Chapter x

WATER MANAGEMENT AND ECONOMICS

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Abstract: The sustainable management of groundwater resources for use in agriculture is a critical issue worldwide. 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 for cities and for 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. In this chapter, we discuss the economics of sustainable agricultural groundwater management, including the importance of dynamic management; the importance of spatial management; the possible perverse consequences of incentive-based agricultural groundwater conservation programs; property rights; the groundwater-energy nexus; and the effects of climate change.

Keywords: groundwater, agriculture, water, dynamic management, spatial management, perverse consequences, groundwater-energy nexus, climate change

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1. Introduction

The sustainable management of groundwater resources for use in agriculture is a critical issue worldwide. 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). Worldwide, about 70 percent of groundwater withdrawn is used for agriculture, and, in some countries, the percent of groundwater extracted for irrigation can be as high as 90 percent (National Groundwater Association, 2016).

Increasing competition for water for cities and for 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 (Lin Lawell, 2016). Approximately 25% of global crops are being grown in water-stressed areas (Siebert et al., 2013).

In this chapter, we discuss the economics of sustainable agricultural groundwater management, including the importance of dynamic management; the importance of spatial management; the possible perverse consequences of incentive-based agricultural groundwater conservation programs; property rights; the groundwater-energy nexus; and the effects of climate change.

Throughout this chapter, we also discuss the application of the economics of sustainable agricultural groundwater management to agricultural groundwater management in Kansas and California. California is 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 in 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 (York and Sumner, 2015). Understanding the economics of sustainable agricultural groundwater management is particularly timely and important for California as legislation allowing regulation of groundwater is being implemented there gradually over the next several years (York and Sumner, 2015).

2. Surface Water

The sources of water can be categorized into two types: surface water and groundwater. Surface water includes lakes, streams, and oceans. Surface water is a renewable resource and is provided by the earth's hydrologic cycle (Hartwick and Olewiler, 1998).

The relevant notion of efficiency for surface water is allocative efficiency. Allocative efficiency arises when natural resources are allocated to their more valuable uses. The efficient allocation and price for surface water is that for which the marginal value of water is equalized among all groups of users and set equal to the marginal cost of supplying water (Hartwick and Olewiler, 1998).

The condition for allocative efficiency for surface water, that the marginal value of water should be equalized among all groups of users and set equal to the marginal cost of supplying water, can be generalized along several dimensions. First, if there are environmental uses for surface water, then the efficient allocation and price for surface water would equalize the marginal value of water for environmental uses with the marginal value of water for each of the other groups of users.

Second, if there are environmental externalities associated with supplying surface water, then the costs of these environmental externalities should be included in the social marginal cost of supplying water used to determine the efficient price for water.

Third, since the marginal costs of supplying water vary over time and by region, the marginal costs used to determine the efficient surface water price should be allowed to vary over time and by region.

In addition to surface water, the other main source of water is groundwater. Groundwater is water that is held in underground aquifers. When managing water, water managers should account for both sources of water. Mani, Tsai and Paudel (2016) find that a conjunctive-use framework for managing surface water and groundwater resources can raise groundwater levels. Tsur and Graham-Tomasi (1991) find that when utilized with a stochastic source of surface water for irrigation, groundwater may serve to mitigate fluctuations in the supply of water, and the benefit corresponding to this service, known as the buffer value of groundwater, is positive.

The economics of managing groundwater for agricultural use is the focus of the remainder of this chapter.

3. Dynamic Management

Aquifers are recharged through the percolation of rain and snow (Hartwick and Olewiler, 1998). If an aquifer receives very little recharge, then it is at least partially a nonrenewable resource and therefore should be managed dynamically and carefully for long-term sustainable use (Lin Lawell, 2018c).

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 (Timmins, 2002; Sears, Bertone Oehninger, Lim, and Lin Lawell, 2018; Sears, Lim and Lin Lawell, 2018b). 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 (Sears, Bertone Oehninger, Lim, and Lin Lawell, 2018; Sears, Lim and Lin Lawell, 2018b).

The appropriate notion of efficiency for a nonrenewable resource is that of dynamic efficiency. The dynamically efficient outcome is one that maximizes the present discounted value of the entire stream of net benefits to society. Because the extraction of groundwater both decreases the future amount of groundwater available and increases the future cost of extracting groundwater, the dynamically efficient price for groundwater is higher than the marginal cost of supplying water. Thus, while the (statically) efficient price for surface water is its marginal cost, the dynamically efficient price for groundwater is higher than marginal cost.

Dynamic management may be important in Kansas, for example, where the portion of the High Plains Aquifer that lies beneath western Kansas receives very little recharge (Lin Lawell, 2018c). Thus, groundwater in Kansas is at least partially a nonrenewable resource and therefore should be managed dynamically (Lin Lawell, 2018c).

Dynamic management may similarly be important in California, where recharge rates are low as well. 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, 2018c). This is higher than recharge rates in the Pacific Northwest and is lower than recharge rates in the Alluvium aquifer system (McMahon et al., 2011). Thus, groundwater in California is at least partially a nonrenewable resource and therefore should be managed dynamically (Sears, Bertone Oehninger, Lim, and Lin Lawell, 2018).

4. Spatial Management

In addition to dynamic 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). Spatial externalities resulting from the inability to completely capture the groundwater to which property rights are assigned can lead to over-extraction (Sears, Lin Lawell and Lim, 2018; Sears, Lim and Lin Lawell, 2018a).

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, 2006; 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).

If spatial externalities in groundwater use are significant, they allow insight into the causes of resource over-exploitation. If they are not significant or are very small in magnitude, a simpler model of groundwater user behavior, where each user essentially owns his own stock, is sufficient. Both outcomes would give guidance to policy-makers, although it is important to note that the results are highly dependent on the hydrological conditions of the aquifer (Lin and Pfeiffer, 2015; Lin Lawell, 2016). To make optimal spatial management more politically feasible, Pitafi and Roumasset (2009) devise an inter-temporal compensation plan that renders switching from the status quo to optimal spatial management Pareto-improving.

Pfeiffer and Lin (2012) empirically examine whether the amount of water one farmer extracts depends on how much water his neighbor extracts. Their 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. Their study is the first study to empirically measure economic relationships between groundwater users.

According to their results, Pfeiffer and Lin (2012) find evidence of a behavioral response to this movement in the agricultural region of western Kansas overlying the High Plains Aquifer. Using an instrumental variable and spatial weight matrices to overcome estimation difficulties resulting from simultaneity and spatial correlation, they find that on average, the spatial externality causes over-extraction that accounts for about 2.5 percent of total pumping. These farmers would apply 2.5 percent less water in the absence of spatial externalities (Pfeiffer and Lin, 2012; Pfeiffer and Lin, 2015; Lin Lawell, 2016).

Strengthening the evidence of the behavioral response to the spatial externalities caused by the movement of groundwater is the empirical result that a farmer who owns multiple wells does not respond to pumping at his own wells in the same manner as he responds to pumping at neighboring wells owned by others. In fact, the response to pumping at his own wells is to marginally decrease pumping, thus trading off the decrease in water levels between spatial areas and internalizing the externality that exists between his own wells (Pfeiffer and Lin, 2012; Pfeiffer and Lin, 2015; Lin Lawell, 2016).

Sears, Lim and Lin Lawell (2018a) present a dynamic game framework for analyzing spatial groundwater management. In particular, they characterize the Markov perfect equilibrium resulting from non-cooperative behavior, and compare it with the socially optimal coordinated solution. In order to analyze the benefits from internalizing spatial externalities in California, they calibrate our dynamic game framework to California, and conduct a numerical analysis to calculate the deadweight loss arising from non-cooperative behavior. Results show that the benefits from coordinated management in California are particularly high under conditions of extreme drought, and also when the possibility of extreme rainfall situations are high.

Spatial externalities in groundwater may arise not only between neighboring farmers, but also between neighboring groundwater management jurisdictions as well. Sears, Lin Lawell and Lim (2018) present a model of inter-jurisdictional spatial externalities in groundwater management. They find that groundwater managers each managing a subset of the plots of land that overlie 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 the patches that are managed by different groundwater managers. Moreover, transactions costs and the difficulty of observing and verifying aquifer boundaries, groundwater levels, and groundwater extraction may preclude individual groundwater managers from coordinating with each other to achieve an efficient outcome (Lin, 2010; Lin Lawell, 2018a; Lin Lawell, 2018b).

In order to internalize any inter-jurisdictional spatial externalities, the jurisdictions of local groundwater managers should be large enough to internalize all externalities, so that there are no trans-boundary issues between jurisdictions. This means that local groundwater managers should each cover an entire groundwater basin, and also that a groundwater basin should not be managed by multiple groundwater managers (Sears, Lin Lawell and Lim, 2018).

In 2015, the California Department of Water Resources developed a Strategic Plan to implement its 2014 Sustainable Groundwater Management Act (California Department of Water Resources, 2015). Under California's 2014 Sustainable Groundwater Management Act and 2015 Strategic Plan for implementing it, each groundwater basin is to be managed at the local level by locally controlled Groundwater Sustainability Agencies (GSAs).

In order to internalize any inter-jurisdictional spatial externalities in California, local agencies should each cover an entire groundwater basin, and a groundwater basin should not be managed by multiple Groundwater Sustainability Agencies (Sears, Lin Lawell and Lim, 2018). However, Sears, Lin Lawell and Lim (2018) find that 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 may not internalize all the spatial externalities. As a consequence, the local agencies may behave non-cooperatively, leading to over-extraction relative to the socially optimal coordinated solution (Sears, Lin Lawell and Lim, 2018).

Inter-jurisdictional jurisdictional externalities may also arise if an aquifer is shared across state or country borders. In these cases, transactions costs may be particularly acute and it may be especially difficult to observe and verify aquifer boundaries, groundwater levels, and groundwater extraction; as a consequence, it may be highly unlikely that individual groundwater managers are able to coordinate with each other to achieve an efficient outcome (Lin, 2010; Lin Lawell, 2018a; Lin Lawell, 2018b).

For example, trans-boundary issues may arise between California and Nevada. The Basin and Range aquifers are located in an area that comprises most of Nevada and the southern California desert, and many of the basins are hydraulically connected (Sears, Lim and Lin Lawell, 2018a). Thus, groundwater managers in California and Nevada may behave non-cooperatively with each other, leading to over-extraction relative to the socially optimal coordinated solution. When inter-jurisdictional externalities arise across state borders, it may be efficient for both the state and federal government to be allocated regulatory authority (Lin, 2010; Lin Lawell, 2018a; Lin Lawell, 2018b).

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). Edwards (2016) uses the introduction of management districts in Kansas to test the effect of underlying aquifer heterogeneity on changes in agricultural land value, farm size, and crop choice. A landowner in a county with hydraulic conductivity one standard deviation higher sees a relative land value increase of 5-8% when coordinated management is implemented. Counties with lower recharge also see relative increases in land value. Changes in farm size and percentage of cropland in corn are also consistent with the proposition that the effect of coordinated management is unequal and depends on the properties of the physical system (Edwards, 2016; Lin Lawell, 2016; Sears, Lim and Lin Lawell, 2017; Sears, Lim and Lin Lawell, 2018a).

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). Kuwayama and Brozovic (2013) use a population data set from irrigation wells in the Nebraska portion of the Republican River Basin to analyze whether adopting spatially differentiated groundwater pumping regulations leads to significant reductions in farmer abatement costs and costs from damage to streams. They find that regulators can generate most of the potential savings in total social costs without accounting for spatial heterogeneity. However, if regulators need to increase the protection of streams significantly from current levels, spatially differentiated policies will yield sizable cost savings (Kuwayama and Brozovic, 2013; Lin Lawell, 2016; Sears, Lin Lawell and Lim, 2018; Sears, Lim and Lin Lawell, 2018a).

5. Perverse Incentives from Policy

When designing groundwater management policies, it is important to consider any possible perverse consequences from the policy. For example, 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, such policies can have perverse consequences (Pfeiffer and Lin, 2010; Lin, 2013; Pfeiffer and Lin, 2014a; Pfeiffer and Lin, 2014b; Lin Lawell, 2016; Sears, Bertone Oehninger, Lim, and Lin Lawell, 2018; Sears, Lim and Lin Lawell, 2017; Sears, Lim and Lin Lawell, 2018b).

In many places, policy-makers have attempted to decrease rates of groundwater extraction through incentive-based water conservation programs. Between 1998 and 2005, the state of Kansas spent nearly $6 million on incentive programs, such as the Irrigation Water Conservation Fund and the Environmental Quality Incentives Program, to fund the adoption of more efficient irrigation systems. Such programs paid up to 75% of the cost of purchasing and installing new or upgraded irrigation technology, and much of the money was used for conversions to dropped nozzle systems (NRCS, 2004). These policies were implemented under the auspices of groundwater conservation, in response to declining aquifer levels occurring in some portions of the state due to extensive groundwater pumping for irrigation (Committee, 2001; Pfeiffer and Lin, 2014a).

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 offered $250 per acre to encourage the transition to pressurized irrigation systems (CEC, 2015a; Sears, Bertone Oehninger, Lim, and Lin Lawell, 2018; Sears, Lim and Lin Lawell, 2017; Sears, Lim and Lin Lawell, 2018b).

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; Sears, Bertone Oehninger, Lim, and Lin Lawell, 2018; Sears, Lim and Lin Lawell, 2017; Sears, Lim and Lin Lawell, 2018b).

However, although they are extremely popular, 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. It 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).

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. Such programs operate on an offer-based contract between the landowner and the coordinating government agency. The contractual relationship is subject to asymmetric information, and adverse selection may arise because the landowner has better information about the opportunity cost of supplying the environmental amenity than does the conservation agent. As a consequence, 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, 2009; Pfeiffer and Lin, 2010; Lin, 2013; Lin Lawell, 2016).

In a recent study 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), Pfeiffer and Lin (2014a) 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 (Pfeiffer and Lin, 2014a; Lin Lawell, 2016). Similarly, land and water conservation and retirement programs are not effective in reducing groundwater pumping, which occurs, by definition, on irrigated, and thus, very productive land (Pfeiffer and Lin, 2009; Pfeiffer and Lin, 2010; Lin, 2013; Lin Lawell, 2016).

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 continue irrigating more marginal lands. Furthermore, this increased efficiency may allow farmers to continue growing more water intensive crops, even as groundwater becomes scarcer. Thus, SWEEP funds could make farmers in water-stressed locations less sensitive to existing price signals as groundwater becomes scarce, thereby slowing their adjustment to depleting groundwater stocks over the long term (Sears, Bertone Oehninger, Lim, and Lin Lawell, 2018; Sears, Lim and Lin Lawell, 2017; Sears, Lim and Lin Lawell, 2018b).

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, farmers and water suppliers who rely relatively little on groundwater as a source may use this program most. 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 (Sears, Bertone Oehninger, Lim, and Lin Lawell, 2018; Sears, Lim and Lin Lawell, 2017; Sears, Lim and Lin Lawell, 2018b).

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 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 (Sears, Bertone Oehninger, Lim, and Lin Lawell, 2018; Sears, Lim and Lin Lawell, 2017; Sears, Lim and Lin Lawell, 2018b).

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 ten 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 (Sears, Bertone Oehninger, Lim, and Lin Lawell, 2018; Sears, Lim and Lin Lawell, 2017; Sears, Lim and Lin Lawell, 2018b).

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 retired about 9,000 acres as part of a planned 100,000-acre retirement (California DWR, 2016).

The modest effect of land retirement programs on groundwater extraction in California is evidence of a design flaw in 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 spending by the Conservation Reserve Program 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 (Sears, Bertone Oehninger, Lim, and Lin Lawell, 2018; Sears, Lim and Lin Lawell, 2017; Sears, Lim and Lin Lawell, 2018b).

The 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). Jevons (1865) found this to be true with the use of coal in a wide range of industries (Lin, 2013). In the case of agricultural groundwater, irrigation technology that increases irrigation efficiency does not necessarily lead to less consumption of groundwater (Lin, 2013; Lin Lawell, 2016). In particular, if demand 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).

Thus, when designing policies, policy-makers need to be wary of any potential unintended consequences. Incentive-based groundwater conservation programs are a prime example of a well-intentioned policy gone awry (Lin Lawell, 2016).

6. Property Rights

An important component of sustainable agricultural groundwater management is 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, 2018c).

The absolute ownership doctrine, which is the groundwater rights doctrine in Texas, gives owners of land the absolute right to extract water from their parcels. The correlative rights doctrine, which is the groundwater rights doctrine in Nebraska and Oklahoma, allows a property right to a portion of the aquifer related to the size of the land parcel owned (Lin Lawell, 2018c).

The prior appropriation doctrine, which is the groundwater rights doctrine in Colorado, Kansas, New Mexico, South Dakota, and Wyoming, allots water rights based on historical use, with priority going to those who claimed their right first. Often, rights holders under the prior appropriation doctrine are allowed a maximum level of extraction per year (Sax and Abrams, 1986). Leonard and Libecap (2017) analyze the economic determinants and effects of prior appropriation water rights that were voluntarily implemented across a vast area of the US West, replacing common-law riparian water rights (Lin Lawell, 2018c).

Current water rights in Kansas follow the prior appropriation doctrine. Before 1945, Kansas applied the common law of absolute ownership doctrine to groundwater. Water rights were not quantified in any way (Peck, 2007). In 1945, following multiple conflicts between water users and several major water cases that reached the Kansas Supreme Court, the "Arid Region Doctrine of Appropriation" was adopted, which permitted water extraction based on the principle of "first in time, first in right" (Peck, 1995).

In Kansas, the earliest appropriators of water maintain the first rights to continue to use water in times of shortage or conflict. The water right comes with an abandonment clause; if the water is not used for beneficial purposes for longer than the prescribed time period, it is subject to revocation (Peck, 2003). To obtain a new water right, an application stating the location of the proposed point of diversion, the maximum flow rate, the quantity desired, the intended use, and the intended place of use must be submitted to and approved by the Department of Water Resources (*Kansas Handbook of Water Rights*, 2006). Since 1945, Kansas has issued more than 40,000 groundwater appropriation permits (Peck, 1995). The permits specify an amount of water that can be extracted each year and are constant over time (Lin Lawell, 2018c).

Through the 1970s, the period of intensive agricultural development in Kansas, groundwater-pumping permits were granted to nearly anyone who requested them. Some permits are as old as 1945, but the majority (about 75 percent) were allocated between 1963 and 1981 (Lin Lawell, 2018c). In 1972, owing to concerns that the aquifer was over-appropriated, Kansas created five groundwater management districts (GMDs). The GMDs regulate well spacing and prohibit new water extraction within a designated radius of existing wells, which varies by GMD (Lin Lawell, 2018c).

The adoption of the prior appropriation doctrine, together with the development of GMDs to regulate new appropriations of water rights, arguably eliminated uncontrolled entry and the resulting over-exploitation commonly associated with common property resources in Kansas. Restricting water rights can reduce groundwater extraction in Kansas even when *ex post* the water rights are not binding (Li and Zhao, forthcoming). However, appropriation contracts distort the incentive to optimize dynamically over the life of the resource, because the farmer is essentially guaranteed his appropriated amount of water until the resource becomes so scarce that it is no longer economical to pump (Lin Lawell, 2018c).

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 that 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; Sears and Lin Lawell, 2018).

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 (Sears and Lin Lawell, 2018).

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).

As part of determining allocation, the California State Water Resources Control Board has monitored groundwater use in four counties in Southern California since the 1950s through the California Groundwater Recordation Program (California Water Code 4999 et. seq.). The program allows the California State Water Resources Control Board to determine both the extraction shares of users and when periods of overdraft occur (Sears and Lin Lawell, 2018).

7. Groundwater-Energy Nexus

Energy is an important input needed to extract groundwater for irrigation. Dumler et al. (2009) estimate that the energy cost of extracting irrigation water represents approximately 10%

of the costs for growing corn in western Kansas, which is a slightly greater share of costs than land rent. Of the acres irrigated from groundwater wells in Kansas, about 50% are supplied by pumps powered with natural gas, 25% are supplied by pumps powered with diesel fuel, and 22% are supplied by pumps powered with electricity (USDA, 2004).

In California, most of the energy for irrigation comes from electricity, though a substantial amount comes from diesel (CEC, 2005). Of the total on-farm energy expense for pumping irrigation water in California in 2013, 86% was for electricity; 13% was for diesel and biodiesel; and the remaining less than 1% was for liquefied petroleum gas, gas propane, butane, natural gas, gasoline, and ethanol (USDA, 2013).

Pfeiffer and Lin (2014c) report that energy prices do have an effect on groundwater extraction, causing water use to decrease along both the intensive and extensive margins. Increasing energy prices would affect crop selection decisions, crop acreage allocation decisions, and the demand for water by farmers. This finding is particularly important in the face of possible increases in energy prices in the future, which may cause farmers to respond by decreasing their water use. Their results also suggest that policies that reduce energy prices would cause groundwater extraction to increase, therefore posing a potential concern to conservationists who are worried about declining water table levels in many of the world's most productive agricultural basins that depend on groundwater.

8. Climate Change

Climate change has the potential to impact groundwater availability in several ways. First, changes in climate may indirectly impact groundwater availability by causing changes in agricultural land use and changes in agricultural practices that then result in changes in water availability. For example, climate change may cause farmers to change the crops they plant or the amount of water they apply, both of which have implications for water availability (Bertone Oehninger, Lin Lawell and Springborn, 2018a).

Second, climate change may affect water availability directly. For example, changing climates may result in melting snowcaps and/or changes in precipitation that would affect the availability of water for agriculture (Bertone Oehninger, Lin Lawell and Springborn, 2018a).

Climate change is characterized by uncertainty and the possibility of catastrophic damages with small but non-negligible probabilities (Weitzman, 2014). Tsur and Zemel (1995) study the optimal exploitation of renewable groundwater resources when extraction affects the probability of the occurrence of an event that renders the resource obsolete. They find that under uncertainty, when the event occurrence level is unknown, the expected loss due to the event occurrence is so high that it does not pay to extract in excess of recharge, even though under certainty doing so would be beneficial (Tsur and Zemel, 1995).

Bertone Oehninger, Lin Lawell, and Springborn (2018a) analyze the effects of changes in temperature, precipitation, and humidity on groundwater extraction for agriculture using an econometric model of a farmer's irrigation water pumping decision that accounts for both the intensive and extensive margins. They find that changes in climate variables influence crop selection decisions, crop acreage allocation decisions, technology adoption, and the demand for water by farmers. Bertone Oehninger, Lin Lawell, and Springborn (2018b) find that such changes in behavior could affect land use and agricultural biodiversity.

9. Conclusion

Sustainable agricultural groundwater management policies need to account for dynamic and spatial considerations that arise with groundwater, as well as for any possible perverse consequences from the policy. Important components of sustainable agricultural groundwater management are complete, measured, enforceable, and enforced property rights that consider the physical properties of the resource, as well as carefully designed policies that internalize any externalities, whether they are caused by the physical movement of water, by environmental damages or benefits, or by other causes (Lin Lawell, 2016). Groundwater management policies should also consider any tradeoffs involved between water quantity and water quality, as it is possible for groundwater management policies to lower quantity while improving quality or vice versa (Roseta-Palma, 2002).

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. 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.

The water management and economics discussed in this chapter – including the importance of dynamic management; the importance of spatial management; the possible perverse consequences of incentive-based agricultural groundwater conservation programs; property rights; the groundwater-energy nexus; and the effects of climate change – have important implications for the design of policies for sustainable agricultural groundwater management worldwide.

An important direction for future research is the design and evaluation of sustainable agricultural groundwater management policies worldwide that synthesize and incorporate the economics of sustainable agricultural groundwater management discussed in this chapter.

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