Spatial Groundwater Management: A Dynamic Game Framework and Application to California[1]

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Abstract

The design of policies and institutions to promote the sustainable management of groundwater resources for use in agriculture is both a long-term and short-term challenge in California and globally. When designing groundwater management policies, it is important to account for spatial externalities that may lead groundwater users to behave non-cooperatively. Spatial externalities 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. In this paper, we present a dynamic game framework for analyzing spatial groundwater management. In particular, we 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, we 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 inefficiencies arising from spatial externalities are driven by higher returns on crops, electricity input prices, whether the crop is an annual crop versus a perennial, the level of the groundwater stock, the climate of the region, and the adjustment costs of fallowing production. We find that the benefits from coordinated management in California are particularly high when crop prices are high.

Keywords: Groundwater management; dynamic games; California agriculture; spatial externalities

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1. Introduction

Groundwater is a critical input for agriculture throughout the world. The proportion of groundwater withdrawn that is used for irrigating agriculture is about 70 percent worldwide, and as high as 90 percent in some countries (National Groundwater Association, 2016). Part of the reason that groundwater has been so instrumental in the development of agriculture is due to its usefulness in areas where rain-fed agriculture is impossible, and where there are few surface water supplies. This has allowed farmers to gain the most from groundwater in areas with little natural recharge, leading to a long-term decline in water table levels in many of the world's most productive agricultural regions. As a result, around one quarter of global crops are grown in water-stressed regions (Siebert et al, 2013).

The design of policies and institutions to promote the sustainable management of groundwater resources for use in agriculture is both a long-term and short-term challenge in California. Over 96 percent of harvested cropland in California was irrigated in 2012 (USDA, 2014). Moreover, there is a large asymmetry between non-irrigated and irrigated farmland, with irrigated farms producing on average three times more revenue than non-irrigated farmland (USDA, 2014). This is due to California's role as a leader in the production of high-value, water-intensive, specialty crops like fruit, nuts, and vegetables (Howitt and Lund, 2014). However, over time this has led to a decline in groundwater stocks in California's most important agriculture regions, including the Central Valley, where areas like the Tulare Basin have experienced an estimated depletion of about 80 km^3 since 1960 (Scanlon et. al., 2012). In recent years, California has experienced its third worst drought in over a century, leading to even greater reliance on groundwater, as surface water supplies from the California State Water Project were severely restricted (Howitt and Lund, 2014; CA DWR, 2016). Calls for greater regulation of groundwater followed, and with the passage of the Sustainable Groundwater Management Act (SGMA) in 2014, legislation that is in the process of being implemented across the state (York and Sumner, 2015; Sears et al., 2018; Sears, Lim and Lin Lawell, 2017; Sears, Lim and Lin Lawell, 2018; Sears and Lin Lawell, 2019).

Groundwater has important spatial properties that must be accounted for in both the monitoring of the resource and the design of policies used to manage it. Groundwater aquifers can be hydraulically connected over a large geographical area, allowing the water across property lines in a manner determined by both the physical properties of the aquifer system, and the effects of groundwater pumping and other human activities. This creates a common pool resource problem in which farmers who share a hydraulically connected groundwater resource can affect the extraction costs and availability of groundwater for their neighbors through their own pumping decisions (Pfeiffer and Lin, 2012; Lin and Pfeiffer, 2015; Lin Lawell, 2016; Sears et al., 2018; Sears, Lim and Lin Lawell, 2018). The extent of this spatial externality then depends on both the physical properties of the aquifer, and the economic incentives governing the behavior of the groundwater users.

In this paper, we present a dynamic game framework for analyzing spatial groundwater management. In particular, we 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, we calibrate our dynamic game framework to California, and conduct a numerical analysis to calculate the deadweight loss arising from non-cooperative behavior.

Our results show that the inefficiencies arising from spatial externalities are driven by higher returns on crops, electricity input prices, whether the crop is an annual crop versus a perennial, the level of the groundwater stock, the climate of the region, and the adjustment costs of fallowing production. We find that the benefits from coordinated management in California are particularly high when crop prices are high.

The balance of the paper proceeds as follows. We discuss spatial externalities in Section 2. Section 3 presents our dynamic game framework. Section 4 presents our numerical application to California. Section 5 presents our results. Section 6 concludes.

2. Spatial Externalities

Groundwater users face two types of spatial externalities that lead to non-cooperative behavior. The first is a pumping cost externality: withdrawal by one user lowers the water table and increases the pumping cost for all users. The second is a strategic externality: what a farmer does not withdraw today will be withdrawn by other farmers, which undermines the farmer's incentive to forgo current for future pumping.

Policy-makers face a tension between tailoring the rules that govern groundwater management to local conditions, and coordinating management over hydraulically connected resources so as to limit the social cost of spatial externalities. The cost of uncoordinated management stems from the spatial externalities arising from groundwater resources that span across political boundaries (Dinar and Dinar, 2016). This tension between localized versus coordinated management is a central trade-off in debates over the optimal degree of decentralization in environmental and resource management (Lin, 2010; Lin Lawell, 2018a; Lin Lawell, 2018b). 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.

Theoretical evidence exists showing that spatial externalities are potentially important causes of welfare loss and resource over-exploitation (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).

Pfeiffer and Lin (2012) use a spatially explicit econometric model to empirically measure the economic relationships between groundwater users in Western Kansas overlying the High Plains Aquifer system. According to their results, Pfeiffer and Lin (2012) find evidence of a behavioral response to this movement of water across space. 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 overextraction that accounts for about 2.5 percent of total pumping. 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).

Strengthening the evidence of the behavioral response to the spatial externalities caused by the movement of groundwater is Pfeiffer and Lin's (2012) empirical result that when a farmer owns multiple wells, he 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, Pfeiffer and Lin (2012) find that the response to pumping at a farmer's 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; Lin and Pfeiffer, 2015; Lin Lawell, 2016).

3. Dynamic Game Framework

To characterize the differences between non-cooperative behavior and optimal spatial management, we present a dynamic game framework that contrasts the decisions of an individual farmer with that of a social planner. Our dynamic game framework builds upon and synthesizes previous theory models that find that 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).

In particular, we characterize the Markov perfect equilibrium resulting from non-cooperative behavior, and compare it with the socially optimal coordinated solution. As seen in our dynamic game framework, farmers behaving non-cooperatively will overextract water relative to the socially optimal coordinated solution if there is spatial movement of water between patches owned by different farmers.

Following Pfeiffer and Lin (2012) and Lin Lawell (2018c), we model an aquifer basin upon which lie many plots of land $i = 1, ..., I$. The equation of motion for groundwater stock s_i is given by:

$$s_{i,t+1} = s_{it} - w_{it} + g_{it}(w_{it}) + \sum_{j=1}^{I} \theta_{ji}(s_{1t}, ..., s_{It}) s_{jt} . \tag{1}$$

where $g_{it}(w_{it})$ is recharge, which is a function of return flow (the proportion of the amount pumped that returns to the groundwater table) and precipitation; and where the net flow rate $\theta_{ji}(\cdot)$ from patch *j* to patch *i*, which is defined by defined as the proportion of the water that starts in patch *j* and disperses to patch *i* by the next period, is given by the Darcy's Law for water movement through a porous material as follows (Pfeiffer and Lin, 2012; Lin Lawell, 2018c):

$$\theta_{ji}(\cdot) = k_j \frac{s_j - s_i}{x_{ji}} , \tag{2}$$

where k_j is the transmissivity (or hydroconductivity) of the material holding the water in patch *j*, and x_{ji} is the distance between plots *i* and *j*.

Owing to the dependence of the stock $s_{i,t+1}$ next period on the stock of farmer *i*'s neighbors *j* via the proportion $\theta_{ji}(\cdot)$ of the water that starts in patch *j* and disperses to patch *i* by the next period, it is possible that a farmer considers the effect that his pumping has on future groundwater levels for both his own patch and that of his neighbors. It is also possible that a farmer's groundwater extraction decisions may depend on the groundwater stock and groundwater extraction of his neighbors. We therefore use a dynamic game framework to model the non-cooperative behavior among farmers sharing an aquifer.

The equilibrium concept we use is that of a Markov perfect equilibrium. Each farmer is assumed to play a Markov "state-space" strategy: the past influences current play only through its effect on the state variables. A farmer's dynamically optimal water extraction policy is then the Markov strategy that it plays in the Markov perfect equilibrium, which is a profile of Markov strategies that yields a Nash equilibrium in every proper subgame (Fudenberg and Tirole, 1998). In our theory model, the state variables are the groundwater stock of each farmer *i*; in our numerical simulations we also add rainfall as an additional state variable.

Let $R_{it}(w_{it})$ denote the per-period revenue that can be generated by producing crops with extracted irrigation water w_{it}, assuming crops are chosen optimally to maximize revenue given extracted irrigation water w_{it}. Let $C_{it}(w_{it}, s_{it})$ denote the cost of extracting water and $\frac{\partial C_{it}(w_{it}, s_{it})}{\partial w_{it}} = C^w(s_{it})$ denote the marginal cost of extracting water, both of which depend on the distance that the water must be pumped from the aquifer to the surface of the ground. The distance the water must be pumped depends on the stock of water s_{it}; as the stock decreases, pumping cost increases: $\frac{\partial C^w(s_{it})}{\partial s_{it}} < 0$. Let the discount rate be denoted by *r*.

An individual dynamically optimizing farmer behaving non-cooperatively with respect to other farmers will choose groundwater extraction w_{it} each period *t* in order to maximize the present discounted value of his entire stream of per-period profits, conditional on the groundwater stocks s_{jt} and water extraction strategies $w_{jt}(\cdot)$ of all his neighbors *j*. We denote the vector of stocks s_{jt} of all of *i*'s neighbors *j* as $s_{-i,t} = (s_{1t}, ...s_{i-1,t}, s_{i+1,t}, ..., s_{It})$. We similarly denote the vector of groundwater extraction strategies $w_{jt}(\cdot)$ of all *i*'s neighbors *j* as $w_{-i,t}(\cdot)$. The optimization problem faced by an individual dynamically optimizing farmer behaving non-cooperatively with respect to other farmers is therefore given by:

$$\max_{\{w_{it}\}_t} \sum_{t=0}^{\infty} \left(\frac{1}{1+r} \right)^t \left(R_{it}(w_{it}) - C_{it}(w_{it}, s_{it}) \right), \tag{3}$$

subject to the equation of motion (1) and to the following transversality condition:

$$\lim_{t \to \infty} \left(\frac{1}{1+r} \right)^t \lambda_{it} s_{it} = 0, \tag{4}$$

and conditional on the groundwater stocks s_{jt} of all of farmer *i*'s neighbors *j*.

For an individual dynamically optimizing farmer behaving non-cooperatively with respect to other farmers, the decision of how much water to pump in the current period versus how much water to pump in future periods can be expressed using the following Bellman equation (Bellman, 1957):

$$V_{it}(s_{it}; s_{-i,t}, w_{-i,t}(\cdot)) = \max_{\{w_{it}\}_t} R_{it}(w_{it}) - C_{it}(w_{it}, s_{it}) + \frac{1}{1+r} EV_{i,t+1}(s_{i,t+1}; s_{-i,t+1}, w_{-i,t+1}(\cdot)), \tag{5}$$

subject to the equation of motion (1).

To determine the socially optimal coordinated solution, consider a single owner or social planner who must make pumping decisions for an entire aquifer basin, upon which lie many plots of land $i = 1,...,I$ with groundwater pumps. This social planner seeks to maximize the present value of aggregate profit by planning for this aquifer basin (assuming there is no flow in or out of the aquifer):

$$\max_{\{\{w_{it}\}_t\}_i} \sum_{t=0}^{\infty} \left(\frac{1}{1+r}\right)^t \sum_{i=1}^{I} \left(R_{it}(w_{it}) - C_{it}(w_{it}, s_{it})\right), \tag{6}$$

where the social planner chooses the set of pumping volumes w_{it} on each plot of land i in each time period t, subject to the equation of motion (1) and the transversality condition (4) for all plots of land i. In this formulation, the social planner is pumping water from each plot for use on that plot's crops. The social planner will consider each plot's shadow value of a unit of groundwater stock when determining the optimal solution, so as to internalize any externality that could occur (Pfeiffer and Lin, 2012).

The social planner's intertemporal choice of water extraction satisfies the following Bellman equation:

$$V_t(s_{1t},...s_{It}) = \max_{\{\{w_{it}\}_t\}_i} \sum_{i=1}^{I} [R^{it}(w_{it}) - C_{it}(w_{it}, s_{it})] + \frac{1}{1+r} EV_{t+1}(s_{1,t+1},...s_{I,t+1}), \tag{7}$$

subject to the system of equations of motion (1) for all plots of land i.

4. Illustrative Example From California

Groundwater management has become an important policy question in California due to the growth of both population centers and high-value agriculture in arid regions. In Southern

California, disputes between agricultural and municipal users have frequently led to lengthy and costly court adjudications (Landridge et. al., 2016). The state's most important agricultural regions -- 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" -- are heavily reliant on groundwater (York and Sumner, 2015). Groundwater extraction in excess of natural and managed recharge has caused historically low groundwater elevations in many regions of California (California Department of Water Resources, 2017a).

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). Each groundwater basin is to be managed at the local level by locally-controlled Groundwater Sustainability Agencies (GSAs). Each Groundwater Sustainability Agency is responsible for developing and implementing a groundwater sustainability plan. The California Department of Water Resources' primary role will be to provide guidance and technical support to local agencies (California Department of Water Resources, 2015).

However, it is not clear whether the 2014 Sustainable Groundwater Management Act (SGMA) nor its 2015 Strategic Plan for implementation adequately addresses spatial externalities that may lead to non-cooperative behavior among groundwater users sharing the same aquifer. For example, farmers who were surveyed in Yolo County differed with one another on potential policy mechanisms in SGMA, such as the development of water markets and drilling moratoriums (Niles and Wagner, 2018). Transactions costs and the difficulty of observing and verifying aquifer boundaries, groundwater levels, and groundwater extraction may preclude individual farmers and/or groundwater managers from coordinating with each other to achieve an efficient outcome (Lin, 2010; Lin Lawell, 2018a; Lin Lawell, 2018b; Sears and Lin Lawell, 2019). Indeed, while farmers in Yolo County felt that they were able to participate in their GSA through irrigation districts involvement, they did not believe that farmer interests were adequately represented in the decision making process (Niles and Wagner, 2018).

In order to analyze the benefits from internalizing spatial externalities in California, we apply our dynamic game framework to California, and conduct a numerical analysis to calculate the deadweight loss arising from non-cooperative behavior. We calibrate the parameters in our dynamic game framework to match those found in different aquifer systems in California, and then vary the underlying spatial and physical parameters governing the system, in order to show how the potential consequences of spatial externalities vary across the state.

For our numerical analysis, we consider two 50-acre plots i of land lying adjacent to one another, with a single well at the center of each. In each period, representing a growing season, the farmer chooses between three levels of groundwater extraction w_{it} for the growing season. Extracted groundwater w_{it} is the only source of water for each plot i's irrigation water in our model. This reflects the fact that precipitation in California occurs outside of the growing season for many crops, leaving agriculture primarily reliant on irrigation. Rain therefore affects groundwater extraction decisions through its effect on recharge. Rain enters our model stochastically as an independent and identically distributed shock each period that is common to both plots. The current value of rain is known to the farmer when making water extraction decisions, but future values of rain are uncertain. Our state variables therefore include not only the groundwater stock of each farmer i, but also rainfall as well.

Each period, crop production is determined using a simple function of irrigation water w_{it}. While inputs such as capital, labor, or fertilizer affect the yield of the crop, in order to focus the intuition on the water extraction decision we assume that these inputs are used at a fixed level.

Each plot *i* has a production technology A_i which represents these and other fixed factors related to the plot that affect production, including soil quality. Finally, we assume the price p_c of the crop is known to the farmer. Thus, the per-period revenue function for a given plot can be written as:

$$R_{it}(w_{it}) = A_i p_c w_{it}^{\alpha}.$$

The cost function for each plot is composed of two parts: the cost of groundwater extraction and a fixed cost of other inputs. Each plot has a fixed maximum quantity of water that its water table can store, which we call storage S_i. The cost of water is dependent on both the quantity extracted w_{it} and the depth of the water table, which is given by the difference between storage S_i and the water stock s_{it}. In our model we use the following cost function:

$$C_{it}(w_{it}, s_{it}) = p_e \frac{\lambda}{e_i}(S_i - s_{it})w_{it} + F_i,$$

where p_e is the price of electricity (in \$/kwh), $\lambda = 1.551$ is a the amount of electricity (in kwh) required to lift 1 acre-foot of water 1 foot in height (Rogers and Alam, 2006), e_i represents the efficiency of the irrigation technology, and F_i represents additional operating costs.

Our model allows for strategic interaction across space through the flow of groundwater between plots. We use the functional form assumption for the net flow rate $\theta_{ji}(\cdot)$ derived from Darcy's Law in equation (2). Thus, both the distance and transmissivity parameters control the spatial linkage of the two farms.

To solve for the socially optimal coordinated solution, we solve the social planner's dynamic optimization problem in equation (6) of choosing water extraction for both plots of land so as to maximize the total expected present discounted value of the entire stream of per-period profits from both plots of land. In particular, we solve for the social planner's value function in the Bellman equation (7) by solving for a fixed point. From Blackwell's Theorem, the fixed point is unique. The value function is the present discounted value of the entire stream of per-period payoffs for each state when the actions are chosen optimally. The solution thus yields the socially optimal coordinated strategy.

To obtain the non-cooperative solution, we solve for the Markov perfect equilibrium in a game in which the plots are managed by two different farmers, each of whom chooses water extraction from his own plot to maximize the expected present discounted value of the entire stream of per-period profits from his plot, conditional on the strategy and stock of the other farmer. As explained above, a Markov perfect equilibrium is a profile of Markov strategies that yields a Nash equilibrium in every proper subgame (Fudenberg and Tirole, 1998). To solve for the Markov perfect equilibrium, we iterate the set of value functions in equation (5) for both farmers until the value functions converge to a fixed point and the best response functions converge to a fixed point. In each iteration, we update the strategies of each player such that they represent the best response to the strategy employed by the other player. Convergence of both the value and policy functions thus yields the Markov perfect equilibrium.

In order to estimate the deadweight loss arising from spatial externalities, we calculate the difference between the present discounted value of the entire stream of per-period payoffs from coordinated management, and the present discounted value of the entire stream of per-period payoffs from non-cooperative behavior. This deadweight loss from non-cooperative behavior is a measure of the benefits from coordinated management.

For our base case simulations, we calibrate our model of the dynamic game between two adjacent 50-acre plots using data from an existing 2016 cost study for a 50-acre alfalfa farm in

Tulare County, California (Clark et al., 2016). Tulare County is in the South San Joaquin Valley, which overlies the Central Valley Aquifer system in California. During the production years, the 50-acre Tulare County alfalfa farm in this study uses border flood irrigation. The water is pumped through alfalfa valves at the head of the field and flows down the alfalfa check between the borders. A semi-permanent drain ditch is dug at the edge of the field using a V-Ditcher pulled by a tractor. All field operations turn inside the field and do not cross the drain. From April to October, 10 irrigations totaling 5.3 acre-feet of water per acre, or 265 acre-feet of water for the entire 50-acre plot, are applied by flooding the checks based on evapotranspiration (ET) requirements. Applied water values are greater than the actual water requirement due to an estimated application efficiency of 75 percent. The actual water requirement will vary each year based on soil, climatic, and plant physiological factors.

The cost shares of irrigation in production yield an exponent on water extraction in the per-period revenue function to equal $\alpha = 0.3$. We also use the estimates in Clark et al. (2016) of the costs of establishing the crop, the irrigation system, land costs, and the cost of equipment, which total \$871 per acre per year, or \$43,550 for the entire 50-acre plot (Clark et al., 2016). We calibrate our model by assuming that productive capital of \$871 per acre, in combination with the irrigation schedule suggested in the cost study, produce a yield of 10 tons per acre. We can then use total expected production of 500 tons over a 50-acre plot to solve for our baseline $A_i = 1.3 * K^{\kappa}$ using values of $K_i(t) = \$43,550$, an exponent on capital of $\kappa = 0.4$, $w_{it} = 265$, and $\alpha = 0.3$. This provides us with our baseline production parameters which will be used in simulation. We take the price of alfalfa from Clark et al. (2016), which uses \$250/ton as a baseline value.

In the base case, our physical system is calibrated to resemble conditions existing in Tulare County, part of the Central Valley aquifer system in California. For precipitation, we use annual precipitation from 1922-2016 recorded at 6 stations by the California Department of Water Resources to produce discretized probability mass functions for annual rainfall of between 0-4 feet per acre (California Department of Water Resources, 2017d). For transmissivity (or hydroconductivity), we use an average hydrological conductivity value estimated for the Tulare basin of 6.55 feet per day (Williamson et al., 1989). The parameter values we use for our base case simulation are presented in Table 1a.

In order to capture the regional diversity of California's crop production, hydrological conditions, and climate, we also calibrate our dynamic game framework for several other regions and crops that are representative of California. In each case we take cost and production parameters from cost-return studies conducted by the University of California Cooperative Extension program, and assume that production is done on two 50-acre farm plots, to make our results comparable to the base case. We use data from cost studies of farms ranging in size from 20-100 acres, and then scale the parameters to two 50-acre farm plots. Our climate conditions are taken from historical annual data from the PRISM Climate Group (2017).

In addition to alfafa in the Tulare County, a second crop-region scenario we simulate is fresh market strawberry production in the Central Coast region, using parameter values calibrated to Bolda et al. (2016) as presented in Table 1b. This involves both more efficient drip irrigation, a more water intensive and higher priced crop, and a more drought prone climate.

A third crop-region we simulate are walnuts grown in the North Coast, using parameter values calibrated to Elkins, Klonsky and Tumber (2012) as presented in Table 1c. Here the primary innovation is that we model a perennial crop. We simplify the growth of the crop into two periods: planting, and production. If the crop is not irrigated, then the orchard must be re-planted, which incurs a planting cost. The crop also must be irrigated for one period before it can return to production. This incentivizes the farmer to maintain irrigation due to the dynamic nature of perennial crop production. The North Coast is also the most precipitation-prone region we examine.

A fourth crop-region we simulate are table olive production in the Sacramento Valley, using parameter values calibrated to Lightle et al. (2016) as presented in Table 1d. Here, we again model a perennial crop, but in a more arid context, and with higher planting costs.

A fifth crop-region we simulate are organic almonds in the Northern San Joaquin Valley, using parameter values calibrated to Holtz et al. (2016) as presented in Table 1e. This is the most arid climate we study. In addition, almonds are a high value perennial crop.

Sixth, we consider avocado production in the South Coast, using parameter values calibrated to Takele, Faber and Vue (2011) as presented in Table 1f. Avocados permit the practice of "canopy stumping", in which the avocado tree is cut to a smaller size in order to temporarily reduce its water demands (Dinar et al., 2017). We model this by allowing the crop to transition from productive state to a non-productive state when farmer chooses to not irrigate the crop. The crop can then be re-grown in a future period through irrigation. Unlike our other perennial crops, this does not involve re-planting the crop, meaning that there is no planting cost entailed.

Seventh, we return to the South San Joaquin Valley to examine orange production, using parameter values calibrated to O'Connell et al. (2015) as presented in Table 1g. Here we use our baseline climate conditions, with a perennial crop produced using micro sprinkler irrigation.

In our final simulation, we use our baseline climate for Tulare County, but allow for the first plot to be used for alfalfa production, while the second is used for oranges. This allows for differences in the productivity of land that shares a hydraulically connected groundwater source.

Owing to computational constraints, we limit the size of our action space in the simulations by discretizing water extraction into bins of 100 acre-feet each. We allow for the farmer to extract 0, 100, 200, or 300 acre-feet of water, representing a range from essentially not planting, to under-watering (or more realistically, reducing the planted acreage), to fully watering (planting and watering the full acreage).

We set the storage S_i on each plot to be 20 acre-feet per acre, or 1000 acre-feet on the entire 50-acre plot, for most of the crop-region scenarios, including the base case.[2] We assume that water beyond the storage S_i is either unavailable, or not economical to access either because of the costs of drilling a deeper well, or the costs of extraction. We take the price per kwh of electricity from the first 2017 Pacific Gas and Electric (PGE) summer AG-1A rate, a flat rate energy charge used for small agricultural users. The electricity price was \$0.28/kwh at the start of 2017. For our discount factor $\beta = \frac{1}{1+r}$, we use a value of 0.9.

5. Results

Table 2 presents the results of our deadweight loss from non-cooperative behavior on the two 50-acre plots of land for our base case scenario of alfafa in Southern San Joaquin Valley, for different combinations of state variables for the groundwater stocks in both plots and the current-year rainfall. The deadweight loss measures the benefits from coordinated management in California. Since the values reported represent the deadweight loss from non-cooperative behavior

[2] Owing to computational constraints, we reduce the storage on each plot to 15 acre feet per acre, or 750 acre-feet on the entire 50-acre plot, for a few crop-region scenarios.

on two 50-acre plots of land, and are therefore orders of magnitude smaller than what the deadweight loss would be if we were to model all the farmers in the entire Tulare Basin or all of California, the Markov perfect equilibrium for which is too computationally intensive to solve, we focus on discussing relative values rather than actual magnitudes of deadweight loss.

According to our base case results in Table 2, the deadweight loss from non-cooperative behavior is highest when there is an imbalance in the stock at each plot, and the stock levels are either moderate or high. This reflects the fact that not using stock in the present allows remaining stock to flow to the neighboring plot. In addition this flow of water significantly changes the cost of extraction from relatively cheap, to much more expensive. Deadweight loss is lowest when stock at one plot is low and the other is moderate. Here the strategic changes in behavior induced by the flow of water between plots may be smaller due to the fact that higher pumping costs make overextraction prohibitively expensive. Deadweight loss in the case of balanced stocks, both high and low, falls in between the extremes, with higher values when both stocks are high. Thus, the benefits from coordinated management of groundwater by farmers in California resembling our baseline case are generally lower when at least one stock is nearly depleted. Similarly, the benefits from coordinated management in California are high when stocks are high, or water is relatively cheap, and especially when there is some imbalance between farmers.

In general we find that high rainfall in the winter preceding the growing season leads to higher deadweight loss. High rainfall replenishes both stocks, making water relatively cheaper. This incentivizes the farmer to use water today rather than wait for future periods when the other farmer's extraction can draw water away from the plot. When stocks are already high, or full, high rainfall fills the aquifer to its capacity, and thus equates the stocks. This diminishes the strategic incentive to overextract, and thus dampens the magnitude of the deadweight loss.

In Figure 1 we plot deadweight loss as a function of stock level at plot 1, holding rain constant at a medium level, and allowing stock at the second plot vary from low (200 acre-feet), to medium (1100 acre-feet), to high (1700 acre-feet). In the case of a high stock value at plot 2, we find that deadweight loss rises with stock at plot 1, reflecting the fact that water is cheapest at both plots when stocks are both high. There is a small dip when the stocks are equal, representing the fact that water does not flow between plots creating an incentive to capture water in the present rather than saving it for the future.

Table 3 presents the results of the deadweight loss from non-cooperative behavior for scenarios varying the parameters in our model. We report the results for moderate groundwater stock levels: 1400 acre-feet in one plot and 600 acre-feet in the other.

We first examine the effects of differences in the physical setting. In their analysis of the Central Valley in California, Williamson et al. (1989) found that hydraulic conductivities have a mean of 25 feet per day and a standard deviation of 13 feet per day. We therefore vary the transmissivity from one standard deviation below to one standard deviation above this mean. We find that variations in transmissivity across this range do not affect the deadweight loss.

The price of electricity represents an important driver of the cost of groundwater extraction. We allow electricity prices to vary from 50 percent lower ($0.14 per kwh) to 100 percent higher ($0.56 per kwh) than our base case value. We find that the deadweight loss is substantially lower when electricity prices are higher.

Next we allow for the possibility of a change in the price of alfalfa. This simulates the effect of a shift in demand for the crop. We allow crop prices to vary from 50 percent lower ($125/ton) to 100 percent higher ($500/ton) than our base case value. We find that deadweight loss is substantially higher when crop prices are high, and lower when crop prices are low.

We then examine the case in which we change the probability distribution of precipitation. This allows us to see how weather patterns may affect the benefits from coordinated management, and how future climate change may exacerbate spatial externalities in California. First, we allow the precipitation to become more temperate. To mimic this we remove the possibility of zero annual precipitation and allow for more frequent cases of 2 feet of annual precipitation. We find that this increases the benefits of coordinated management in each case.

Next we allow for the case in which droughts become more frequent, and high rain years (4 feet of precipitation) become less frequent. We find that this increases the benefits from coordinated management although the change is small.

Third, we allow for more frequent droughts and high rain years. We find that more extreme rainfall conditions substantially decreases the benefits of coordinated management, regardless of current-year rainfall.

We then model the extreme case in which droughts, high rain years (4 feet of precipitation), and medium rainfall levels are all relatively equally likely. We find that these conditions again substantially lower the benefits to coordinated management.

Finally, we simulate a more extreme drought situation in which droughts become even more frequent, and high rain years (4 feet of precipitation) become even less frequent. Here we find a mixed picture. When the plots are already experiencing a drought, this leads to a small increase in the benefits of coordinated management. However, in years following moderate or high rainfall, the benefits of coordinated management are much lower than in the base case.

We also examine how changes in the efficiency of capital may affect the problem. While our initial calibration assumes the use of flood irrigation, policies like the State Water Efficiency and Enhancement Program (SWEEP) in California may incentivize a shift towards more efficient irrigation practices (Sears and Lin Lawell, 2019; Sears, Lim and Lin Lawell, 2017; Sears, Lim and Lin Lawell, 2018). To see how this affects the dynamic game between farmers, we allow for capital to have an efficiency rating of 90 percent, an upgrade in line with a shift to more efficient drip irrigation technology. We find that increases in irrigation efficiency increases the benefits from coordinated management in California. As seen in Figure 2, under this technological shift deadweight loss rises smoothly in the case of high or medium stock levels However, when stock at the second plot is small, deadweight loss follows the opposite pattern, falling and then rising with stock at plot 1.

Overall we find that deadweight loss in this context is most sensitive to the prices of output and the inputs (electricity). This represents both the direct effect, as differences in production are now scaled up or down by the change price of alfalfa, as well as the less direct dynamic effect of dampening or increasing the strategic incentive to overextract. The benefits from coordinated management in California are particularly high when crop prices are high. We find that the effects of climate are mixed. Drought does indeed generally increase the benefit of coordinated management, especially when it is part of an extended dry period. However this is only a moderate effect, and can be offset by an increase in high rainfall years. This is likely in part due to the modeling constraints we have imposed, as at least some of the rain in wet years will likely be lost due to runoff and may even create damage through flooding. Finally, we find that increases in irrigation efficiency are unlikely to eliminate the costs of this strategic behavior. We find that a shift from our base case to one resembling drip irrigation actually leads to larger deadweight losses. This happens through the channel of raising the marginal revenue of extraction, which induces overextraction in the non-cooperative case.

Next we examine how deadweight loss is impacted by both the crop grown in each plot, and by the physical setting of the game. Here we also introduce the idea of perennial crops, which allows for extraction in each period to have an additional dynamic effect on the maturity of the crop in future periods. Results for these additional scenarios are summarized in Table 4.

First, turning to a higher value crop, strawberries, grown in the Central Coast of California, we find that deadweight loss and water extraction are both higher than in the base case. As seen in Figure 3, the deadweight loss declines with the groundwater stock. We also see that fallowing for a year when stocks are low is not chosen as it was in the base case. This suggests first that marginal returns to irrigating are generally higher, both due to the higher value nature of the crop, and due to the higher efficiency of irrigation technology in this scenario. Our results therefore imply that higher value annual crops will likely be irrigated at a higher rate when stocks are high, and that land is less likely to be fallowed when stocks are low.

We next examine a perennial crop, walnuts, grown in a less arid climate, the North Coast. As seen in Table 4 and Figure 4, deadweight loss is low to none, and only occurs in a small subset of states, when stock is relatively high on both plots. This finding suggests that high precipitation offsets some of the strategic consequences of groundwater management, by replenishing stocks at both plots. We also see that fallowing and failing to irrigate are not chosen when water is available This suggests that farmers of perennial crops may choose to irrigate in cases when annual crop growers would choose to fallow their fields. Thus, we expect less response to droughts from perennial crops.

For olives grown in the Sacramento Valley, we find that deadweight loss is higher than in the base case. In Figure 5, we see that the deadweight increases and then decreases with stock. Extraction generally alternates between the minimum and an increased level (200 acre-feet) when stocks are both high in the non-cooperative case. This suggests that in areas with less precipitation, there are strategic groundwater management consequences, and that this generally happens through the channel of overextraction when water is relatively cheaper.

For almonds in the context of the Northern San Joaquin Valley, we find that deadweight loss is actually lower than in the baseline when stock at plot 1 is low. In Figure 6, we see that it remains low when the stock at plot 2 is low, but rises with stock at plot 1 in the other cases. This is driven by the fact that extraction rises to 200 acre-feet at a lower stock level in the non-cooperative case than in the social optimum. In addition, when both stocks are very high, the extraction in the non-cooperative scenario rises to the maximum of 300 acre-feet. Generally it is optimal to plant the crop if none is planted, except when stocks at both plots are very low. The results therefore show that deadweight loss is driven by overextraction when stocks are high. This is likely due to the fact that when both stocks are high, there is an incentive to increase irrigation and receive flows from the neighboring stock.

Avocados in the South Coast can be stumped when costs of extraction are high, and thus, production and irrigation can be temporarily halted. As seen in Table 4 and Figure 7, we find that this induces a case of no deadweight loss. Irrigation is higher when stock at both plots is high. We also see that it in all cases the crop is stumped when stock levels are very low at both plots. Similarly, when the crop is currently stumped, it remains stumped when stocks are low. This suggests that features unique to the crop allow for better drought management, as the crop does not need to be irrigated in order to avoid future re-planting costs. In effect, this allows the farmer to draw stock down to 0, and then wait for replenishment, rather than conserving water so that the crop can be kept alive during dry times. This suggests that avocados may be less responsive to changes in groundwater stock when the stock is moderate to high, but more responsive to changes in groundwater conditions than other crops, as the stock gets very low. Another factor influencing the efficiency of avocado production is the relatively low transmissivity of soil in the South Coast (0.1 ft/day). In conditions like these, differences in stock levels lead to smaller flows of water between plots than in more porous aquifer systems. This allows farmers to manage their own stock more dynamically efficiently, and not overextract for fear of losing stock to their neighbors.

We next turn back to our base case climate and physical conditions, but examine orange production instead of alfalfa. We find that deadweight loss and extraction are similar to the case of North Coast walnut production. We again have a relatively less arid climate than in our other cases, and a perennial crop. Here, as shown in Figure 8, the inefficiency occurs only at a small subset of states, and is driven by increased groundwater use at slightly lower levels of stock in the non-cooperative case. This difference with some of the other perennial crops is likely due to the more forgiving climate conditions, while differences with the base case are driven by the perennial nature of the crop.

Finally we allow for different crops on each plot. We fix plot 1 as an alfalfa plot, while the neighboring plot is used to grow oranges. As shown in Table 4 and Figure 9, deadweight loss is lower in magnitude than in the base case, however, it has a more chaotic pattern, as deadweight loss generally rises with stock at plot 1, although it goes to 0 at several ranges, including when stocks at both plots are high. When stock at the orange plot is low, the deadweight loss becomes highest when stock at the alfalfa plot is high. This suggests that the alfalfa plot's management is likely driving the results, and that overextraction in years when water is relatively cheap may account for this loss of efficiency.

In summary, we find in general that inefficiencies arising from the spatial externality is driven by higher returns on crops, electricity input prices, whether the crop is an annual crop versus a perennial, the level of stock, the climate of the region, and the adjustment costs of fallowing production. Crops with higher marginal returns encourage higher extraction in periods when stock is high and water is cheap. This is exacerbated by the strategic incentive to overextract when there is no cooperation. Perennial crops lock farmers in to a certain level of extraction each year, which limits some of the responsiveness of production to price signals, and may discourage some overextraction in cheap years due to dynamic considerations. Areas that are more arid are associated with higher deadweight loss due to the incentive to use water before it is lost to the neighbor, since it is unlikely to be naturally replaced. Finally, limiting adjustment costs, as in the case of avocados, allows farmers to respond more elastically to the price of water, and limits the cost of strategic inefficiency.

6. Conclusion

When designing groundwater management policies, it is important to account for spatial considerations that may lead groundwater users to behave non-cooperatively. Groundwater is a common pool resource, where each user's pumping has spatially differential effects on the costs and availability of the resource for all other users (Pfeiffer and Lin, 2012; Lin and Pfeiffer, 2015; Lin Lawell, 2016; Sears et al., 2018). Spatial externalities resulting from groundwater users' inability to completely capture the groundwater to which property rights are assigned can lead to overextraction (Sears et al., 2018).

In this paper, we present a dynamic game framework for analyzing spatial groundwater management. As seen in our dynamic game framework, farmers behaving non-cooperatively will overextract water relative to the socially optimal coordinated solution if there is spatial movement of water between patches owned by different farmers. In order to analyze the benefits from internalizing spatial externalities in California, we calibrate our dynamic game framework to California, and conduct a numerical analysis to compare the Markov perfect equilibrium arising from non-cooperative behavior with socially optimal coordinated management.

According to our results, the benefits from coordinated management in California are particularly high when crop prices are high. Inefficiencies arising from the spatial externality are driven by higher returns on crops, electricity input prices, whether the crop is an annual crop versus a perennial, the level of stock, the climate of the region, and the adjustment costs of fallowing production. In addition, the benefits from coordinated management in California are higher when there is an asymmetry between neighboring groundwater stocks and when stock levels are higher. Intuitively, we expect the degree of water extraction to be highest when water is relatively cheap to extract, and when it is likely to be lost to the neighboring plot.

We also see that years in which winter rainfall is high are also the years in which farmers use water least efficiently and deadweight loss is high, except in the case in which stocks are completely full and equal. Thus, policy-makers should be aware especially of wet years following periods of drought.

Our results also show that an extreme drought situation can increase the benefits from coordinated management in California. This is particularly salient for California, which has been experiencing its third-worst drought in 106 years (Howitt and Lund, 2014), and in light of the possibility of extreme drought as a result of climate change. However, we find that within our model, this can be reversed by a corresponding increase in wet years. Our results also indicate that fluctuations in commodity prices have an important role in determining the magnitude of these efficiency losses. Although it is beyond the scope of this paper, the role of risk tolerance and price uncertainty has important implications in determining the dynamic behavior of farmers, and thus may affect the sensitivity of deadweight loss to changes in input and output prices.

Our results show that California, a state with diverse regional climates, and crops, faces substantially different groundwater management problems across contexts. We find that in the case of higher value specialty annual crops like strawberries, deadweight loss becomes substantially larger, while in the case of a perennial crop like oranges, walnuts, and avocados, deadweight loss is limited to only a few cases, and behavior in the non-cooperative case aligns with the social optimum. We find that perennials are not invulnerable to strategic behavior though, as almonds, and especially table olives, grown in relatively arid regions induce substantial deadweight losses. Here deadweight loss appears to be dampened by the inability of perennial farmers to adjust seamlessly to changes in the size of the stock, as fallowing forgoes profits in both the present and the following period. We also see that high value crops have a higher marginal revenue of water, and thus can encourage over-extraction relative to the social optimum. We see that drought management practices like stumping avocado crops can play an import role in allowing farmers to temporarily halt production of perennials and conserve water in periods when water is most expensive. Finally, we see in the context of the South Coastal region that the physical conditions governing the aquifer's ability to transmit water between users plays an important role in aligning private behavior with socially optimal practices.

This result provides support generally for the idea that policies meant to induce sustainable groundwater management should tailored to reflect regional differences in economic and physical conditions. However, the efficiency losses due to strategic and spatial considerations indicate that the policies governing management of the resource should be coordinated across regions in which water supplies are hydraulically connected. The efficiency losses due to splitting management of hydraulically connected groundwater stocks is thus an important area of research for the implementation of the 2014 Sustainable Groundwater Management Act in Californa (Sears, Lin Lawell and Lim, 2018).

Our research has important implications for the design of policies for sustainable agricultural groundwater management for California and globally. Our findings provide predictive results for policy-makers currently implementing the 2014 Sustainable Groundwater Management Act in California. Furthermore, with long term shifts in global climate and crop patterns, groundwater management problems resembling California's may very well present themselves elsewhere in the future.

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Table 1a. Parameter values: Alfafa in Southern San Joaquin Valley (Base case)

Alfafa, Southern San Joaquin Valley		
	Value	**Source**
County	Tulare	
Aquifer System	Central Valley	
Yield	10 tons per acre	Clark et al. (2016)
Cost of water	$130 per acre-foot	Clark et al. (2016)
Quantity of water	5.3 acre-feet per acre	Clark et al. (2016)
Cost of capital	$871 per acre	Clark et al. (2016)
Exponent α on water	0.3	
Exponent κ on capital	0.4	
Crop price	$250/ton	Clark et al. (2016)
Irrigation efficiency	75%	Clark et al. (2016)
Establishment/planting cost	$0	
Transmissivity (or hydroconductivity)	6.55 ft/day	Williamson et al. (1989)
Storage	20 acre-feet per acre	
Precipitation	Tulare	California Department of Water Resources (2017d)
Electricity price	$0.28/kwh	2017 Pacific Gas and Electric (PGE) summer AG-1A rate

Table 1b. Parameter values: Strawberries in Central Coast

Strawberries, Central Coast		
	Value	**Source**
County	Monterey	
Aquifer System	California Coastal Basin	
Yield	7000 trays per acre	Bolda et al. (2016)
Cost of water	\$270 per acre-foot	Bolda et al. (2016)
Quantity of water	2.29 acre-feet per acre	Bolda et al. (2016)
Cost of capital	\$517 per acre	Bolda et al. (2016)
Exponent α on water	0.0271	
Exponent κ on capital	0.0226	
Crop price	\$14/tray	Bolda et al. (2016)
Irrigation efficiency	90%	Bolda et al. (2016)
Establishment/planting cost	\$0	Bolda et al. (2016)
Transmissivity (or hydroconductivity)	8.25 ft/day	Hanson et al. (2002)
Storage	20 acre-feet per acre	
Precipitation	Monterey	PRISM Climate Group (2017)
Electricity price	\$0.28/kwh	2017 Pacific Gas and Electric (PGE) summer AG-1A rate

Table 1c. Parameter values: Walnuts in North Coast

Walnuts, North Coast		
	Value	**Source**
County	Lake	
Aquifer System	California Coastal Basin	
Yield	5000 lbs per acre	Elkins, Klonsky and Tumber (2012)
Cost of water	$63.24 per acre-foot	Elkins, Klonsky and Tumber (2012)
Quantity of water	2 acre-feet per acre	Elkins, Klonsky and Tumber (2012)
Cost of capital	$1345 per acre	Elkins, Klonsky and Tumber (2012)
Exponent α on water	0.043	
Exponent κ on capital	0.459	
Crop price	$1.25/lb	Elkins, Klonsky and Tumber (2012)
Irrigation efficiency	80%	Elkins, Klonsky and Tumber (2012)
Establishment/planting cost	$1813 per acre	Elkins, Klonsky and Tumber (2012)
Transmissivity (or hydroconductivity)	40 ft/day	Napa County (2014)
Storage	15 acre-feet per acre	
Precipitation	Lake	PRISM Climate Group (2017)
Electricity price	$0.28/kwh	2017 Pacific Gas and Electric (PGE) summer AG-1A rate

Table 1d. Parameter values: Table Olives in Sacramento Valley

Table Olives, Sacramento Valley		
	Value	**Source**
County	Sacramento	
Aquifer System	Central Valley	
Yield	5 tons per acre	Lightle et al. (2016)
Cost of water	\$90 per acre-foot	Lightle et al. (2016)
Quantity of water	4 acre-feet per acre	Lightle et al. (2016)
Cost of capital	\$801 per acre	Lightle et al. (2016)
Exponent α on water	0.143	
Exponent κ on capital	0.318	
Crop price	\$1020/ton	Lightle et al. (2016)
Irrigation efficiency	90%	Lightle et al. (2016)
Establishment/planting cost	\$5000 per acre	Lightle et al. (2016)
Transmissivity (or hydroconductivity)	3.825 ft/day	Williamson et al. (1989)
Storage	15 acre-feet per acre	
Precipitation	Sacramento	PRISM Climate Group (2017)
Electricity price	\$0.28/kwh	2017 Pacific Gas and Electric (PGE) summer AG-1A rate

Table 1e. Parameter values: Organic Almonds in Northern San Joaquin Valley

Organic Almonds, Northern San Joaquin		
	Value	**Source**
County	Merced	
Aquifer System	Central Valley	
Yield	1800 lbs per acre	Holtz et al. (2016)
Cost of water	\$100 per acre-foot	Holtz et al. (2016)
Quantity of water	3.67 acre-feet per acre	Holtz et al. (2016)
Cost of capital	\$925 per acre	Holtz et al. (2016)
Exponent α on water	0.091	
Exponent κ on capital	0.229	
Crop price	\$3.5/lb	Holtz et al. (2016)
Irrigation efficiency	90%	Holtz et al. (2016)
Establishment/planting cost	\$6000 per acre	Holtz et al. (2016)
Transmissivity (or hydroconductivity)	5.875 ft/day	Williamson et al. (1989)
Storage	15 acre-feet per acre	
Precipitation	Merced	PRISM Climate Group (2017)
Electricity price	\$0.28/kwh	2017 Pacific Gas and Electric (PGE) summer AG-1A rate

Table 1f. Parameter values: Avocados in South Coast

Avocados, South Coast		
	Value	**Source**
County	Ventura	
Aquifer System	California Coastal Basin	
Yield	12,400 lbs per acre	Takele, Faber and Vue (2011)
Cost of water	$200 per acre-foot	Takele, Faber and Vue (2011)
Quantity of water	2.50 acre-feet per acre	Takele, Faber and Vue (2011)
Cost of capital	$5027 per acre	Takele, Faber and Vue (2011)
Exponent α on water	0.055	
Exponent κ on capital	0.551	
Crop price	$1.07/lb	Takele, Faber and Vue (2011)
Irrigation efficiency	90%	Takele, Faber and Vue (2011)
Establishment/planting cost	$0	
Transmissivity (or hydroconductivity)	0.1 ft/day	Hanson et al. (2003)
Storage	15 acre-feet per acre	
Precipitation	Ventura	PRISM Climate Group (2017)
Electricity price	$0.28/kwh	2017 Pacific Gas and Electric (PGE) summer AG-1A rate

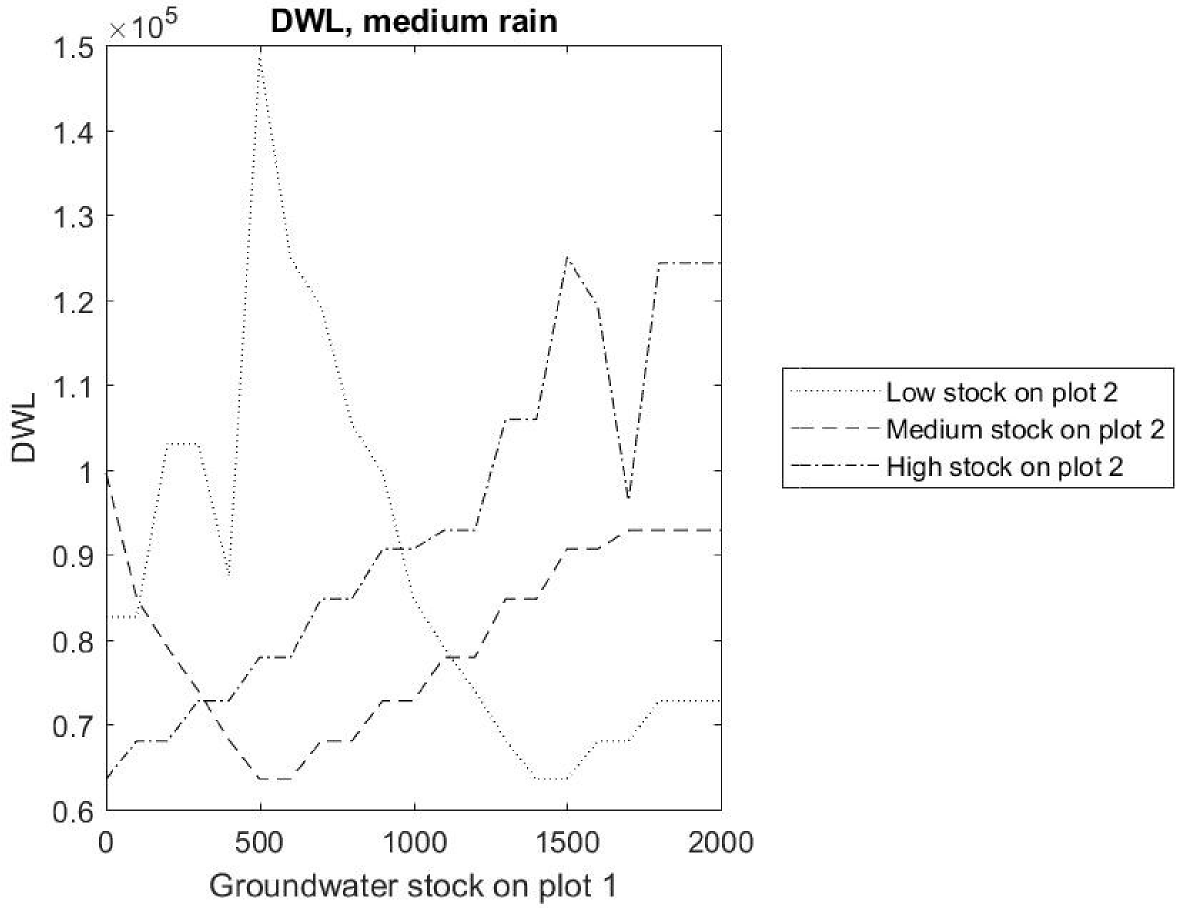
Table 1g. Parameter values: Oranges in South San Joaquin Valley

Oranges, South San Joaquin		
	Value	**Source**
County	Tulare	
Aquifer System	Central Valley	
Yield	550 cartons per acre	O'Connell et al. (2015)
Cost of water	\$114 per acre-foot	O'Connell et al. (2015)
Quantity of water	2.50 acre-feet per acre	O'Connell et al. (2015)
Cost of capital	\$1735 per acre	O'Connell et al. (2015)
Exponent α on water	0.059	
Exponent κ on capital	0.357	
Crop price	\$12/cartons	O'Connell et al. (2015)
Irrigation efficiency	85%	O'Connell et al. (2015)
Establishment/planting cost	\$2445 per acre	O'Connell et al. (2015)
Transmissivity (or hydroconductivity)	6.55 ft/day	Williamson et al. (1989)
Storage	20 acre-feet per acre	
Precipitation	Tulare	California Department of Water Resources (2017d)
Electricity price	\$0.28/kwh	2017 Pacific Gas and Electric (PGE) summer AG-1A rate

Table 2. Deadweight loss: Alfafa in Southern San Joaquin Valley (base case)

State variables			Deadweight loss from non-cooperative behavior
Stock in plot 1	**Stock in plot 2**	**Rainfall**	
Low stocks in both plots			
300 acre-feet	300 acre-feet	None	$82,669
300 acre-feet	300 acre-feet	Medium	$87,467
300 acre-feet	300 acre-feet	High	$105,398
Low stock in one plot; moderate stock in the other			
900 acre-feet	300 acre-feet	None	$73,982
900 acre-feet	300 acre-feet	Medium	$68,069
900 acre-feet	300 acre-feet	High	$77,923
Moderate stocks			
1400 acre-feet	600 acre-feet	None	$84,801
1400 acre-feet	600 acre-feet	Medium	$92,878
1400 acre-feet	600 acre-feet	High	$125,006
High stocks			
1800 acre-feet	1600 acre-feet	None	$125,006
1800 acre-feet	1600 acre-feet	Medium	$98,192
1800 acre-feet	1600 acre-feet	High	$98,192
Stocks full			
2000 acre-feet	2000 acre-feet	None	$98,192
2000 acre-feet	2000 acre-feet	Medium	$98,192
2000 acre-feet	2000 acre-feet	High	$98,192

Figure 1. Deadweight loss: Alfafa in Southern San Joaquin Valley (base case)



Notes: Low stock, medium stock, and high stock on plot 2 correspond to 200 acre-feet, 1100 acre-feet, and 1700 acre-feet, respectively.

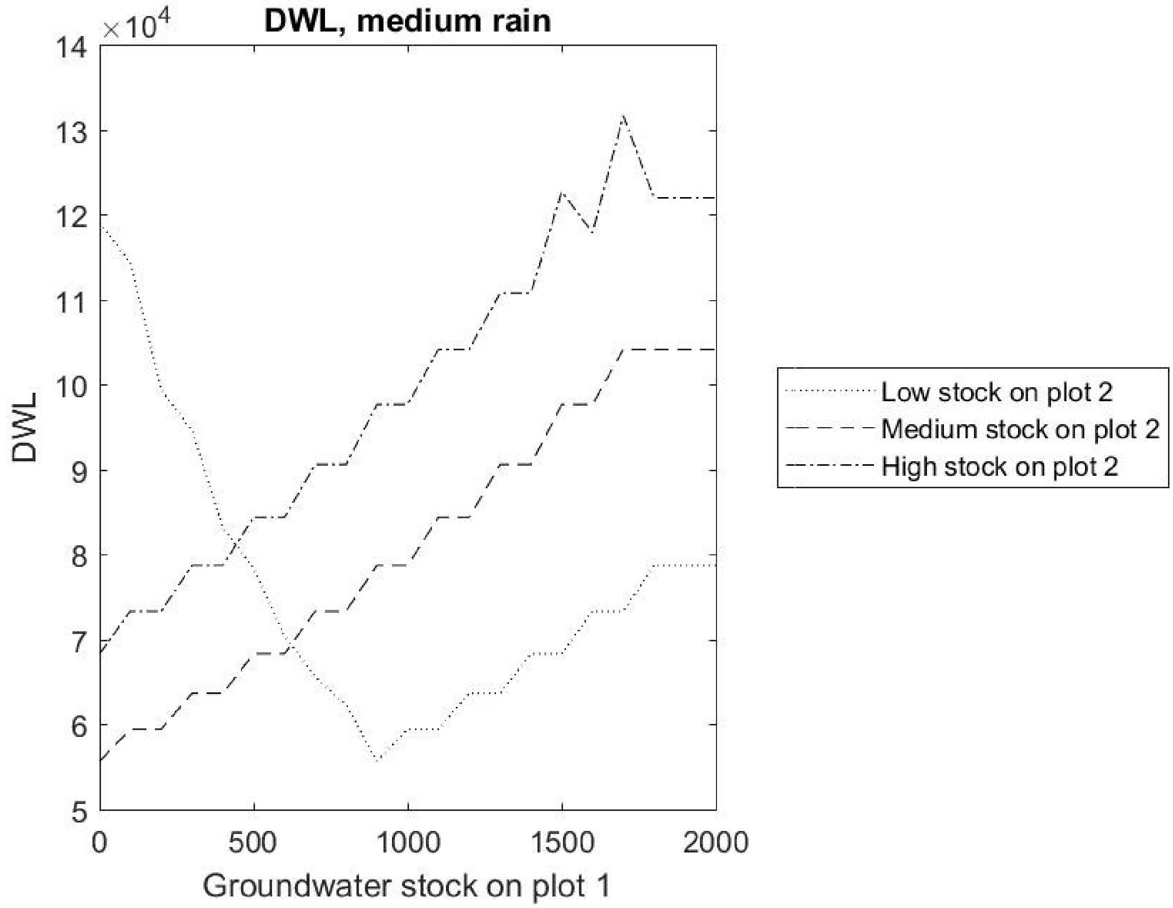
Table 3. Deadweight loss: Alfafa in Southern San Joaquin Valley, Sensitivity analysis

Scenario	**Deadweight loss from non-cooperative behavior**		
Rainfall in current year:	None	Medium	High
Transmissivity scenarios			
Base, representing Tulare basin (6.55 ft/day)	\$63,585.77	\$72,822.26	\$84,801.48
Mean transmissivity in California (25 ft/day)	\$63,585.77	\$72,822.26	\$84,801.48
Mean + std. dev. in California (38 ft/day)	\$63,585.77	\$72,822.26	\$84,801.48
Mean – std. dev. in California (12 ft/day)	\$63,585.77	\$72,822.26	\$84,801.48
Electricity price scenarios			
Base (\$0.28/kwh)	\$63,585.77	\$72,822.26	\$84,801.48
50% lower (\$0.14/kwh)	\$88,304.87	\$103,346.34	\$116,106.11
100% higher (\$0.56/kwh)	\$30,861.06	\$30,529.48	\$45,545.26
Crop price scenarios			
Base (\$250/ton)	\$63,585.77	\$72,822.26	\$84,801.48
50% lower (\$125/ton)	\$15,430.59	\$15,264.80	\$22,772.69
100% higher (\$500/ton)	\$176,609.61	\$206,692.56	\$232,212.10
Rain distribution scenarios			
Base (from distribution of annual rain in California over 1922-2016)	\$63,585.77	\$72,822.26	\$84,801.48
More temperate (always at least some rain)	\$71,575.25	\$77,640.94	\$92,308.10
Drought	\$64,443.45	\$73,865.46	\$85,769.58
More drought and more high rain	\$47,361.82	\$53,079.04	\$62,040.83
Drought, medium rainfall, and high rainfall relatively equally likely	\$51,564.60	\$50,878.32	\$58,628.40
Extreme drought	\$67,778.88	\$42,671.72	\$56,213.06
Irrigation efficiency scenarios			
Base (75%)	\$63,585.77	\$72,822.26	\$84,801.48

Enhanced (90%)	\$68,310.32	\$78,723.20	\$90,597.15

Notes: We assume moderate groundwater stock levels: 1400 acre-feet in one plot and 600 acre-feet in the other. The relative deadweight losses are similar across other groundwater levels.

Figure 2. Deadweight loss: Alfafa in Southern San Joaquin Valley with drip irrigation technology

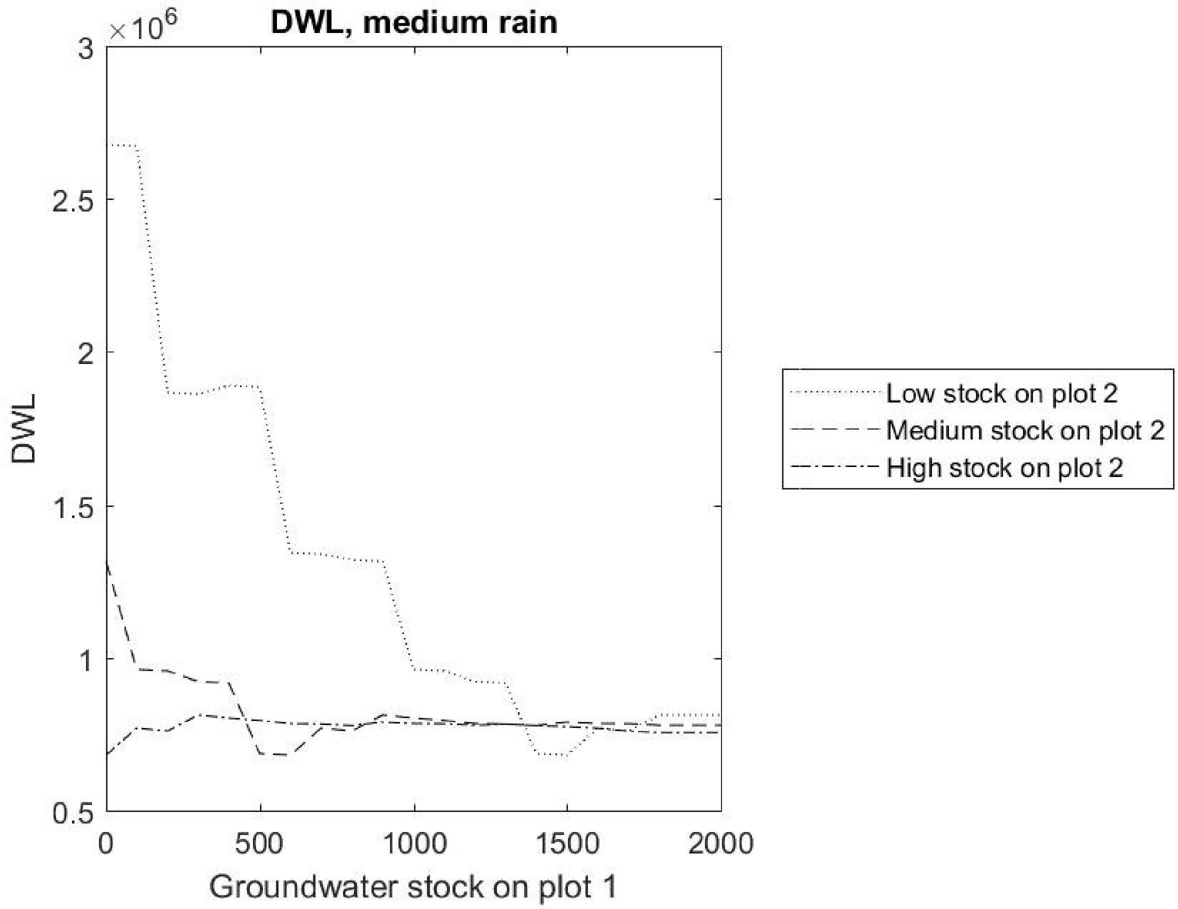


Notes: Low stock, medium stock, and high stock on plot 2 correspond to 200 acre-feet, 1100 acre-feet, and 1700 acre-feet, respectively.

Table 4. Deadweight loss: Different crop-region scenarios

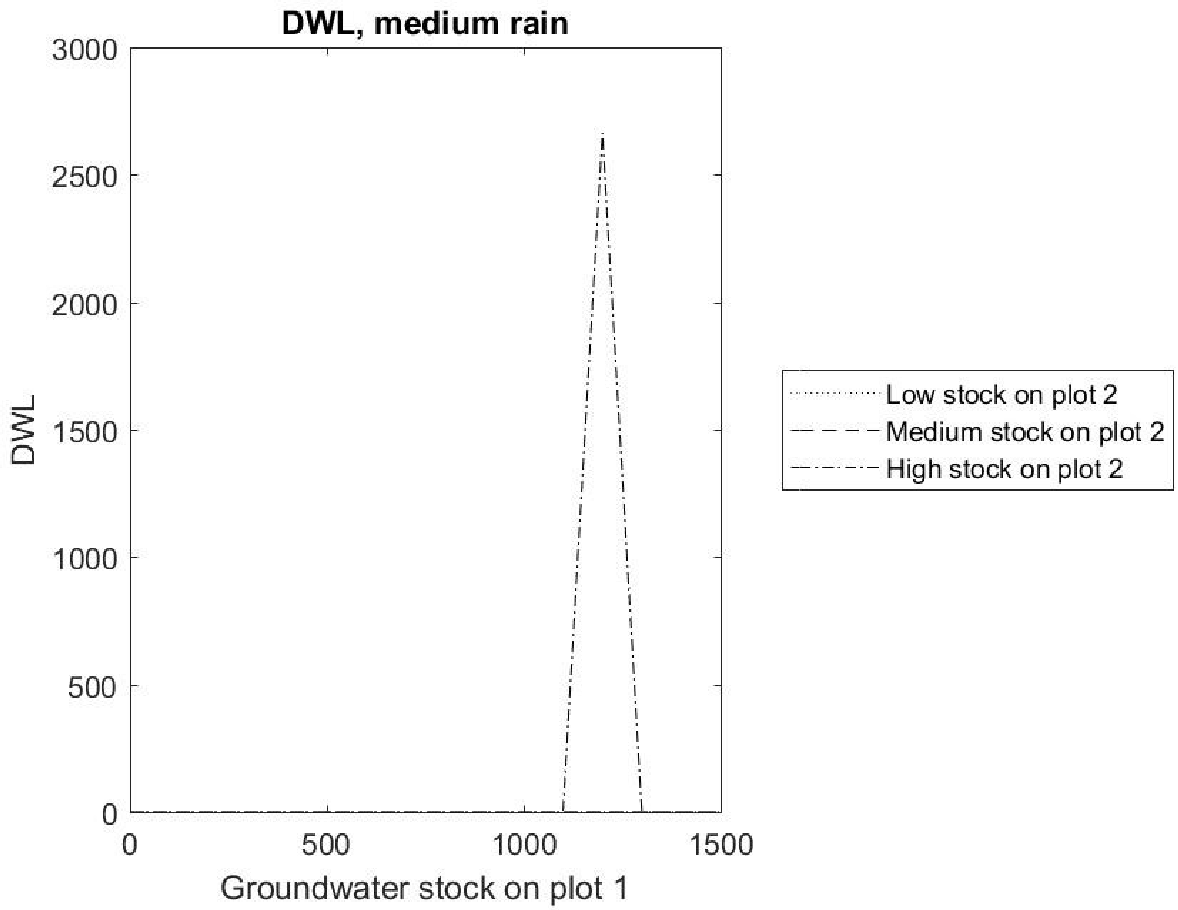
Scenario	**Deadweight loss from non-cooperative behavior**		
Rainfall in current year:	None	Medium	High
Crop-Region Scenarios			
Alfalfa, South San Joaquin Valley (base case)	$63,586	$72,822	$84,801
Strawberries, Central Coast	$686,015	$812,226	$782,559
Walnuts, Northern Coast	$0	$0	$0
Table Olives, Sacramento Valley	$251,210	$287,967	$327,449
Organic Almonds, Northern San Joaquin Valley	$15,594	$33,886	$73,639
Avocados, South Coast	$0	$0	$0
Oranges, South San Joaquin Valley	$0	$0	$0
Alfalfa and Oranges, South San Joaquin Valley	$18,447	$18,446	$18,147

Figure 3. Deadweight loss: Strawberries in Central Coast



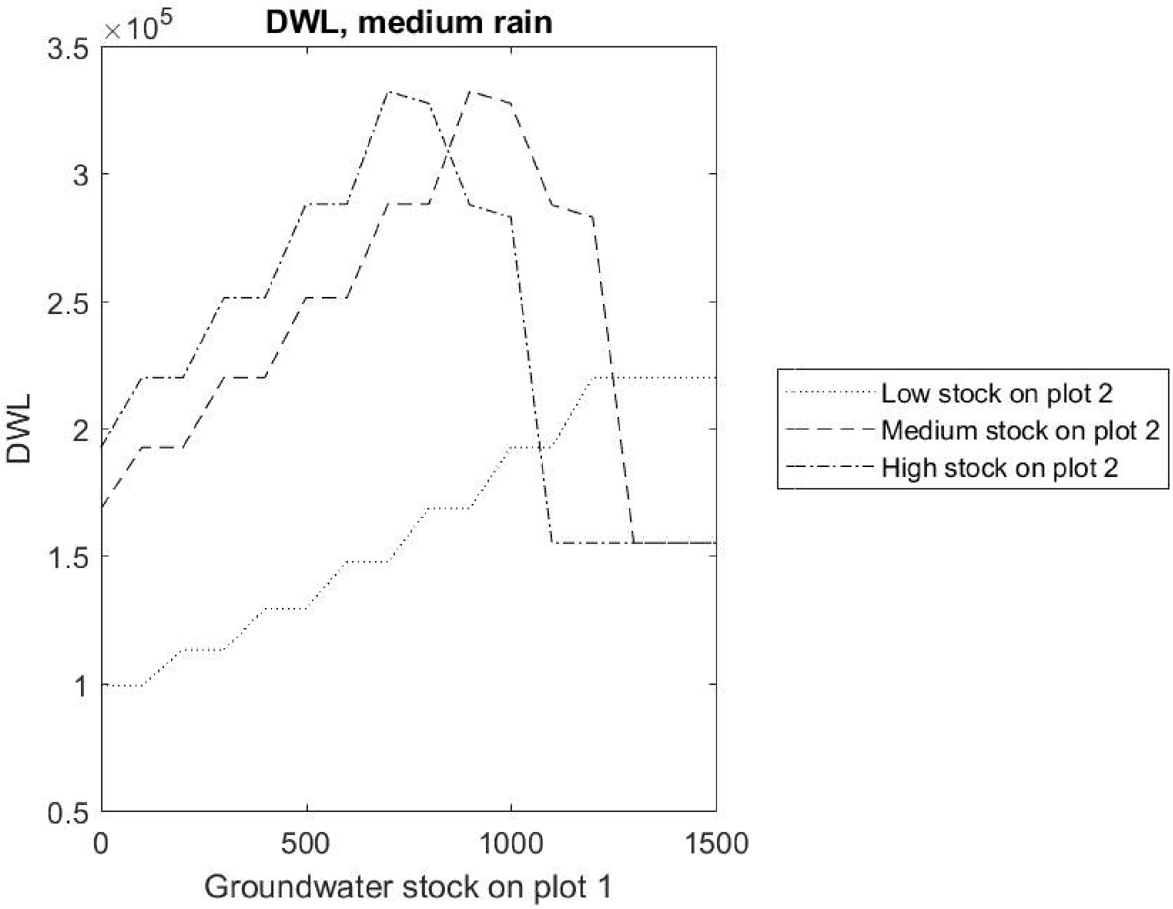
Notes: Low stock, medium stock, and high stock on plot 2 correspond to 200 acre-feet, 1100 acre-feet, and 1700 acre-feet, respectively.

Figure 4. Deadweight loss: Walnuts in North Coast



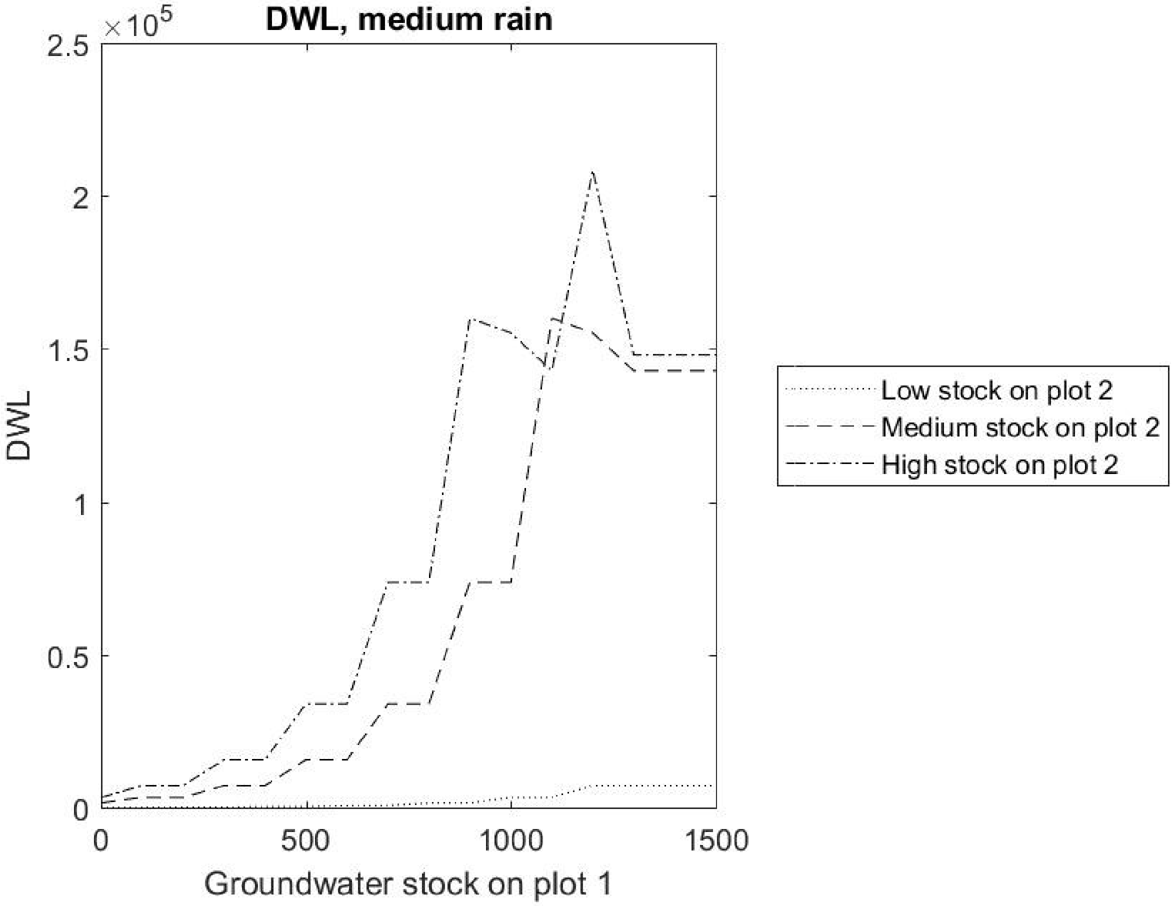
Notes: Low stock, medium stock, and high stock on plot 2 correspond to 200 acre-feet, 1100 acre-feet, and 1700 acre-feet, respectively.

Figure 5. Deadweight loss: Table olives in Sacramento Valley



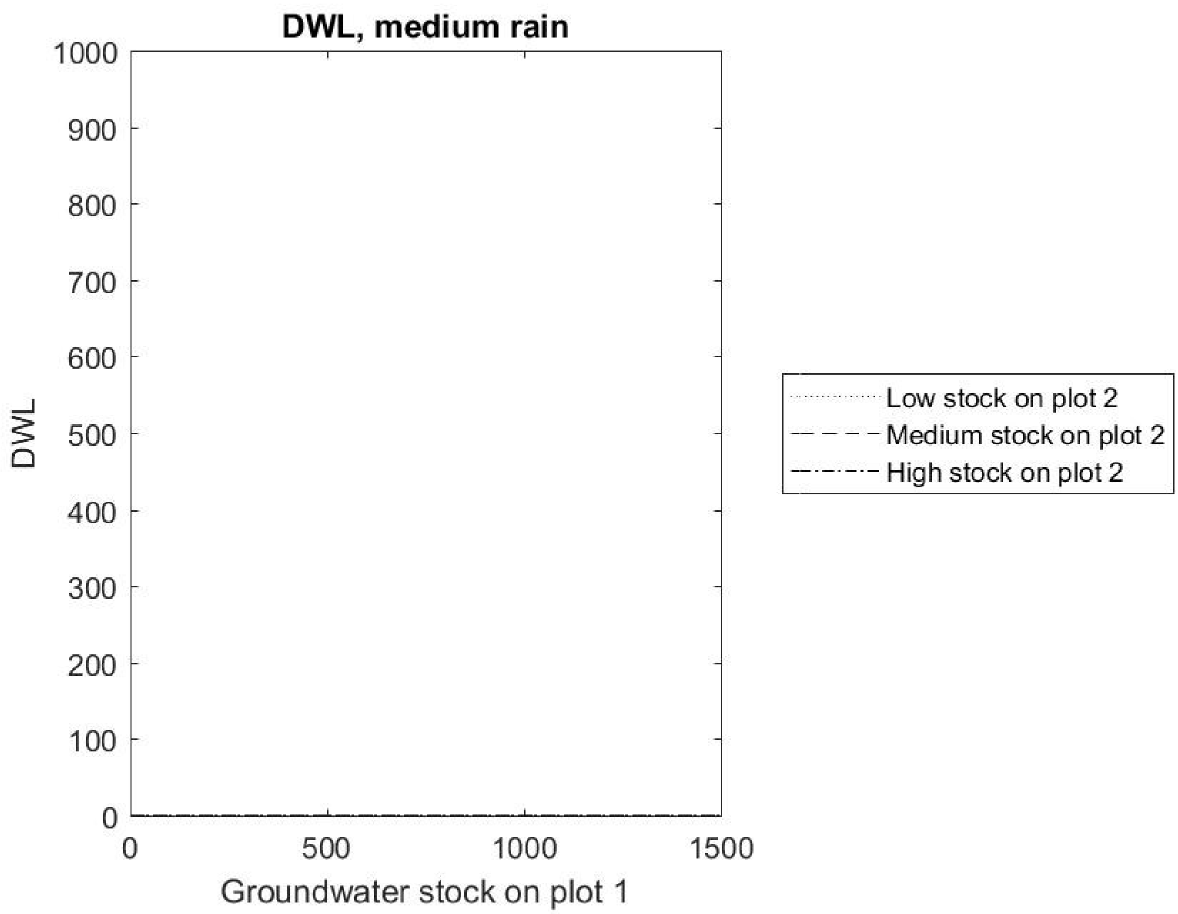
Notes: Low stock, medium stock, and high stock on plot 2 correspond to 200 acre-feet, 1100 acre-feet, and 1700 acre-feet, respectively.

Figure 6. Deadweight loss: Organic almonds in North San Joaquin Valley



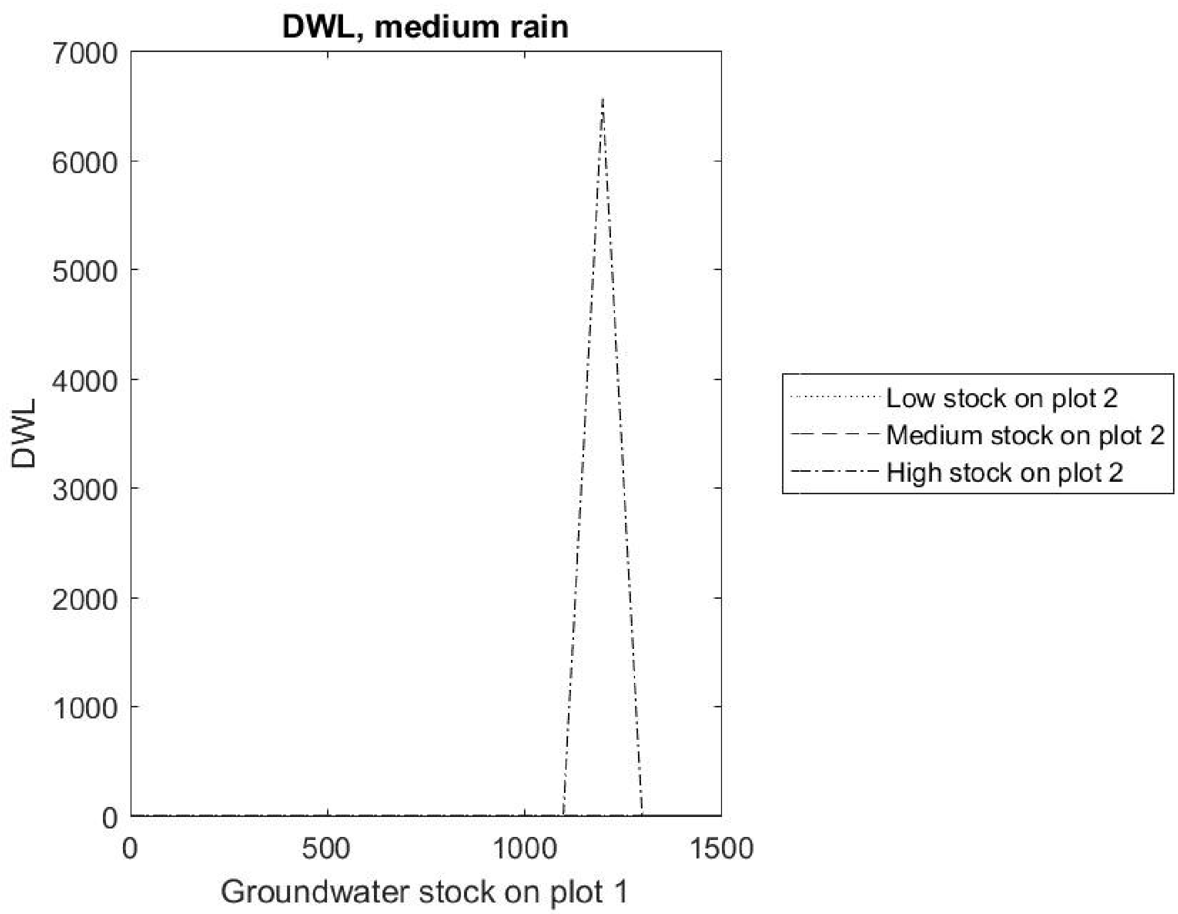
Notes: Low stock, medium stock, and high stock on plot 2 correspond to 200 acre-feet, 1100 acre-feet, and 1700 acre-feet, respectively.

Figure 7. Deadweight loss: Avocados in South Coast



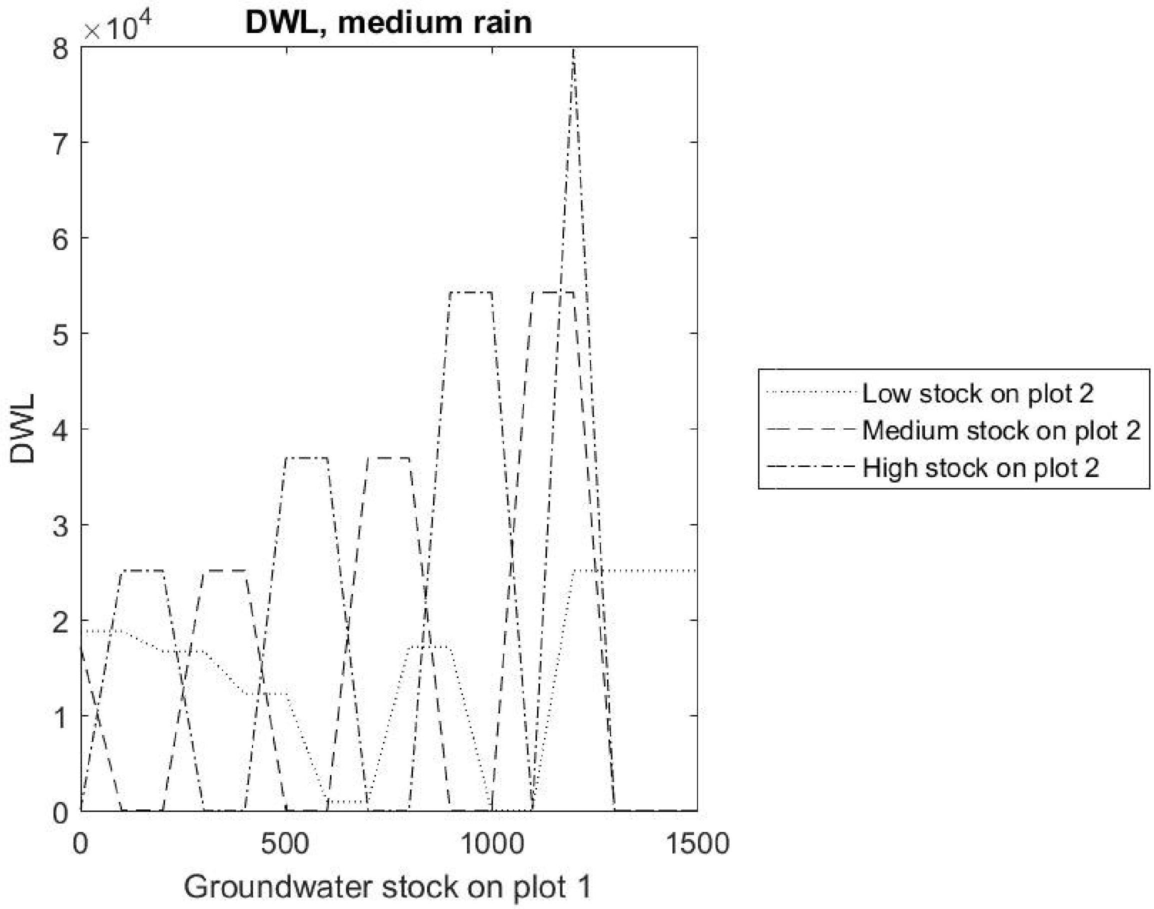
Notes: Low stock, medium stock, and high stock on plot 2 correspond to 200 acre-feet, 1100 acre-feet, and 1700 acre-feet, respectively.

Figure 8. Deadweight loss: Oranges in Southern San Joaquin Valley



Notes: Low stock, medium stock, and high stock on plot 2 correspond to 200 acre-feet, 1100 acre-feet, and 1700 acre-feet, respectively.

Figure 9. Deadweight loss: Oranges and alfalfa in Southern San Joaquin Valley



Notes: Low stock, medium stock, and high stock on plot 2 correspond to 200 acre-feet, 1100 acre-feet, and 1700 acre-feet, respectively.