The economics of agricultural groundwater management institutions: The case of California[1]

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Abstract

The sustainable management of groundwater resources for use in agriculture is a critical issue in California and globally. Many of the world's most productive agricultural basins depend on groundwater and have experienced declines in water table levels. The food consumers eat, the farmers who produce that food, and the local economies supporting that production are all affected by the availability of groundwater. Increasing competition for water from cities and environmental needs, as well as concerns about future climate variability and more frequent droughts, have caused policy-makers to look for ways to decrease the consumptive use of water. When designing groundwater management policies and institutions, it is important to consider any possible perverse consequences from the policy. In this paper, we discuss the economics of sustainable agricultural groundwater management institutions, including the possible perverse consequences of incentive-based agricultural groundwater conservation programs; the importance of dynamic management, conjunctive management, and spatial management; and property rights.

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1. Introduction

The sustainable management of groundwater resources for use in agriculture is a critical issue in California and globally. Many of the world's most productive agricultural basins depend on groundwater and have experienced declines in water table levels. The food consumers eat, the farmers who produce that food, and the local economies supporting that production are all affected by the availability of groundwater (Lin Lawell, 2016). Approximately 25% of global crops are being grown in water-stressed areas (Siebert et al., 2013).

California has been experiencing its third-worst drought in 106 years (Howitt and Lund, 2014). While California Governor Jerry Brown officially ended the drought state of emergency in all California counties except Fresno, Kings, Tulare, and Tuolumne in April 2017, the hydrologic effects of the drought will take years to recover (USGS, 2017). From 1960 to the present, there has been significant deterioration in the groundwater level of the Central Valley of California, making current levels of groundwater use unsustainable (Famiglietti, 2014). Groundwater management is particularly important in California as the state produces almost 70 percent of the nation's top 25 fruit, nut, and vegetable crops (Howitt and Lund, 2014).

Most crops in California come from two areas: the Central Valley, including the Sacramento and San Joaquin valleys; and the coastal region, including the Salinas Valley, often known as America's "salad bowl". Farmers in both areas rely heavily on groundwater, especially during periods of drought when traditional surface water sources, including dams and reservoirs, face shortages (York and Sumner, 2015). For example, during the recent drought, most farmers did not use water from the Central Valley Project, a network of dams, reservoirs, and canals; and surface sources in the Salinas Valley, including Lake San Antonio, fell to 5 percent of their storage capacity (York and Sumner, 2015). Climate change is expected to increase variability in precipitation and reliance on irrigation to maintain crop productivity (Khanna and Zilberman, 2017).

Understanding the economics of sustainable agricultural groundwater management is particularly timely and important for California as legislation allowing regulation of groundwater is being implemented gradually in California over the next several years (York and Sumner, 2015).

When designing groundwater management policies and institutions, it is important to consider any possible perverse consequences from the policy. In this paper, we discuss the economics of sustainable agricultural groundwater management, including the possible perverse consequences of incentive-based agricultural groundwater conservation programs; the importance of dynamic management, conjunctive management, and spatial management; and property rights.

2. Perverse Incentives From Policy

Incentive-based water conservation programs are extremely popular policies for water management. Farmers can receive a subsidy for upgrading their irrigation systems; less groundwater is "wasted" through runoff, evaporation, or drift; marginal lands can be profitably retired; and farmers can choose whether to participate. However, as our research demonstrates, such policies can have perverse consequences (Pfeiffer and Lin, 2010; Lin, 2013; Pfeiffer and Lin, 2014a; Pfeiffer and Lin, 2014b).

In many places, policy-makers have attempted to decrease rates of groundwater extraction through incentive-based water conservation programs. In California, the State Water Efficiency and Enhancement Program (SWEEP) provides financial assistance in the form of grants to implement irrigation systems that reduce greenhouse gases and save water on California agricultural operations, including evapotranspiration-based irrigation scheduling to optimize water efficiency for crops; and micro-irrigation or drip systems (California DWR and CFDA, 2017). San Luis Canal Company in the San Joaquin Valley offers $250 per acre to "encourage the transition to pressurized irrigation systems among other actions" (CEC, 2015a).

Similarly, though funding for this order was not passed, under the Water and Energy Saving Technologies Executive Order B-29-15, the California Energy Commission, Department of Water Resources, and State Water Resources Control board were to provide funding for innovative technologies, including rebates for conversion from high pressure to low-pressure drip irrigation systems (CEC, 2015b).

Taylor and Zilberman (2017) find that the adoption of drip irrigation technology has historically been driven in many cases by its yield enhancing properties. For example, early adoption was limited to high-value tree crops like avocados, whose yields could be increased through more efficient irrigation without raising costs (Taylor and Zilberman, 2017). While there was widespread adoption of drip during the extended drought of the late 1980s and early 1990s, this was accompanied by increased well drilling and reliance on groundwater, as surface water supplies became scarce (Taylor and Zilberman, 2017). Since then, the adoption of drip irrigation technology has been concentrated in lower-value crops, where other technological changes have made the yield effect of a switch to drip technology more advantageous (Taylor and Zilberman, 2017).

Adoption of more efficient irrigation technology may also be driven in part by other agricultural input subsidies. According to evidence from an agricultural input subsidy program in Malawi, subsidies to fertilizer and other productivity enhancing inputs were found to be positively correlated with investment in some efficiency enhancing technologies related to water conservation, likely due to a switch in crop allocation from staple crops to cash crops (Koppmair et al., 2017).

Although they are extremely popular policies for water management, we find that policies that encourage the adoption of more efficient irrigation technology may not have the intended effect. Irrigation is said to be "productivity enhancing"; it allows the production of higher value crops on previously marginal land. Thus, a policy of subsidizing more efficient irrigation technology can induce a shift away from dry-land crops to irrigated crops. They may also induce the planting of more water-intensive crops on already irrigated land, as by definition, more efficient irrigation increases the amount of water the crop receives per unit extracted (Pfeiffer and Lin, 2014a; Lin Lawell, 2016). In addition, farmers may self-select into incentive programs, and some participants would have purchased the technology even without the subsidy (Wallander, 2017); as a consequence, public funds used to provide these farmers with the subsidy may have been unnecessary expended.

Similarly, land and water conservation and retirement programs may not necessarily reduce groundwater extraction, although they are billed as such. An example of a land retirement program is the Conservation Reserve Program (CRP) created by the federal government in 1985 to provide technical and financial assistance to eligible farmers and ranchers to address soil, water, and related natural resource concerns on their lands in an environmentally beneficial and cost-effective manner (USDA, 2014). These programs include payments to landowners to retire, leave fallow, or plant non-irrigated crops on their land. However, theory predicts that farmers may enroll their least productive, least intensively farmed lands in the programs while receiving payments higher than their opportunity costs, thus accruing rents. It is quite unlikely that an irrigated parcel, which requires considerable investment in a system of irrigation (which, in turn, enhances the productivity of the parcel), will be among a farmer's plots with the lowest opportunity cost and thus enrolled in the program. Instead, farmers may opt to enroll non-irrigated plots in the CRP program, which does not have any effect on the amount of irrigation water extracted (Pfeiffer and Lin, 2014a; Lin Lawell, 2016).

In Pfeiffer and Lin (2014a), which has been featured in such media outlets as the New York Times (Wines, 2013), the Washington Post (Howitt and Lund, 2014), Bloomberg View (Ferraro, 2016), and AgMag Blog (Cox, 2013), we focus on incentive-based groundwater conservation policies in Kansas and find that measures taken by the state of Kansas to subsidize a shift toward more efficient irrigation systems have not been effective in reducing groundwater extraction. The subsidized shift toward more efficient irrigation systems has in fact increased extraction through a shift in cropping patterns. Better irrigation systems allow more water-intensive crops to be produced at a higher marginal profit. The farmer has an incentive to both increase irrigated acreage and produce more water-intensive crops. Similarly, we find essentially no effect of land conservation programs on groundwater pumping, since farmers may opt to enroll non-irrigated plots instead (Pfeiffer and Lin, 2014a; Lin Lawell, 2016).

Our result that increases in irrigation efficiency may increase water consumption is an example of a rebound effect, or "Jevons' Paradox", which arises when the invention of a technology that enhances the efficiency of using a natural resource does not necessarily lead to less consumption of that resource (Jevons, 1865). In the case of agricultural groundwater, we find that irrigation technology that increases irrigation efficiency does not necessarily lead to less consumption of groundwater (Lin, 2013; Lin Lawell, 2016). In particular, if demand for water by farmers is elastic enough, the higher efficiency technology operates at a lower marginal cost, and the higher efficiency technology increases revenue, then irrigation efficiency will increase applied water (Pfeiffer and Lin, 2014a; Lin Lawell, 2016).

Indeed, evidence from a framed field experiment suggests that farmers respond elastically to price signals related to groundwater extraction, such as electricity prices (Foster, Rapaport and Dinar, 2016). Empirical evidence also shows that farms respond to energy prices (Pfeiffer and Lin, 2014c). Using panel data from a period of water rate reform, Schoengold, Sunding and Moreno (2006) estimate that the price elasticity of agricultural water demand is greater than that found in previous studies. Similarly, Smith et al. (2017) use panel data to show that farmers' response to groundwater pumping fees is more elastic than it was previously believed to be, and also that in the short-term this response operates through irrigation intensive margin adjustments rather than through crop acreage adjustments or technological change. Moreover, the long-term demand for irrigation water is likely to be more elastic than the short-term demand (Hendricks and Peterson, 2012).

In California, SWEEP grant funds cannot be used to expand existing agricultural operations or to convert additional new acreage to farmland (California DWR and CFDA, 2017), which may limit how much a farmer can respond to the increased irrigation efficiency resulting from SWEEP grant funds to increase irrigated acreage. However, by lowering the marginal cost of irrigation, SWEEP grant funds may encourage farmers to irrigate more marginal lands, and may also discourage them from exiting irrigated cropping even as groundwater becomes more scarce. Furthermore, this increased efficiency may enable farmers to grow high revenue crops that are more water intensive, even as groundwater becomes more scarce. Thus, SWEEP funds could make farmers in water-stressed locations less sensitive to price signals as groundwater becomes scarce, thereby slowing their adjustment to depleting groundwater stocks over the long term.

The California Department of Agriculture and the California Department of Water recently introduced a pilot program within SWEEP that incentivizes joint action by farmers and larger water suppliers to implement more efficient irrigation technology in return for an agreement to halt the use of groundwater for agricultural purposes (California DWR and CFDA, 2016). However, this program may be used most by farmers and water suppliers who rely relatively little on groundwater as a source. In this case, while irrigation may become more efficient, this may have little effect on groundwater use, the target of the policy. As a result, the costs of the program may unfortunately exceed its benefits.

While heavily irrigated, California's cropland still includes almost one million acres of dry land farming, or non-irrigated land used for planting crops. Dry land farming constitutes about 9 percent of total cropland and 3.5 percent of total farmland in California. Another half a million acres of cropland is currently left to pasture, but could be converted to cropland without improvements. In addition, farmland in California includes about 13 million acres of rangeland and pasture, only about half a million of which is irrigated (USDA, 2012). Thus, a possible perverse consequence of California's SWEEP grant funds is that farmers have may choose to convert more marginal land that is currently used for rangeland and dry land farming to more productive irrigated cropland as part of any efficiency gains from new irrigation technology purchased with state incentives, and this possible increase in irrigated acreage may lead to an increase in groundwater consumption. Similarly, if farmers are credit-constrained, then the additional profits from subsidized irrigation technology might be used to expand production on other lands, which may also lead to an increase in groundwater consumption. Furthermore, cultivation of marginal land often requires excessive use of chemicals, and can damage other nearby water sources (Myers and Kent, 1998; Sinclair, 1987).

An equity concern that arises with incentive programs is that their benefits may accrue to larger, wealthier farmers. Dinar et al. (2017) finds in a survey of farmers in Southern California that larger farmers, and farmers with either vineyards, orchards, or a mix of crops were much more likely to adopt soil moisture monitoring technologies than their counterparts. As the authors note, this suggests the need to tailor policies to separate types of farms, in order to ensure broader adoption of these technologies (Dinar et al., 2017).

Land retirement programs at the federal and state level have had limited effectiveness in California, and may also have perverse consequences. The largest federal land retirement program, the Conservation Reserve Program, provides rental payments to landowners who retire their land and follow conservation practices for a contracted period of time, usually 10 years. While this program has retired 35 million acres of land nationally, it had only enrolled about 138,000 acres in California as of 2007, well below its share in total farmed acres (Champetier de Ribes and Sumner, 2007). This is due in large part to the relatively high value of agricultural land, particularly irrigated farmland, in California.

The most important state-level land retirement program in California is the Central Valley Project Improvement Act Land Retirement Program, which purchases land and water rights from owners (Land Retirement Technical Committee, 1999). Between 1992-2011, the program has retired about 9,000 acres as part of a planned 100,000 acre retirement (California DWR, 2016a).

The modest effect of land retirement programs on groundwater extraction in California is evidence of a design flaw of land retirement programs. In areas of high value agricultural production like California, farmers will demand much higher payments to voluntarily abandon crop production. Since California's most water-stressed regions coincide with areas of high value irrigated agricultural production, land retirement programs in these areas may be limited in their effectiveness, or very costly. In addition, the relatively low levels of Conservation Reserve Program spending in California suggest that the land that has been enrolled in the program is likely low-value land. Thus, just as in Kansas, land conservation programs may be ineffective in reducing groundwater extraction in California.

Although much funding and effort has been expended by the federal government, state governments, and others for incentive-based water conservation programs that are at least partially intended to reduce pumping of groundwater, there is little empirical evidence to support this justification – in fact, our empirical research in Pfeiffer and Lin (2014a) shows that such programs may have the opposite effect of increasing rather than decreasing groundwater extraction.

When designing policies and regulation, policy-makers therefore need to be aware of the full range of implications of their policy, including any potential perverse consequences. In order to better design policy and evaluate their possible perverse consequences, it is important to for policy-makers to gather detailed data on groundwater extraction, groundwater levels, crop acreage, and irrigation technology, ideally for each groundwater user at least at an annual frequency. Having detailed panel data will better enable researchers to empirically analyze the effects of past and ongoing policies, and to better design future policies. Ongoing groundwater management reform in California via the California's 2014 Sustainable Groundwater Management Act and 2015 Strategic Plan provides an important opportunity to assess the effectiveness of different policies and to better design future policies.

3. Dynamic Management

In addition to avoiding any potential perverse consequences, another important aspect of sustainable groundwater management is dynamic management. If an aquifer receives very little recharge, then it is least partially a nonrenewable resource and therefore should be managed dynamically (Lin Lawell, 2017). The idea behind dynamic management is that water managers need to account for the future when making current decisions. In particular, water managers may wish to extract less groundwater today in order to save more for tomorrow (Gisser and Sanchez, 1980; Feinerman and Knapp, 1983).

There are two main reasons why groundwater needs to be managed dynamically, particularly if the aquifer receives very little recharge. First, groundwater extraction today decreases the amount of groundwater available tomorrow. Second, groundwater extraction today increases the cost of extraction tomorrow because removal of water today increases the "lift-height" needed to lift the remaining stock to the surface tomorrow, thereby increasing the pumping cost. Thus, because the extraction of groundwater both decreases the future amount of groundwater available and increases the future cost of extracting groundwater, sustainable agricultural groundwater extraction may entail extracting less groundwater today in order to avoid future supply shocks.

Dynamic management may be important in California, where recharge rates are low. Comparing aquifer systems found in irrigated agricultural regions in the U.S., aquifers in the Central Valley have recharge rates of between 420-580 mm per year, which is within the range found in the High Plains, an aquifer which receives little recharge (Lin Lawell, 2017); and is lower than recharge rates in the Aluvium aquifer system (McMahon et al., 2011). Thus, groundwater in California is at least partially a nonrenewable resource and therefore should be managed dynamically.

4. Conjunctive Management

In addition to being dynamic, efficient management of groundwater must involve conjunctive management, which is the management of the groundwater resource alongside surface water supplies. California's water supply uses state-of-the-art infrastructure to transport supplies of surface water from where they are most plentiful, in the north, to the state's largest population centers and most productive agriculture regions. However since these flows of water are highly variable year to year, in dry years water managers must close a large deficit in water supply.

Here groundwater plays two important roles: first, it supplies users with water in dry years; and second, through managed recharge, it allows water managers to store excess water in wet years for use in future dry periods (Tsur and Graham-Tomasi, 1991). This second property, or "buffer value", represents the added benefits to users from a stabilization of water supply over time (Tsur and Graham-Tomasi, 1991). Tsur (1997) finds this value is substantial in a case study analysis of the Arvin-Edison Water Storage District of Kern County, where the stabilization value of groundwater represents around 50 percent of the total value of groundwater.

The value of conjunctive management of groundwater and surface water resources suggests that benefits of artificial recharge are quite high in areas that both rely on surface water supplies and have low natural recharge. Indeed, in 2016, California's Department of Water Resources classified 18 sites as Category 1 active recharge areas (California DWR, 2016b).

However, managed recharge faces several potential limiting factors to its effectiveness. First, upfront costs are high, making coordinated investment and thus management by large groups of users necessary. Second, benefits are highly unpredictable, due to the inability to completely characterize the aquifer's hydrology (Maliva, 2014). For example, the Las Posas Basin ASR system in California, which cost $150 million to construct, did not achieve its expected increase in aquifer levels when water was stored, making it an ineffective “bank” (Maliva, 2014). Furthermore, recharge facilities face the risk of contamination from nearby agricultural activities and industrial activity (California DWR, 2016b). Limiting these activities nearby recharge facilities then raises the opportunity cost of maintaining them. Finally, future climate change could lead to higher sea levels, which would threaten recharge facilities near California’s coast through salinization (California DWR, 2016b).

5. Spatial Management

In addition to dynamic and conjunctive considerations, sustainable agricultural groundwater management needs to account for spatial considerations as well. Spatial considerations arise because groundwater users face a common pool resource problem: because farmers are sharing the aquifer with other farmers, other farmers’ pumping affects their extraction cost and the amount of water they have available to pump. Consequently, groundwater pumping by one user raises the extraction cost and lowers the total amount that is available to other nearby users (Pfeiffer and Lin, 2012; Lin and Pfeiffer, 2015; Lin Lawell, 2016). These spatial externalities can lead to over-extraction.

Theoretically, spatial externalities are potentially important causes of welfare loss (Dasgupta and Heal, 1979; Eswaran and Lewis, 1984; Negri, 1989; Provencher and Burt, 1993; Brozovic, Sunding and Zilberman, 2002; Rubio and Casino, 2003; Msangi, 2004; Saak and Peterson, 2007). Owing in large part to spatial externalities, the issue of managing water resource use across political boundaries is particularly important (Dinar and Dinar, 2016). To make optimal spatial management more politically feasible, Pitafi and Roumasset (2009) devise an intertemporal compensation plan that renders switching from the status quo to optimal spatial management Pareto-improving.

In Pfeiffer and Lin (2012), we empirically examine whether the amount of water one farmer extracts depends on how much water his neighbor extracts. Our econometric model is spatially explicit, taking advantage of detailed spatial data on groundwater pumping from the portion of western Kansas that overlies the High Plains Aquifer system, and enables us to isolate the effects of neighbors' pumping on a farmer's own pumping decision. Unlike previous studies of spatial implications (e.g., Suter et al., 2012), our study is the first study to empirically measure economic relationships between groundwater users using observational data. We find that on average, Kansas farmers would apply 2.5 percent less water in the absence of spatial externalities (Pfeiffer and Lin, 2012; Lin and Pfeiffer, 2015; Lin Lawell, 2016).

In Sears, Lim and Lin Lawell (2017b), we discuss spatial groundwater management in California. We develop a dynamic game model that shows that farmers who are behaving non-cooperatively will over-extract water relative to the socially optimal coordinated solution if there is spatial movement of water between patches owned by different farmers (Sears, Lim and Lin Lawell, 2017b).

Spatial externalities in groundwater may arise not only between neighboring farmers, but also between neighboring groundwater management jurisdictions as well. Groundwater managers each managing a subset of the plots of land over an aquifer and each behaving non-cooperatively with respect to other groundwater managers will over-extract water relative to the socially optimal coordinated solution if there is spatial movement of water between patches that are managed by different groundwater managers. Thus, in order to internalize any interjurisdictional externalities, the jurisdictions of local agencies should be large enough to internalize all externalities, so that there are no transboundary issues between jurisdictions (Sears, Lim and Lin Lawell, 2017a).

Although California's 2014 Sustainable Groundwater Management Act and 2015 Strategic Plan for implementing it may have specified the efficient allocation of regulatory responsibility between central and local tiers of government, the jurisdictions for the local agencies do not internalize all the spatial externalities. Under California's 2014 Sustainable Groundwater Management Act and 2015 Strategic Plan for implementing it, the local agencies do not each cover an entire groundwater basin, and a groundwater basin can be managed by multiple Groundwater Sustainability Agencies. As a consequence, the local agencies may behave non-cooperatively, leading to over-extraction relative to the socially optimal coordinated solution (Sears, Lim and Lin Lawell, 2017a).

Aquifer heterogeneity can affect the extent of the spatial externality. Aquifers vary in rock composition, which determines the extent to which the water resource is shared. Portions of an aquifer where water moves rapidly, or those with high hydraulic conductivity, as well as those that receive less yearly recharge, face a more costly common-pool problem and therefore receive higher benefits from coordinated management (Edwards, 2016).

Spatial considerations also matter due to the existence of "spatial stock externalities": the extent of groundwater aquifers depends on the overall depth of the stock, and groundwater becomes unavailable gradually over space as the aquifer is depleted (Merrill and Guilfoos, 2017). This differs from existing models in which a single stock is depleted at a single time. This gradual depletion model could be adapted in future research to better understand the set of unique problems that face California. For example, in coastal areas sea water intrusion leads to a loss of the resource through salination, setting up a spatially explicit gradual depletion relationship between depth of water and distance from the coast.

Another aspect of spatial management is the possible need for spatially differentiated groundwater pumping regulations. One reason it may be important to have spatially differentiated groundwater pumping regulations is that groundwater pumping from aquifers can reduce the flow of surface water in nearby streams through a process known as stream depletion. Although the marginal damage of groundwater use on stream flows depends crucially on the location of pumping relative to streams, current regulations are generally uniform over space (Kuwayama and Brozovic, 2013).

Implementing spatial policies with respect to groundwater requires the coordination between nearby extractors. Banerjee (forthcoming) finds in a laboratory setting that the success rate of coordinated spatial policy depends critically on the information available to decision-makers about the decisions made by other users. In particular, information spillovers from the reporting of the decision-making history of non-neighbors may lead participants to coordinate with their neighbors over repeated interactions at a significantly higher rate (Banerjee, forthcoming). In the context of groundwater, this suggests the importance of both improved monitoring of groundwater extraction, and transparent publication of basin-wide information regarding extraction, as a lower cost alternative to incentive policies.

6. Property Rights

An important component of sustainable agricultural groundwater management are complete, measured, enforceable, and enforced property rights that consider the physical properties of the resource (Lin Lawell, 2016). A variety of property rights doctrines and institutions governing groundwater have evolved in the western United States. Many more institutions, both formal and informal, are in place in other locations around the world (Lin Lawell, 2017).

Zilberman et al. (2017) argue that the development of water rights in California and the West generally has been context dependent. Initial determinations to assign rights to landowners were more concerned with encouraging the settlement and productive use of arable land than with allocative or dynamic economic efficiency (Zilberman et al., 2017). Indeed, policy-makers only began to consider efficiency of how water was allocated after the surplus of unused land had disappeared. Similarly, water trading has historically been viewed with suspicion, as smaller extractors fear negative equity effects, and water right holders object to the idea of the auctioning of rights (Zilberman et al., 2017). Policies must then account for equity concerns, and consider the initial allocation of permits if trading is implemented.

California has historically relied on a system of two forms of groundwater property rights. First, overlying property rights allow owners of land to beneficially use a reasonable share of any groundwater basin lying below the surface of the land. Second, any surplus groundwater from the basin may then be beneficially used or sold by individuals or businesses who do not own land directly overlying the basin through an appropriative right. This system of dual rights arose from a 1903 California Supreme Court decision in the case of Katz v. Walkinshaw, which put an end to a period of "absolute ownership" rights, which guaranteed landowners the right to unlimited use of water underneath their properties (California State Water Resources Control Board, 2011).

The system of dual rights in California is designed to operate under both instances of surplus groundwater, when inflow exceeds the use of overlying users; and overdraft, when the groundwater table begins to decline due to extraction exceeding inflows. Appropriative groundwater rights are subordinate to overlying rights, and in times of overdraft a “first in line” system requires that more recent appropriative users cease their extraction.

In practice, though, this relies on California’s court system adjudicating property rights during periods of overdraft. The court’s response to these periods has varied widely over time. Prior to 1949, appropriative right holders could obtain a “prescriptive right” that was senior to overlying rights by demonstrating that they had extracted from an overdrafted basin for at least five consecutive years (Lambert, 1984).

The California State Supreme Court moderated this position in 1949 by creating a system of “mutual prescription” in which users of an overdrafted basin were allocated extraction in proportion to their prior use, and total extraction was to be within a “safe yield” (California DWR, 2003). This created an incentive for overdrafted basin users to expand their groundwater use during times of overdraft, in order to receive a more favorable court allocation. Mutual prescription was modified in 1975 so that it could not infringe on public water agencies’ rights to groundwater (California DWR, 2003). In addition, the state legislature later moderated this by allowing the adjudicated allocation to be based also on supplemental water used in lieu of groundwater during an overdraft period (Lambert, 1984; California Water Code 1005.1-4).

In more recent adjudications, the larger water users in a basin negotiate a solution, which can then be either accepted or rejected in whole or in part by the court (Landridge et al., 2016). In an analysis of California’s adjudicated basins for the State Water Resource Control Board, Landridge et al. (2016) find that the determinants of how water rights are quantified in court adjudications vary considerably across basins. In particular, the “sustainable yield” or quantity of water that can be extracted sustainably from the aquifer is defined differently across cases, and in some cases accounts for artificial recharge, or expected inflows of outside water (Landridge et al., 2016). This in combination with the length and expense of the adjudication process makes the outcomes of adjudication less predictable, and water rights less secure.

In Sears and Lin Lawell (2017), we develop a theory of a dual rights system for groundwater, and evaluate the inefficiencies that arise both analytically and numerically. In particular, we use a combination of dynamic programming, optimal control theory, and game theory to analyze a dual rights system and compare it to a single rights system and to the social optimum. We then make theoretical predictions about the optimal path of water use in California, and how imperfections in the property rights system governing groundwater may impact its use over time. Our results show that a dual rights system can be inefficient and lead to deadweight loss even in the absence of inefficient spending on legal investment. In particular, owing to the common pool nature of the groundwater resource, and to differences in the marginal value of water and in the incentives for capital investment between the farmer and the appropriator, a dual rights system can lead to overextraction of water and underinvestment in capital by the farmer (Sears and Lin Lawell, 2017).

A key component of California's 2014 Sustainable Groundwater Management Act (SGMA) is to allow the newly formed Groundwater Sustainability Agencies (GSA's) to establish local water markets involving the trading of groundwater by users. While this is dependent on GSA's first establishing limits on pumping to allocate groundwater rights, trading can under the right circumstances lead to more efficient allocation, at least locally, as permits can be purchased by users with the highest willingness to pay.

However, there are several practical limits to reaching dynamically efficient behavior even with trading of groundwater rights. For example, rights that are transferred between users will shift the location of pumping within the basin, and can thus create spatial pumping externalities for nearby users (Green Nylen et al., 2017). Permit trading must also be set up with an eye to environmental externalities, as damages from seawater intrusion, or subsidence will not be borne only by the purchaser of a groundwater right, but also throughout the basin (Green Nylen et al., 2017). Finally, improvements in both reporting of groundwater extraction and basin wide conditions must be improved throughout the state. In order for permits to be sustainably allocated, basin managers must be able to understand the physical conditions governing their domains, and whether or not users are abiding by the basin's regulations (Green Nylen et al., 2017). Furthermore, in the absence of metering, Wallander (2017) notes that farmers may over-irrigate due to an incomplete understanding of how much water has been applied. Metering and the publication of results also allow for peer comparisons which has been shown to promote conservation in domestic water use (Ferraro and Price, 2013; Wallander, 2017).

7. Conclusion

An important component of sustainable agricultural groundwater management are complete, measured, enforceable, and enforced property rights that consider the physical properties of the resource (Lin Lawell, 2016). Sustainable agricultural groundwater management policies and institutions need to account for dynamic and spatial considerations that arise with groundwater, as well as for any possible perverse consequences from the policy. Unfortunately, groundwater management policies throughout the world, including recent reforms in groundwater management in California, still fall short of what is needed for agricultural groundwater management to be sustainable, effective, cost-effective, and efficient.

Incentive-based groundwater conservation programs are a prime example of a well-intentioned policy that may have perverse consequences, meaning that they may actually increase rather than decrease groundwater extraction. Irrigation efficiency incentives may actually lead to an increase in groundwater use by lowering the marginal cost of irrigation, and by making marginal land cheaper to irrigate. On the other hand, land retirement programs may prove ineffective since they incentivize the farmer to retire his or her least productive, and thus least likely to be irrigated, land. Thus, when designing policies and regulation, policy-makers need to be aware of the full range of implications of their policy, including any potential perverse consequences.

In order to better design policy and evaluate their possible perverse consequences, it is important to for policy-makers to gather detailed data on groundwater extraction, groundwater levels, crop acreage, and irrigation technology, ideally for each groundwater user at least at an annual frequency. Having detailed panel data will better enable researchers to empirically analyze the effects of past and ongoing policies, and to better design future policies. Ongoing groundwater management reform in California via the California's 2014 Sustainable Groundwater Management Act and 2015 Strategic Plan provides an important opportunity to assess the effectiveness of different policies and to better design future policies.

Policy-makers should also consider incorporating insights from behavioral economics into policy design. Behavioral "nudges" are typically non-financial changes in the manner in which options are presented to decision-makers that may increase the likelihood of a certain behavior. Ferraro, Messer, and Wu (2017) argue that the phenomenon of status quo bias may explain the under-use of the USDA's Conservation Client Gateway, an online suite of services farmers must opt in to use. Changes to this choice structure would then be predicted to increase the utilization of these services (Ferraro, Messer, and Wu, 2017). Similarly, by framing the decision to participate in incentive-based programs in terms of the potential gains from participation, rather than the potential losses from non-participation, conservation programs may not be taking advantage of the phenomenon of loss aversion, in which decision-makers attach greater importance to potential losses than to potential gains (Ferraro, Messer, and Wu, 2017).

Policy-makers may also wish to employ metering and the publication of results that allow for peer comparisons, which has been shown to promote conservation in domestic water use (Ferraro and Price, 2013; Wallander, 2017). In addition, information spillovers from the reporting of the decision-making history of non-neighbors may lead participants to coordinate with their neighbors over repeated interactions at a significantly higher rate (Banerjee, forthcoming). Thus, improved monitoring of groundwater extraction and transparent publication of basin-wide information regarding extraction may be important lower cost alternatives to incentive policies.

The economics of sustainable agricultural management discussed in this paper, including possible perverse consequences, dynamic management, conjunctive management, spatial management, and property rights, have important implications for the design of policies and institutions for groundwater management in California and globally.

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