	51,830	66,940	129,576	214,207	343,783	302,846
2004	48,016	30,478	70,774	76,194	226,478	302,673	218,722
2005	42,263	21,682	85,323	54,205	273,035	327,240	302,846
2006	27,101	31,118	91,049	77,796	291,356	369,152	336,496
2007	28,230	24,305	96,732	60,763	309,543	370,306	201,898
2008	35,654	21,126	92,488	52,815	295,960	348,775	117,774
2009	49,169	10,108	89,991	25,270	287,971	313,241	134,598
2010	42,795	14,236	92,237	35,590	295,159	330,749	168,248
2011	42,146	18,320	88,802	45,799	284,167	329,966	269,197
2012	40,813	15,143	93,311	37,858	298,596	336,454	218,722
2013	40,686	11,414	97,168	28,535	310,937	339,471	117,774
2014	52,043	5,832	91,393	14,581	292,457	307,037	33,650
2015	49,705	3,309	96,254	8,272	308,014	316,286	67,299
2016	40,874	12,303	96,091	30,757	307,492	338,249	201,898

	Groundwater districts						
Year	Fallowing	Annuals	Permanents	Annual Crop Water Demand	Permanent Crop Water Demand	Total Water demand	Surface Water Delivery
1999	172,047	499,624	276,477	1,249,061	884,727	2,133,788	1,003,912
2000	153,961	501,006	293,182	1,252,515	938,182	2,190,696	1,017,148
2001	174,219	491,289	282,641	1,228,223	904,450	2,132,673	534,894
2002	170,124	493,556	284,469	1,233,890	910,300	2,144,190	780,341
2003	166,716	497,259	284,173	1,243,148	909,353	2,152,501	949,094
2004	176,226	481,332	290,591	1,203,330	929,890	2,133,220	713,229
2005	146,709	486,356	315,084	1,215,890	1,008,268	2,224,158	1,222,790
2006	147,277	460,955	339,917	1,152,387	1,087,733	2,240,120	1,144,164
2007	133,756	466,100	348,293	1,165,250	1,114,538	2,279,787	612,675
2008	106,552	480,579	361,017	1,201,447	1,155,256	2,356,702	569,138
2009	138,345	447,867	361,937	1,119,668	1,158,198	2,277,865	664,697
2010	138,605	441,759	367,784	1,104,398	1,176,909	2,281,307	909,563
2011	124,680	441,784	381,685	1,104,460	1,221,391	2,325,852	1,086,108
2012	89,078	466,651	392,420	1,166,628	1,255,743	2,422,370	640,610
2013	93,508	440,957	413,684	1,102,392	1,323,788	2,426,180	456,750
2014	100,090	424,746	423,313	1,061,865	1,354,600	2,416,465	157,180
2015	76,999	423,879	447,270	1,059,698	1,431,265	2,490,964	155,595
2016	79,541	403,886	464,721	1,009,715	1,487,107	2,496,822	656,949

The units on land are acres and the units on water are acre-feets.

TABLE 3

PLOT LEVEL SUMMARY STATISTICS

	Annuals	Permanents	Fallowing	Fallowing (SWO)	Fallowing (G)
Aggregate:					
12102	35%	39%	26%	32%	25%
By year:					
1999	49%	32%	19%	2%	17%
2000	47%	33%	20%	3%	17%
2001	46%	33%	20%	2%	18%
2002	43%	32%	25%	4%	21%
2003	43%	31%	26%	5%	21%
2004	39%	32%	29%	6%	23%
2005	37%	35%	28%	6%	22%
2006	35%	38%	27%	4%	22%
2007	33%	40%	27%	5%	23%
2008	32%	41%	27%	5%	23%
2009	30%	41%	29%	6%	23%
2010	31%	41%	28%	5%	22%
2011	30%	42%	28%	5%	23%
2012	29%	44%	27%	5%	22%
2013	27%	46%	27%	5%	22%
2014	25%	47%	28%	6%	22%
2015	24%	48%	29%	6%	22%
2016	23%	49%	28%	6%	22%

TABLE 4

CROP TRANSITION MATRIX

Panel A: All districts

			crop choice in 1999		
			annual	permanent	fallow
		Total	5,916	3,871	2,315
crop choice in 2016	annual	2,777	2,095	192	490
	permanent	5,968	2,123	3,213	632
	fallow	3,357	1,698	466	1,193

Panel B: Districts without groundwater

			crop choice in 1999		
			annual	permanent	fallow
		Total	829	711	267
crop choice in 2016	annual	116	60	15	41
	permanent	1,014	331	607	76
	fallow	677	438	89	150

Panel C: Districts with groundwater

			crop choice in 1999		
			annual	permanent	fallow
		Total	5,087	3,160	2,048
crop choice in 2016	annual	2,661	2,035	177	449
	permanent	4,954	1,792	2,606	556
	fallow	2,680	1,260	377	1,043

TABLE 5

Moran's I in districts w/o groundwater

	I	E(I)	sd(I)	z	p-value*
1999	0.166	-0.001	0.001	155.605	0
2016	0.126	-0.001	0.001	118.889	0

*1-tail test

TABLE 6

Crop Decision on Growing Permanents

	(1)	(2)	(3)	(4)
VARIABLES		Logit		PML
SWP allocation	-1.110***	-0.202	0.0991	-0.159
	(0.22)	(0.23)	(0.08)	(0.19)
Surface water rights	-0.559	0.115	-0.561	0.0823
	(1.09)	(0.24)	(1.09)	(0.20)
Groundwater access	-1.087***	-0.491***	-1.090***	-0.399***
	(0.37)	(0.13)	(0.38)	(0.11)
CSI (Potato)	0.232	0.19	0.233	0.163
	(0.37)	(0.15)	(0.37)	(0.13)
CSI (Wheat)	-0.051	0.0564	-0.0516	0.0497
	(0.26)	(0.08)	(0.26)	(0.07)
Price ratio (p/a)	0.971***	0.868***	-0.113	0.705***
	(0.18)	(0.24)	(0.07)	(0.20)
Agricultural capacity	0.178***	0.125***	0.179***	0.103***
	(0.02)	(0.02)	(0.02)	(0.01)
Lagged crop choice		6.284***		6.659***
		(0.11)		(0.13)
Network influence		1.705***		
		(0.18)		
Time trend			0.0725***	
			(0.01)	
Spatial correlation				0.150***
				(0.03)
Constant	-3.628**	-7.777***	-148.5***	-7.526***
	(1.43)	(0.74)	(29.50)	(0.54)
Observations	108,918	108,918	108,918	108,918

Note: 1. Standard errors in parentheses and clustered at water district level.

2. All even years are included.

3. Spatial weight matrix: Neighbors within 1 mile circle.

TABLE 7

Chance of growing annuals in water districts without groundwater before 2004

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES		Logit & all data		High fallow density	PML	PML& High fallow density
SWP allocation	0.372	0.576	0.72	2.506**	0.405	2.205**
	(0.29)	(1.35)	(1.45)	(1.09)	(0.99)	(0.95)
Surface water rights	-6.154***	5.983***	6.148***	12.49*	1.193	-7.309**
	(0.79)	(1.72)	(1.88)	(7.00)	(3.45)	(3.62)
CSI (Potato)	-0.0772	-0.570***	-0.569***	-5.698	-0.426***	-1.2
	(0.15)	(0.06)	(0.06)	(4.59)	(0.10)	(1.22)
CSI (Wheat)	-1.178*	-0.0718	-0.0524	0.229	-0.111	-0.0156
	(0.67)	(0.23)	(0.26)	(0.56)	(0.22)	(0.30)
Price ratio (p/a)	-3.191**	-5.182*	-5.867	-7.327*	-3.839*	-3.908**
	(1.31)	(3.06)	(3.71)	(3.91)	(2.29)	(1.76)
Agricultural capacity	0.0824	0.158***	0.160***	0.241***	0.114***	0.173***
	(0.06)	(0.03)	(0.03)	(0.07)	(0.03)	(0.05)
Lagged crop choice		1.935***	2.010***	3.175**	3.625***	3.058***
		(0.40)	(0.52)	(1.57)	(0.85)	(0.80)
Network influence		3.029***	3.028***	1.650**		
		(0.77)	(0.77)	(0.83)		
Time trend			0.0802			
			(0.15)			
Spatial correlation					0.385***	0.898**
					(0.04)	(0.38)
Constant	12.33***	0.858	-159.2	28.47	2.965	11.98***
	(4.66)	(4.19)	(298.50)	(19.81)	(4.80)	(3.31)
Observations	9,035	9,035	9,035	1,432	9,035	1,432

Note: 1. Standard errors in parentheses and clustered at water district level.

2. Years before 2004 are included.

3. Spatial weight matrix: Neighbors within 1 mile circle.

TABLE 8

Causes to fallow in water districts with groundwater

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	Logit & all data		High fallow density	Non-permanent	PMLE	
SWP allocation	0.118	0.0895	-0.282	0.0583	0.259	0.0385
	(0.13)	(0.06)	(0.25)	(0.28)	(0.30)	(0.04)
Surface water rights	0.870***	0.199	1.665***	0.433*	0.856**	0.345
	(0.29)	(0.17)	(0.33)	(0.24)	(0.33)	(0.21)
CSI (Potato)	-0.244**	-0.133	-0.173	-0.235***	-0.299*	-0.142*
	(0.12)	(0.09)	(0.14)	(0.09)	(0.17)	(0.08)
CSI (Wheat)	-0.000554	-0.0523	0.0288	-0.0235	-0.138	0.018
	(0.11)	(0.07)	(0.20)	(0.14)	(0.13)	(0.08)
Price ratio (p/a)	-0.232*	-0.140**	0.194	-0.219	-0.482	-0.0517*
	(0.13)	(0.07)	(0.24)	(0.29)	(0.34)	(0.03)
Agricultural capacity	-0.359***	-0.199***	-0.422***	-0.236***	-0.430***	-0.212***
	(0.02)	(0.02)	(0.03)	(0.02)	(0.03)	(0.01)
Lagged crop choice	5.273***		3.395***	3.756***	5.263***	
	(0.23)		(0.48)	(0.32)	(0.27)	
Network influence	-4.272***	2.310***				
	(0.50)	(0.35)				
Spatial correlation					-0.416***	0.398***
					(0.02)	(0.13)
Constant	3.882***	1.910**	1.237	2.252**	4.292***	2.517***
	(0.984)	(0.890)	(1.324)	(0.982)	(1.42)	(0.76)
Observations	72,065	72,065	11,160	32,186	72,065	72,065

Note: 1. Standard errors in parentheses and clustered at water district level.

2. Year 2004, 2006, 2008, 2010, 2012, 2014 and 2016 are included.

3. Spatial weight matrix: Neighbors within 1 mile circle.

TABLE 9

Robustness check: with continous outcome measure

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VARIABLES	Permenant				Annual w/o groundwater before 2004		Fallow with groundwater	
	OLS		SAR model: MLE		OLS	SAR model: MLE	OLS	SAR model: MLE
SWP allocation	-0.180***	-0.0031	-0.0133**	0.0285***	0.0262	0.00434	0.00686	-0.00377
	(0.01)	(0.00)	(0.01)	(0.00)	(0.05)	(0.03)	(0.01)	(0.01)
Surface water/ total demand	-0.146***	-0.00706*	-0.117***	-0.0108**	-0.0513	-0.194	0.0465***	0.234***
	(0.02)	(0.00)	(0.04)	(0.00)	(0.07)	(0.23)	(0.01)	(0.03)
Groundwater access	-0.202***	-0.0107***	-0.156***	-0.00835***				
	(0.01)	(0.00)	(0.02)	(0.00)				
CSI (Potato)	-0.0107*	-0.00119	-0.0268*	-0.00339*	-0.0245	0.0536	-0.0111***	-0.0530***
	(0.01)	(0.00)	(0.02)	(0.00)	(0.02)	(0.06)	(0.00)	(0.01)
CSI (Wheat)	-0.000718	0.00132	0.0125	0.00521***	-0.00455	-0.0439	0.00667	-0.0235
	(0.01)	(0.00)	(0.02)	(0.00)	(0.02)	(0.05)	(0.00)	(0.02)
Price ratio	0.160***	0.0198***	0.00855	-0.00966**	-0.653***	0.0955	-0.0240***	0.000658
	(0.01)	(0.00)	(0.01)	(0.00)	(0.10)	(0.08)	(0.01)	(0.01)
Agricultural capacity	0.0300***	0.00250***	0.0221***	0.00258***	0.0102***	0.0432***	-0.0163***	-0.0540***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Lagged crop choice		0.953***		0.924***	0.676***	0.0726***	0.675***	0.287***
		(0.00)		(0.00)	(0.02)	(0.03)	(0.01)	(0.01)
Spatial correlation			0.976***	0.221***		0.601***		0.848***
			(0.01)	(0.02)		(0.08)		(0.05)
Constant	0.263***	-0.0115	0.0777	-0.0663***	0.955***	-0.354	0.296***	0.809***
	(0.04)	(0.01)	(0.09)	(0.01)	(0.19)	(0.49)	(0.03)	(0.08)
Observations	9,414	9,414	9,414	9,414	815	815	6,181	6,181
R̂2	29%	94%	11%	94%	59%	14%	79%	66%

Note: 1. Standard errors in parentheses and clustered at water district level.

2. Spatial weight matrix: Inverse distance.

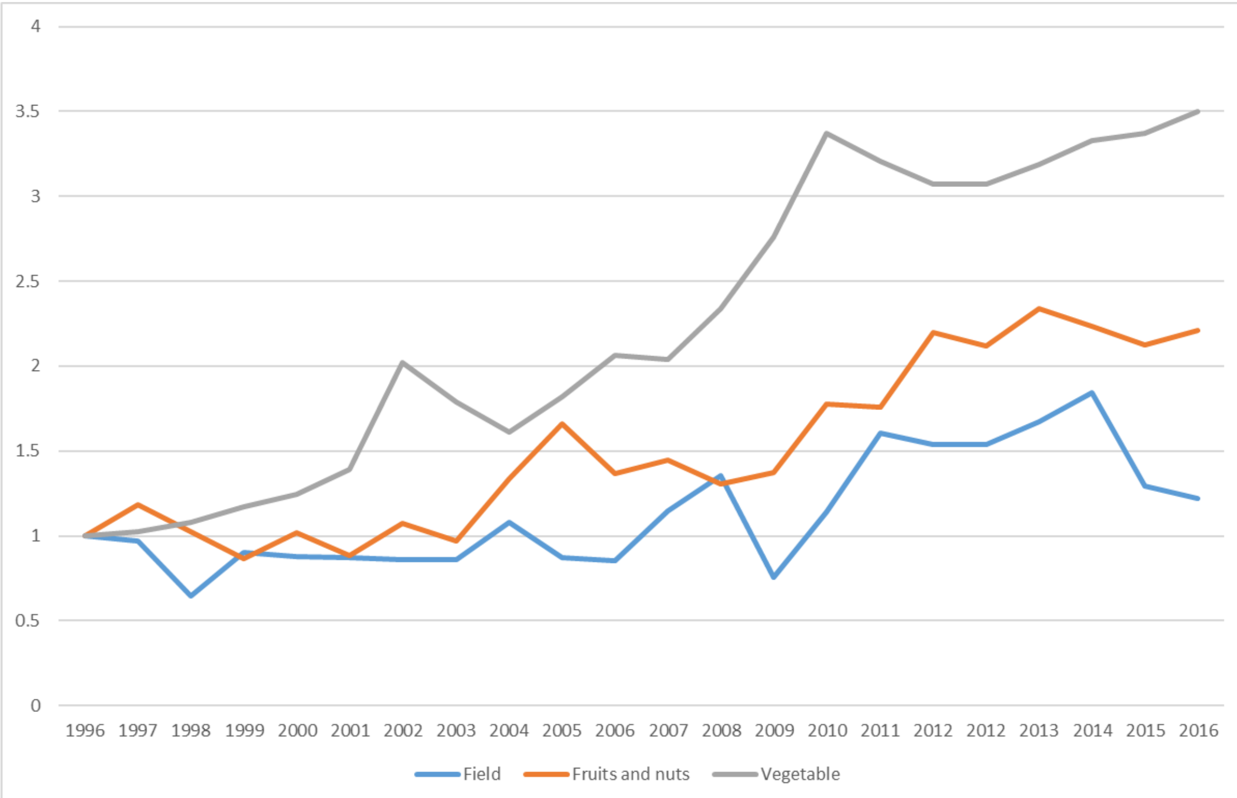
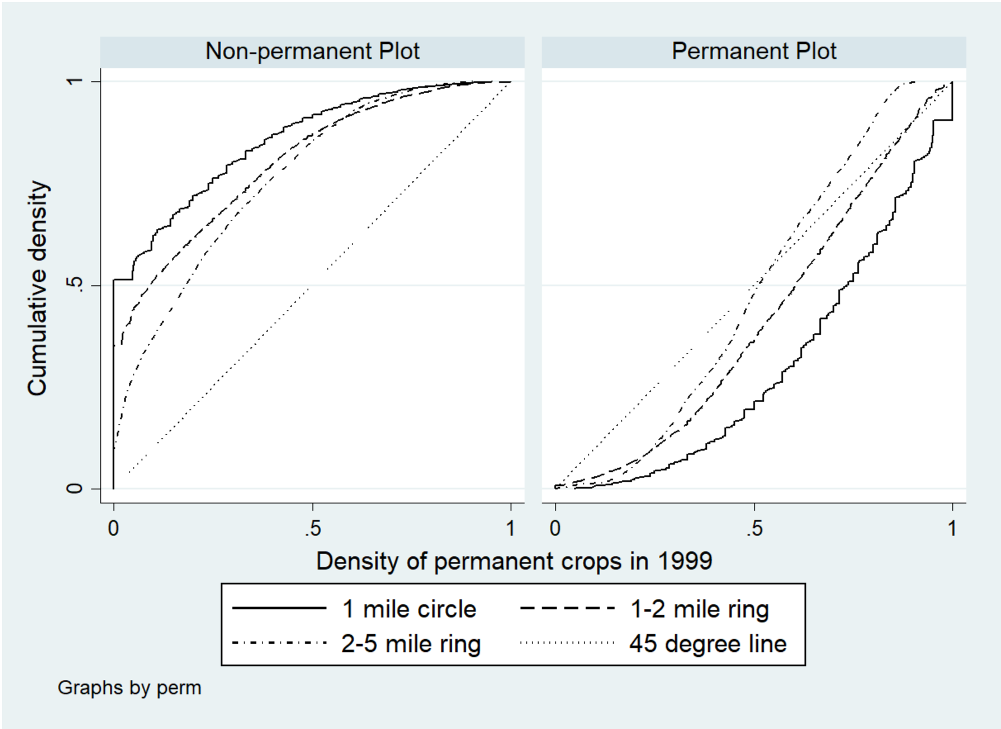
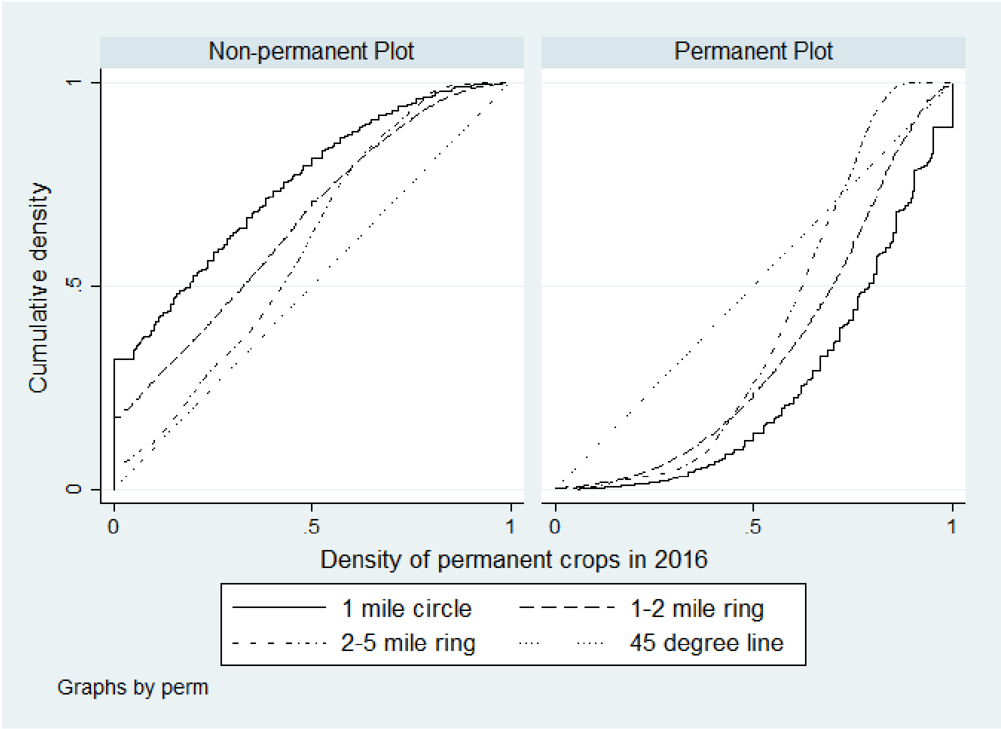


Figure 1: Change of normalized price of different types of crops over time



(a) Distribution of permanent density in 1999



(b) Distribution of permanent density in 2016

Figure 2: Density of permanent crops by space and time

Appendix

A Consistency of PML estimator

When deriving the PML estimator, I make a simplification of the weight matrix by assuming away the spatial effects of orders larger than three:

$$A \approx \tilde{A} = I + \rho W + \rho W \tag{62}$$

Below I show how the estimator will behave if I use a full Taylor expansion of A instead of taking the approximation.

Take the observation j as an example. Let i_K denotes its order K neighbor. The influence coefficient from its first-order (direct) neighbor is:

$$I_1 = \frac{1}{n_j} d_{ji_1} \tag{63}$$

where n_j is the number of j's neighbors and d_{1i_1} is a neighbor indicator that equals to 1 if observation j and i_1 are neighbors and 0 otherwise. Influence on observation j from its first order neighbors is thus:

$$x_j^1 = \rho \sum_{i_1} I_1 x_{i_1} \tag{64}$$

Similarly, the influence coefficient from j's second-order neighbor is:

$$I_2 = \sum_{i_1} I_1 \frac{1}{n_{i_1}} d_{i_1 i_2} \tag{65}$$

Influence on observation j from its second order neighbors is thus:

$$x_j^2 = \rho^2 \sum_{i_2} I_2 x_{i_2} \tag{66}$$

Following the same procedure, the influence coefficient from j's order-K neighbor is:

$$I_K = \sum_{i_{K-1}} I_{K-1} \frac{1}{n_{i_{K-1}}} d_{i_{K-1} i_K} \tag{67}$$

Influence on observation j from its order-K neighbors is thus:

$$x_j^K = \rho^n \sum_{i_K} I_K x_{i_K} \tag{68}$$

By definition, the sum of j's order-1 influence coefficients is $\sum_{i_1} I_1 = 1$. Apply this to I_2, I_3,..., we have $\sum_{i_K} I_K = 1$. If the independent variable x's are of the same order across the observations, the order-K spatial influence on j is of order ρ^K. Since $|\rho| \in [0,1]$, the higher the order of spatial influence included in the estimation process, or the smaller the spatial autocorrelation coefficient ρ, the larger consistency of the estimated coefficients we get. Nevertheless, to show the robustness of the tests, I present the PML estimation results including order-1 and order-3 spatial influence in the Appendix Table 1.

As shown below, the estimated coefficients from order-1 and order-3 spatial influence are very similar and do not deviate too much from the order-2 PML estimation results we present in the main tables. Therefore, taking the approximation of the weight matrix helps simplify the estimation process while not causing the estimated outcome vary too much.

TABLE A1

Spatial Influence: PMLE at Order 1 & 3

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	Permenant		Annual w/o groundwater before 2004		Fallow with groundwater	
	Order 1	Order 3	Order 1	Order 3	Order 1	Order 3
SWP allocation	-0.17	-0.199	0.459	0.413	0.896	1.312
	(0.20)	(0.20)	(1.11)	(0.97)	(0.87)	(1.01)
Surface water/ total demand	0.0764	0.0583	1.278	1.526	1.164***	0.822**
	(0.21)	(0.21)	(3.83)	(3.60)	(0.43)	(0.42)
Groundwater access	-0.414***	-0.432***				
	(0.11)	(0.11)				
CSI (Potato)	0.168	0.172	-0.473***	-0.420***	-0.523	-0.272
	(0.13)	(0.13)	(0.09)	(0.10)	(0.35)	(0.37)
CSI (Wheat)	0.0488	0.0472	-0.129	-0.149	-0.252	-0.372
	(0.07)	(0.07)	(0.24)	(0.23)	(0.27)	(0.33)
Price ratio	0.730***	0.754***	-4.344*	-3.933*	-1.553	-2.370**
	(0.20)	(0.20)	(2.61)	(2.11)	(1.03)	(0.97)
Agricultural capacity	0.105***	0.109***	0.126***	0.119***	-1.990*	-2.836***
	(0.01)	(0.01)	(0.03)	(0.04)	(1.09)	(0.24)
Lagged crop choice	6.790***	6.667***	4.045***	3.645***	7.627***	8.579***
	(0.16)	(0.13)	(0.87)	(0.88)	(0.97)	(0.39)
Network influence						
Spatial correlation	0.251***	0.183***	0.534***	0.297***	-0.738***	-0.884***
	(0.03)	(0.02)	(0.10)	(0.08)	(0.10)	(0.01)
Constant	-6.613***	-6.621***	3.452	2.955	18.80**	24.43***
	(0.65)	(0.67)	(5.27)	(4.78)	(8.86)	(2.28)
Observations	108,918	108,918	9,035	9,035	72,065	72,065

Note: 1. Standard errors in parentheses and clustered at water district level.

2. Spatial weight matrix: Neighbors within 1 mile circle.