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The Impacts of Market Power in Agricultural Groundwater Markets

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1. Introduction

Many agricultural areas worldwide use groundwater for irrigation and have seen decreases in groundwater storage over time. Groundwater is either used as an exclusive water source or in conjunction with surface water, where it acts as a buffer against natural variability in surface water supplies. Due to concern for maintaining a long-run groundwater supply, California passed legislation in 2014 that provides a statewide framework for local agencies to manage groundwater. It requires overdrafted basins throughout California to reach and maintain long-term stable groundwater levels. Since groundwater is a key component of the water supply, pumping restrictions will have impacts on irrigated agriculture. The passage of the Sustainable Groundwater Management Act in California may represent a movement towards regulation of this common-pool resource in other groundwater-dependent regions around the world.

Regulators will be considering economic instruments for management, as some will need to incentivize users to pump less groundwater. Among other reasons, groundwater markets are a desirable tool because they eliminate uncertainty in reaching basin-wide groundwater sustainability goals. Prior to the implementation of groundwater markets, it will be important to understand the magnitude of potential gains from trade and how these gains are influenced by market conditions and market structure. Market power may be a defining component of groundwater markets in California due to the presence of large, vertically integrated farming operations and/or competition among a few water agencies on a shared basin.

Using a flexible model framework that can reflect any degree of buyer or seller market power in the input market for groundwater, we define the relationship between market power and the efficiency of water trading. Although others have discussed the notion of tradable permits for groundwater use, we formalize the concept by deriving supply and demand curves for permits from the underlying production functions. We then calculate the net benefits to groundwater users from voluntary water trading. With a simulation model, we show how these benefits change with the demand elasticity, a market power index, and other measures of market conditions.

Stemming from the seminal paper by Hahn (1984), a branch of literature evaluates the impacts of market power in permit markets. With applications to fisheries and pollution, it considers the initial distribution of property rights, strategic behavior of competitors, and impacts in the final product market (e.g., Misiolek and Elder (1989) and Montero (2009)). Previous literature makes assumptions regarding the degree of competition, e.g., Cournot competition, or one or two dominant firms with a competitive fringe (Westskog (1996) and Montero (2009)). This paper expands on this literature by using a flexible framework for imperfect competition in the permit market, allowing us to capture the entire range of possible market power settings. We use this framework to quantify the impacts of market power on welfare in a permit market more generally, and see how market outcomes change with different degrees of market power.

Many economists have espoused the merits of markets to efficiently allocate water from low-value to high-value users, but their arguments rest on assumptions regarding transaction costs, information, and competition that may not always apply. Several papers have evaluated gains from additional surface water transfers, suggesting that there are large benefits to be had from the reallocation of water (e.g., Vaux and Howitt (1984), Hearne and Easter (1997)). This is often to the detriment of the aquifer, which is assumed to be an unmanaged, open-access resource.

Few have considered the role that imperfect competition may play in the functioning of water markets, or considered the specific institutional framework and geographic scope of groundwater markets (Ansink and Houba, 2012). Most closely related to this paper, Gao et al. (2013) investigate potential benefits from groundwater trade in Australia. We expand on this groundwater market literature by investigating the degree to which different factors influence the potential benefits from trade. We emphasize the role of market power, a feature not previously discussed, yet predicted to be a defining component of many agricultural groundwater markets.

In the following section, we provide background on the 2014 Sustainable Groundwater Management Act and the avenues through which market power may arise in groundwater markets. In Section 3, we develop a theoretical framework for studying agricultural groundwater use and trading. We first derive unconstrained groundwater demands and then assign property rights for pumping such that the aggregate use is restricted. Section 4 introduces trade; we derive permit demand and permit supply curves. Within this framework, we compare the perfectly competitive and imperfectly competitive solutions and determine the effects of market power on market outcomes. Section 5 contains an application to the Coachella Valley, CA followed by a sensitivity analysis in Section 6. The final section concludes.

2. Background

Groundwater is a significant component of California's water supply that has historically been unmeasured and unmanaged at the state level. Prompted by years of severe drought, the California state legislature passed a groundwater law in 2014 that provides a statewide framework for local agencies, established within individual basins, to coordinate data management and organize basin management plans to eliminate overdraft. The Sustainable Groundwater Management Act allows flexibility among local agencies in how to reach these targets.

Overdrafted basins will likely need to reduce pumping to achieve groundwater sustainability. Regulators may choose to do this by restricting individual pumping, after properly establishing property rights for groundwater. However, absent perfect information on behalf of the regulating agency, this may cause efficiency loss in the absence of water markets. Thus, groundwater trading may emerge as one possible avenue for reaching sustainability targets. Prior to implementation, it is important to understand how groundwater markets will function and how they might be impacted by market power. As groundwater markets become more prevalent in California and elsewhere, determining the competitive outlook for these markets and the subsequent behavior resulting from any market power abuses will be one of the fundamental challenges facing policy-makers.

Due to the nature of water institutions and the market structure of agricultural production in California, market power may be a defining component of future groundwater trading. Several scenarios likely give rise to imperfectly competitive groundwater markets. For many groundwater basins in California, multiple groundwater management agencies are emerging to jointly manage the groundwater on a shared basin. When trading occurs among a handful of groundwater agencies, it will be characterized by a small-numbers problem. Also, a significant amount of current surface water trading and groundwater banking (artificial aquifer recharge) in California is organized at the district or county level among districts on behalf of the farmers within their service areas. Water districts may be able to act as implicit, legal cartels that have influence over price in purchases or sales of groundwater.

Even under the authority of a single agency on a given groundwater basin, there is the opportunity to exercise market power in water trading if there are a small number of players on one side of the market. The agricultural sector has seen significant structural change over the last several decades, leading to fewer, larger, and vertically integrated farming operations. Most groundwater rights in California are overlying rights, which are based on ownership of the land above the aquifer and give the landowner the right to pump. It is likely that the structure of

California agricultural production will give rise to consolidation of groundwater rights when they become properly defined under the Sustainable Groundwater Management Act. As a result, market structure may play an important role in effectively managing groundwater.

In this paper, we focus specifically on the Coachella Valley Groundwater Basin in southern California. Multiple water agencies in the Coachella Valley have been approved by the California Department of Water Resources as "Groundwater Sustainability Agencies" to jointly manage the Coachella Valley Groundwater Basin over the coming years. They are required to work together to reach sustainability targets for the entire basin; perhaps this will be done by trading groundwater pumping rights among agencies. Additionally, since the Valley is home to large grower-shippers like Grimway Farms for vegetables and Sun World for table grapes, the market structure of Coachella's agricultural production may give way to the exercise of market power in the permit market if property rights for pumping become well-defined and trading occurs.

3. Modeling Framework

We start by developing a theoretical model for studying agricultural groundwater use and trading. It is framed as if a single authority governs an entire groundwater basin, the groundwater basin defines the market, and permit trading occurs among farmers. However, this framework may be adapted to represent an aquifer with several governing agencies where trade occurs among agencies. Within this framework, we will investigate the magnitude of the gains from trade, how those gains are affected by market power, and the impacts of imperfect competition on market outcomes and welfare.

We build up from an unmanaged, open-access groundwater setting to tradable property rights for pumping. Throughout, we assume farmers draw groundwater from a common aquifer.

For simplicity, we assume there are two types of farmers pulling from the aquifer, low (L) and high (H), that are homogenous within their type. Each produces a single output. Farmers of type L grow a low-value crop, such as rice or cotton, with individual production functions denoted $q_{L,j} = g_j(x_{L,j}, y)$. Farmers of type H grow a high-value crop, e.g., produce commodities or tree nuts, with individual production functions denoted $q_{H,j} = f_j(x_{H,j}, z)$.[1] Production functions are assumed to exhibit diminishing marginal returns. The variable x represents applied groundwater and y and z are other inputs to production.

There are N_i identical individuals $j = \{1, \dots N_i\}$ within each type $i \epsilon \{H, L\}$. We distinguish the two types such that growers of the high-value crop have a higher willingness to pay for water at any given quantity. Aggregate water quantities are denoted by X or x without individual-specific or type-specific subscripts, where uppercase is for pumped groundwater and lowercase is for applied groundwater. That is, $X = X_H + X_L$ and $x = x_H + x_L$ where total H-type pumped water is $X_H = \sum_{j=1}^{N_H} X_{H,j}$ (uppercase) and total H-type applied water $x_H = \sum_{j=1}^{N_H} x_{H,j}$ (lowercase). The relationship between pumped and applied water is given by the efficiency parameter δ with $0 \leq \delta \leq 1$ such that $x_i = \delta X_i$. This is to represent system distributional losses. We must distinguish pumped groundwater from applied groundwater because applied water is what determines production decisions, whereas pumped groundwater is the good to be traded.

The marginal pumping cost of water is denoted by $c(X)$ and is an increasing function of the total amount pumped out of the aquifer due to reducing the water table. Marginal pumping

[1] This formulation assumes farmers have already preselected into producing certain crops, e.g., based on heterogeneous ability levels or land quality. This is a short-run analysis. We do not consider changes in cropping patterns that might occur due to alternative groundwater management regimes.

costs are positive, increasing, and differentiable, i.e. $c(X) > 0$ and $c'(X) > 0$. We are thereby incorporating the endogeneity of pumping costs as a function of total pumping. When individual pumping is small relative to the basin total, farmers face the same costs and take the marginal pumping cost as given, but collectively their decisions determine basin-wide pumping costs. [2]

3.1 Open-Access Groundwater Use

We begin with the profit maximization problem for farmers in the unmanaged, open-access case. Total costs of production come from groundwater pumping costs and the costs of other inputs, which might include fertilizers and pesticides. The price of groundwater is denoted w_x and the prices of the other inputs are denoted w_y and w_z. When the aquifer is an unmanaged common-pool resource, the price of groundwater equals the marginal pumping cost, which individual users regard as constant, and is denoted by $w_x = c$. Firms are assumed to choose inputs $\{x_H, z\}$ for H types or $\{x_L, y\}$ for L types to maximize farm profits, where P_i is the output price for the crop produced by type $i, i \in \{L, H\}$. An individual of type H faces the following profit maximization problem.

(1) $$\max_{\{x_{H,j}, z\}} \pi_{H,j} = P_H f_j\left(x_{H,j}, z\right) - c\,\frac{x_{H,j}}{\delta} - w_z z_j$$

The first-order conditions for each of the H types are:

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[2] One possible extension of this work is to expand on this farm-level groundwater optimization problem by allowing individual firms to believe they pump enough to influence their own pumping costs. This may be because they are big enough to impact the water table with their consumption or they pump enough to create a cone of depression at the site of a well.

(2) $$P_H \frac{\partial f_j(x_{H,j}, z)}{\partial x_{H,j}} = \frac{c}{\delta} \text{ and } P_H \frac{\partial f_j(x_{H,j}, z)}{\partial z_j} = w_z$$

and are similar for each of the L types. Solving for $x_{H,j}$ and $x_{L,j}$ reveals the groundwater demand curves for each farmer j, which are functions of crop output price, input prices, and the marginal pumping cost of groundwater: $x_{H,j}(P_H, w_Z, c)$, $x_{L,j}(P_L, w_Y, c)$. When optimizing, farmers equate the marginal value product of an additional unit of groundwater to its price, which here is the marginal pumping cost adjusted by the efficiency parameter. These expressions recognize that a unit pumped yields less than a unit applied due to inefficiencies in delivery.

3.2 Competitive Equilibrium

The market equilibrium comes from equating the aggregate water demand relationships across both types with the aggregate water supply relationship. Aggregate applied water demands are given by $x_H + x_L = \sum_{j=1}^{N_L} x_{L,j} + \sum_{j=1}^{N_H} x_{H,j}$. The aggregate water supply relationship is just marginal pumping costs as a function of total pumping, adjusted by system distributional losses. Thus, the equilibrium condition is $c(X) = c\left(\frac{x_H(w_x)}{\delta} + \frac{x_L(w_x)}{\delta}\right) = w_x$.

To obtain analytical solutions, we assume aggregate demands for applied water are linear and parallel such that the H type demand curve is higher than that of the L type for all quantities of applied water.[3] As shown below, we have intercepts of γ and $\alpha\gamma$ for the H and L types, respectively, with $0 < \alpha < 1$, and slope coefficients assumed to be the same, given by $\frac{\beta}{2}$:

(3) $$x_H = \gamma - \frac{\beta}{2} w_{x_H} \text{ and } x_L = \alpha\gamma - \frac{\beta}{2} w_{x_L}.$$

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[3] We choose to define functional forms for water demands at the aggregate level for analytical simplicity. We divide aggregate demands by the number of agents in each type to reveal individual water demands.

Throughout, we assume marginal pumping costs are increasing and linear with positive intercept and slope coefficients, $c(X) = \theta + \mu X$ with $\theta, \mu > 0$. Aggregate applied water demand is the sum of the total water demands from each type: $x = x_H + x_L = (\alpha + 1)\gamma - \beta w_x$. The intersection of this with the supply relationship of applied water, $w_x = \theta + \frac{\mu}{\delta} x$, reveals the competitive, open-access equilibrium price (w_x^*) and quantity (x^*)

(4) $$x^* = \frac{\delta\gamma(\alpha+1) - \delta\beta\theta}{\delta + \beta\mu}, \quad w_x^* = \theta + \mu\left(\frac{\gamma(\alpha+1) - \beta\theta}{\delta + \beta\mu}\right).$$

In what follows, we invoke a normalization such that the competitive market equilibrium price (i.e., pumping cost) and quantity are each equal to one $(x^*, w_x^*) = (1,1)$. Evaluated at the competitive equilibrium, the absolute value of the demand elasticity is given by $\eta = \beta$ and the supply elasticity is $\varepsilon = \frac{\delta}{\mu}$.[4] Given the normalizations, we can rewrite the demands for L and H types and the aggregate supply relationship as functions of readily interpretable terms: the supply and demand elasticities evaluated at the competitive equilibrium, ε and η respectively, the demand shift parameter, $\alpha \in (0,1)$, reflecting differences in water demands between H and L types, and the water distribution efficiency parameter $\delta \in [0,1]$. This substitution eliminates the dependence of the model on units of measurement, as all parameters defining the market are pure numbers. We restate all solutions with respect to this normalization:

(5) Equilibrium groundwater quantity and price: $(x^*, w_x^*) = (1, 1)$

[4] The elasticity of demand is given by $\eta = \left|\frac{\partial x^D}{\partial w_x} * \frac{w_x}{x^D}\right| = \beta$ evaluated at the equilibrium (1,1) with $x^D(w_x) = (\alpha + 1)\gamma - \beta w_x$. The elasticity of supply is given by $\varepsilon = \frac{\partial x^S}{\partial w_x} * \frac{w_x}{x^S} = \frac{\delta}{\mu}$ at (1,1) where $x^S(w_x) = \frac{\delta}{\mu} w_x - \frac{\delta}{\mu}\theta$. These imply the following substitutions, which are used to rewrite the original expressions: $\beta = \eta, \theta = 1 - \frac{1}{\varepsilon}, \gamma = \frac{1+\eta}{1+\alpha}, \mu = \frac{\delta}{\varepsilon}$.

Aggregate High-type Demand: $x_H = \frac{1+\eta}{1+\alpha} - \frac{\eta}{2} w_{x_H}$

Aggregate Low-type Demand: $x_L = \alpha\left(\frac{1+\eta}{1+\alpha}\right) - \frac{\eta}{2} w_{x_L}$

Individual Marginal Value Products:

$$MVP_{Hj} = \frac{2}{\eta}\left(\frac{1+\eta}{1+\alpha} - N_H x_{H,j}\right)$$

$$MVP_{Lj} = \frac{2}{\eta}\left(\frac{\alpha(1+\eta)}{1+\alpha} - N_L x_{L,j}\right)$$

Aggregate Inverse Groundwater Supply: $w_x = \left(1 - \frac{1}{\varepsilon}\right) + \frac{1}{\varepsilon} x$

3.3 Establishing Property Rights for Groundwater

Let us assume that a regulatory agency intervenes by establishing non-tradable property rights for pumping. If the agency sets an aggregate endowment that is less than the amount pumped in the open-access scenario, there will be conservation. Without the ability to trade, both types must cut back to their assigned allocation. We assume the agency sets allocations based on some simple rule, such as equal amounts to each farmer or on a pro rata basis by land size, and thus it is unlikely that the binding endowment will equate marginal value products across types. Although it is possible to arrive at the socially optimal solution through a discriminatory set of water allocations where each type is allocated the amount they would pump in the socially optimal setting, we logically assume the regulator lacks such information or the political ability to implement discriminatory allocations.

Suppose each farmer receives an initial groundwater allocation, denoted X_{ij}^0, that is assumed to be the same across farmers within each farmer type. In the absence of markets, where the regulating agency simply imposes a cap on individual pumpers, each farmer is constrained to choose $x_{ij}(\cdot) \leq \delta X_{ij}^0$ where $0 \leq \delta \leq 1$. The new constraint on groundwater pumping incorporates the same distributional losses between pumped and applied water as before. Assuming farmers take pumping costs as given, we have the following constrained optimization problem for all individual H types, where $\lambda_{H,j}$ is the Lagrange multiplier associated with the constraint for individual j.

(6) $$\max_{\{x_H, z, \lambda_H\}} \pi_{H,j} = P_H f_j(x_{H,j}, z) - c\frac{x_{H,j}}{\delta} - w_z z - \lambda_{H,j}(x_{H,j} - \delta X_{Hj}^0)$$

The Kuhn-Tucker conditions are:

(7) $$P_H \frac{\partial f_j(x_{Hj}, z)}{\partial x_H} - \frac{c}{\delta} - \lambda_H \leq 0 \text{ and } x_H\left(P_H \frac{\partial f_j(x_{Hj}, z)}{\partial x_H} - \frac{c}{\delta} - \lambda_{H,j}\right) = 0$$

$$P_H \frac{\partial f_j(x_{Hj}, z)}{\partial z} - w_z \leq 0 \text{ and } z\left(P_H \frac{\partial f_j(x_{Hj}, z)}{\partial z} - w_z\right) = 0$$

$$x_{H,j} - \delta X_{Hj}^0 \leq 0 \text{ and } \lambda_H(x_{H,j} - \delta X_{Hj}^0) = 0$$

$$\lambda_{H,j} \geq 0, x_{H,j} \geq 0, z \geq 0$$

Any meaningful allocation of property rights in this setting will cause a binding constraint on pumping, at least for the high types. Therefore, in equilibrium we must have a strictly positive shadow price $\lambda_{H,j}^* > 0$. When optimizing, the H types utilize the full allocation, i.e. $x_{Hj}^* = \delta X_{Hj}^0$. The constrained maximization problem and associated Kuhn-Tucker conditions are similar for the L types. However, the constraint does not necessarily bind for the L types even if it binds for the H types. Assuming the constraint binds for both types, we get the following expressions for the shadow prices.

(8) $$\lambda_{H,j}^* = P_H \frac{\partial f_j(\delta X_{Hj}^0, z)}{\partial x_H} - \frac{c}{\delta}$$

$$\lambda_{L,j}^* = P_L \frac{\partial g_j(\delta X_{Lj}^0, y)}{\partial x_L} - \frac{c}{\delta}$$

This framework is important for establishing the baseline for a water market to emerge; we derive the excess demand/excess supply functions for permits based on this constrained equilibrium. A necessary condition for water markets to emerge is that the shadow price for the H types must be strictly greater than that of the L types, otherwise there would be no trading. Applying functional forms to the expressions above, we can characterize the necessary condition in terms of aggregate demands for each type. Since farmers are identical within each type, we can drop the individual-specific subscript and define X_i^0 as the aggregate endowment for one type, such that $X_i^0 = N_i X_{ij}^0$.

(9)
$$\lambda_H^* = \frac{2}{\eta}\left(\frac{1+\eta}{1+\alpha} - \delta X_H^0\right) - \frac{c}{\delta}$$
$$\lambda_L^* = \frac{2}{\eta}\left(\frac{\alpha(1+\eta)}{1+\alpha} - \delta X_L^0\right) - \frac{c}{\delta}$$

Equation (10), which is equivalently the difference in marginal value products between types evaluated at the optimum $x_{ij}^* = \delta X_{ij}^0$, gives the necessary condition for trading to occur:

(10)
$$\lambda_H^* - \lambda_L^* = MVP_H(\delta X_H^0) - MVP_L(\delta X_L^0) = \frac{2}{\eta}\left\{\frac{(1-\alpha)(1+\eta)}{1+\alpha} + \delta X_L^0 - \delta X_H^0\right\} > 0$$

Thus, we assume (10) holds in the following parts. We define $\Omega = \frac{(1-\alpha)(1+\eta)}{1+\alpha} + \delta X_L^0 - \delta X_H^0$ for simplicity in what follows. Since the first term, $\frac{(1-\alpha)(1+\eta)}{1+\alpha}$, is positive for all values of α and η, we can see that an initial allocation which distributes permits equally between types is sufficient for trading to occur.

4. Tradable Property Rights

Now we build off this and introduce trade, using the groundwater demand functions to create excess demand and excess supply functions for pumping permits. Let us consider a homogeneous product market for groundwater permits where two types are buying and selling water pumping permits. Selling or supplying groundwater in this context is simply being paid not to pump up to one's allocation of groundwater. Therefore, we define trade in terms of pumped groundwater, as opposed to applied groundwater. Let S represent permit price and X_i^T be the quantity of permits traded by type.

Each farmer receives an allocation appropriate for his type as above and relates this to his input demand for water to formulate excess demand/excess supply functions. We define the excess function for farmer j in type i, denoted $E_{ij}(S)$, as the difference between his water demand (for pumped water) at price S and water allowance, ${X_{ij}}^0$

(11) $$E_{ij}(S) \equiv \frac{x_{ij}(S)}{\delta} - {X_{ij}}^0.$$

If $E_{ij}(S) > 0$, individual j has excess demand at groundwater price S because his water demand exceeds his endowment of water rights. If $E_{ij}(S) < 0$ at groundwater price S, then individual j has excess supply because his water demand is less than his allocation. In that case, he will sell the remaining permits. As before, we drop the individual-specific subscript and define X_i^0 as the aggregate endowment for one type since farmers are identical within each type. Given that (10) holds, the H types will be net demanders and the L types will be net suppliers in the water market. Applying functional forms to the excess equation $E_i(S) \equiv \frac{x_i(S)}{\delta} - {X_i}^0$ obtains the following excess demand and excess supply curves.

(12) $$\text{Excess Demand: } X_H^T = \frac{1}{\delta}\left(\frac{1+\eta}{1+\alpha}\right) - X_H^0 - \frac{\eta}{2\delta}S$$

$$\text{Excess Supply: } X_L^T = X_L^0 - \frac{1}{\delta}\frac{\alpha(1+\eta)}{1+\alpha} + \frac{\eta}{2\delta}S$$

The excess demand/supply curves are functions of the demand elasticity and other parameters from the profit maximization problem. Fixing these exogenous parameters at particular levels fixes the intercepts for the excess functions. Figure 1 below shows a graphical derivation of excess supply and excess demand created from an initial endowment shown by the vertical line. In equilibrium, the L-type farmers sell permits to the H-type farmers. In the figure, (S^*, X^{T^*}) denote the market-clearing permit price and quantity pumped under perfect competition.

[Figure 1: Excess Supply and Demand for Water]

4.1 Perfectly Competitive Solution

Now we take the excess demand and excess supply curves and solve for the perfectly competitive equilibrium where $X_L^T = X_H^T = X^T$. Equating supply and demand yields the following market-clearing price and quantity.

(13) $$(X^{T^*}, S^*) = \left(\frac{\Omega}{2\delta}, \frac{1}{\eta}(1 + \eta - \delta(X_H^0 + X_L^0))\right)$$

The permit market alters the farmer optimization problem. Marginal pumping costs now consist of the permit equilibrium price plus the physical marginal pumping costs, adjusted by the efficiency parameter. Additional benefits are captured by farmers when we allow agents to buy and sell excess pumping rights. The gains from trade are given by the following expression, denoted G, which is calculated as the sum of consumer and producer surplus in the permit market.

(14) $$G = \frac{\Omega^2}{2\delta\eta}$$

Welfare in the permit market depends on the demand elasticity, the demand shift and efficiency parameters, and the original endowment of property rights to both types. It is strictly positive by (1), demonstrating the existence of net benefits from voluntary trading.

For use in the sensitivity analysis in section 6, we also express the gains as a percent increase from the surplus under non-tradable property rights for pumping. Surplus in the no-trade scenario is given by $\frac{(\delta X_H^0)^2+(\delta X_L^0)^2}{\eta}$ and calculated from the area under the demand curves and above price when types are restricted to pumping X_i^0. The percentage increase in gains due to trading relative to the no-trade scenario is given by following expression.

(15) $$\%\,\Delta = \frac{\frac{\Omega^2}{2\delta}}{(\delta X_H^0)^2+(\delta X_L^0)^2} * 100$$

4.2 Imperfectly Competitive Solutions

Next, we want to evaluate how groundwater markets are impacted by market power. We focus on within-basin market power with two cases: (1) a small number of sellers that exercise oligopoly power over many buyers and (2) a small number of buyers that exercise oligopsony power over many sellers. In the first case, the H types are assumed to behave competitively. In the second case, sellers are competitive while permit buyers are not.

A convenient way to introduce either buyer or seller market power into our model is to introduce market power parameters ξ and θ, also known as conjectural elasticities, that lie on the unit interval. This allows for the complete spectrum of competition among buyers and sellers to be represented, where $\xi, \theta = 0$ gives the perfectly competitive solution and $\xi, \theta = 1$ gives the monopoly/monopsony solution. Various papers have used this approach (e.g. Huang and Sexton (1996), Zhang and Sexton (2002)).

Sexton and Zhang (2001) among others derive the market power parameters ξ and θ using a conjectural variations framework. They show that the market power parameters can be related to the concepts of perceived marginal revenue and perceived marginal cost curves. The perceived marginal revenue curve is a linear combination of the monopoly marginal revenue curve and the market demand curve (perfect competition marginal revenue curve), with weights given by the seller market power parameter ξ. The intersection of the perceived marginal revenue curve with the sellers' excess supply function determines the permit market outcomes. Figure 2 shows the perceived marginal revenue curve and the equilibrium price and quantity that result in this flexible framework when sellers are assumed to be imperfectly competitive. In the figure, (S_{SP}, X_{SP}^{T}) denote the permit price and quantity with seller market power.

[Figure 2: Water Permit Market with Seller Market Power]

We introduce seller market power ($\xi > 0, \theta = 0$) into the existing modeling framework. Starting from the excess demand and excess supply curves for permits from before, we first derive the perceived marginal revenue curve, as shown in Figure 2. As noted, the perceived marginal revenue curve ($PMR(X_H^T)$) is derived as a linear combination of the monopoly marginal revenue curve ($MR(X_H^T)$) and the market inverse demand curve ($S(X_H^T)$) with weights determined by the seller market power parameter, ξ.

(16) $$PMR(X_H^T) = \xi MR(X_H^T) + (1-\xi)S(X_H^T) = \frac{2}{\eta}\left(\frac{1+\eta}{1+\alpha} - \delta X_H^0\right) - (1+\xi)\frac{2}{\eta}\delta X_H^T$$

Equating the perceived marginal revenue curve with the sellers' excess inverse supply, we can derive the optimal quantity of permits and characterize this as a function of the optimal quantity under perfect competition. Plugging that back into excess demand reveals the equilibrium price charged by the sellers, S_{SP}, which can be written as a function of the perfectly competitive permit price.

(17) $$X_{SP}^{T} = \frac{1}{\delta}\frac{\Omega}{2+\xi} = \left(\frac{2}{2+\xi}\right) X^{T^*}$$

$$S_{SP} = \frac{2}{\eta}\left(\frac{1+\eta}{1+\alpha} - \delta X_H^0 - \frac{\Omega}{2+\xi}\right) = S^* + \left(1 - \frac{2}{2+\xi}\right)\frac{\Omega}{\eta}$$

These results are completely summarized in terms of the demand elasticity parameter, the demand shift and efficiency parameters, the initial assignment of property rights, plus the degree of competition on the seller side (ξ). If $\xi = 0$, the equilibrium outcomes match that of the previous perfect competition solution. By taking the derivative with respect to the market power parameter, we can see how seller market power affects market outcomes:

(18) $$\frac{\partial X_{SP}^{T}}{\partial \xi} = -\frac{1}{\delta}\frac{\Omega}{(2+\xi)^2} < 0$$

$$\frac{\partial S_{SP}}{\partial \xi} = \frac{2}{\eta}\left(\frac{\Omega}{(2+\xi)^2}\right) > 0$$

The greater the market power exercised by the sellers, the fewer the permits that are traded and the higher the permit price.[5] This creates an inefficiency relative to a perfectly competitive permit market. The deadweight loss (DWL) due to market power is given by the following area.

(19) $$DWL = \frac{1}{2}\left(X^{T^*} - X_{SP}^{T}\right)\left(S_{SP} - ES(x_{SP}^{T})\right)$$

$$= \frac{\Omega^2}{2\delta\eta}\left(\frac{\xi}{2+\xi}\right)^2 > 0$$

[5] These inequalities always hold because of the assumption on (10).

Since $\frac{1}{2\delta\eta} > 0$, we know this term is strictly positive. This deadweight loss is equal to the total permit market welfare calculated above, multiplied by the term $\left(\frac{\xi}{2+\xi}\right)^2$, which depends on the degree of market power in the permit market. We can use this to characterize the gains from trading under seller market power, denoted G_{SP} and given by the expression below.

(20) $$G_{SP} = \left(1 - \left(\frac{\xi}{2+\xi}\right)^2\right)\frac{\Omega^2}{2\delta\eta}$$

As shown by (21), gains under seller power are a decreasing function of market power.

(21) $$\frac{\partial G_{SP}}{\partial \xi} = -\frac{2\Omega^2}{\delta\eta}\frac{\xi}{(2+\xi)^3} < 0$$

We can also express these gains as a percentage lost relative to the perfectly competitive solution. The expression below gives the percent change in surplus due to the presence of market power.

(22) $$\%\,\Delta = -\left(\frac{\xi}{2+\xi}\right)^2 * 100$$

In the same way, we can alternatively introduce buyer market power ($\xi = 0, \theta > 0$) into the framework. In this case, the buyers exploit the perceived marginal factor cost curve to drive down the price in the water market. The perceived marginal factor cost curve is a linear combination of the monopsony marginal factor cost curve ($MFC(X_L^T)$) and the market supply curve ($S(X_L^T)$) with weights given by the market power parameter, θ.

(23) $$PMFC(X_L^T) = \theta MFC(X_L^T) + (1-\theta)S(X_L^T) = \frac{2}{\eta}\left[\frac{\alpha(1+\eta)}{1+\alpha} - \delta X_L^0\right] + (1+\theta)\frac{2}{\eta}\delta X_L^T$$

Where the marginal factor cost is given by $MFC(X_L^T) = \frac{2}{\eta}\left(2\delta X_L^T - \delta X_L^0 - \frac{\alpha(1+\eta)}{1+\alpha}\right)$. Quantity, denoted X_{BP}^T, is determined by the intersection of the perceived marginal factor cost curve and the buyers' excess demand. Permit price, S_{BP}, is determined by the excess supply curve.

(24) $$X_{BP}^{T} = \frac{1}{\delta}\frac{\Omega}{2+\theta} = \left(\frac{2}{2+\theta}\right)X^{T^*}$$

$$S_{BP} = \frac{2}{\eta}\left[\frac{\alpha(1+\eta)}{1+\alpha} - \delta X_{L}^{0} + \frac{\Omega}{2+\theta}\right] = S^{*} + \left(\frac{2}{2+\theta} - 1\right)\frac{\Omega}{\eta}$$

By taking the derivative with respect to the market power parameter, we can see how seller market power affects market outcomes:

(25) $$\frac{\partial X_{BP}^{T}}{\partial \theta} = -\frac{1}{\delta}\frac{\Omega}{(2+\theta)^{2}} < 0$$

$$\frac{\partial S_{BP}}{\partial \theta} = -\frac{2}{\eta}\frac{\Omega}{(2+\theta)^{2}} < 0$$

The solutions to the buyer market power case are symmetrical to the seller power scenario. In either case, a larger market power parameter implies fewer permits traded and thus efficiency loss relative to the competitive equilibrium. As one would expect, the price is higher than the competitive counterpart when there is seller power, and lower in the presence of buyer power. Both sets of solutions depend on the demand elasticity and other parameters from the profit maximization problems.

5. Application to Coachella Valley, California

With values for the groundwater demand elasticity, the demand shift parameter, and the efficiency parameter that are reflective of real-world settings, we can quantify the gains to trade and express the benefits relative to the surplus under a no-trade scenario. For this analysis, we focus on the Coachella Valley, which is an agricultural area in southern California with a total crop production value of over half a billion dollars a year. Receiving less than 6 inches of annual average precipitation, agriculture depends on groundwater and imported Colorado River water for irrigation. The groundwater basin has suffered at times from groundwater overdraft, the condition wherein groundwater pumping exceeds groundwater recharge over a period of years. Three of the

Coachella Valley's four groundwater subbasins have been classified as "medium-priority" by the California Department of Water Resources, meaning they are subject to a timeline and set of goals mandated by the Sustainable Groundwater Management Act.

All parameter estimates were calibrated with data from the Coachella Valley, CA. The demand shift parameter, the ratio of marginal value products between low and high value crops, was calculated by first solving for the marginal product of water by crop. For simplicity, we focused on just the top four crops (table grapes, lemons, bell peppers, and dates), which are listed with production value and acreage in Table 1. Average product was calculated by dividing per-acre production by applied water (acre-feet per acre) as reported in the University of California Cooperative Extension Cost and Return Studies for these four crops. With the per-acre value reported in Riverside County's 2015 Crop Report for Coachella Valley, we derived a point on the marginal revenue product curve, extrapolated to the intercept with an elasticity estimate, and compared across crops. The estimate of α is given from the ratio of the intercepts. We used dates as the low-value crop and generated a high-value crop bundle consisting of table grapes, lemons, and bell peppers.

[Table 1: Top Four Crops Grown in the Coachella Valley, CA]

The groundwater demand elasticity estimate comes from a fixed effects estimation using monthly, well-level pumping and price data from the Coachella Valley Water District (Bruno and Jessoe, 2017). Using panel data spanning 17 years, they report the causal effect of a flat, volumetric pumping fee on well-level groundwater extraction with individual well and time fixed effects. For δ, an irrigation efficiency of 85% was chosen because this is the reported average distribution efficiency for drip technology. Drip technology is used by growers of grapes, lemons, and bell peppers in the Coachella Valley (Rogers et al., 1997). An irrigation efficiency of 85% is also the distribution efficiency used in UCCE Cost and Return Studies for drip irrigation systems (O'Connell et al., 2015). Lastly, the total endowment of pumping rights, $X_H^0 + X_L^0$, was estimated to be 0.8, representing a 20% reduction in water use to correct for basin overdraft. This was calculated by comparing the average annual groundwater extraction in Coachella to that which would be allowed on the basin if it were to eliminate its reported 70,000 AF/year of groundwater overdraft (Coachella Valley Water District, 2016). These parameters are summarized in Table 2.

[Table 2: Parameter Estimates]

Magnitudes generated with base Coachella values represent possible gains to Coachella Valley groundwater users from water trading, if the water district imposed pumping restrictions of a reasonable magnitude and distributed permits equally between types. Using these estimates, we calculated the gains from trade to be over three times greater than the benefits under a no-trade scenario.

(26) $$\%\,\Delta = \frac{\frac{\Omega^2}{2\delta}}{\left(\delta X_H^0\right)^2 + \left(\delta X_L^0\right)^2} * 100 = 237\%$$

Where $\Omega = \frac{1.062}{1.1}$.

Since we have no information on the magnitude of potential market power in this area, these gains are calculated assuming a perfectly competitive permit market. Given the model assumptions and parameter estimates of Table 2, the gains from trade are large. These estimates suggest that surplus is 237% greater with trade than without.

6. Sensitivity Analysis

Other settings may differ from Coachella due to a variety of factors. Other agricultural regions in the state grow different bundles of crops and have different groundwater overdraft conditions. The crops being grown in an area impact the demand shift parameter, the demand elasticity, and level of groundwater extraction. With simulations that vary market conditions, we perform a sensitivity analysis to see how reasonable alternative values for market conditions affect the results.

Simulations allow us to determine how the potential gains to trade are impacted by various market factors. In what follows, we express the gains from groundwater trade as a percentage change from the surplus under a no-trade scenario. Table 1 summarizes the base parameter values chosen for the simulations; these values are shown with a vertical line in Figure 3.

The first panel of Figure 3 shows the percentage increase in surplus from allowing trade (relative to the no-trade scenario) as we vary the alpha parameter. The demand shift parameter $\alpha \in (0,1)$, defined as the ratio of marginal value products between types, reflects the differences in water demands. The larger the value of α, the smaller is the difference in water demands between the two types. We expect there to be greater potential gains from trade when there is a bigger difference between demands (α small). We see this to be true in Figure 3.A; the gains from trade decrease as alpha increases. The gains from trade relative to the no trade scenario converge to zero as $\alpha \to 1$.

The second panel of figure 3 shows the percentage increase in surplus from allowing trade (relative to the no-trade scenario) as a function of the demand elasticity. Published empirical estimates of the demand elasticity for irrigation water vary widely, so we consider the range of values from 0 to 2 to capture the entire spectrum of reported values (Scheierling, Loomis, Young, 2006). More elastic values lead to a greater percentage increase in the gains from trade. Because of the large percentage range shown on the y-axis, we see the gains to trade are highly sensitive to the choice of the elasticity value.

The bottom panel of Figure 3 depicts the gains from trade as a function of the endowment of property rights for pumping, maintaining the assumption that pumping endowments are distributed equally between L-types and H-types. Expressed again as a percentage change from the no-trade scenario, gains are decreasing at a decreasing rate as the endowment increases. Even as the total endowment approaches the aggregate quantity pumped in open-access ($X_L^0 = X_H^0 = .5$), there are positive and significant gains from trade. Thus, even if the total restriction on pumping is small relative to the open-access consumption, an endowment of property rights that does not equate marginal value products across types will hurt farmers relative to a trading scenario.

[Figure 3: Gains from Trade]

Since market power is a concern for future groundwater trading, we also perform a simulation that varies market structure. Simulations that vary the market power parameter allow us to see how the potential gains to trade are impacted by market power. When gains from trade under market power are expressed as a percentage change from surplus under perfect competition, they become an expression of ξ only, and are thus robust to assumptions on parameters $\alpha, \delta, \eta, X^0$.

From Figure 4, we can see that the additional gains from trade decline monotonically and at an increasing rate with increasing seller power. Gains from trade in Figure 4 are expressed as a percentage change relative to the gains from trade under perfect competition. As the market power parameter converges to 1 (monopoly case), the additional surplus from trading is 11% smaller than that under perfect competition. Given the magnitude of possible gains to trade shown in Figures

2 through 4, this loss is relatively small. Although the potential for market power is a concern for developing groundwater markets, that concern is unjustified as an argument against having a trading regime.

[Figure 4: Gains from Trade with Seller Market Power]

7. Conclusion

As water regulators around the world strive for groundwater sustainability over the next several decades, they may consider using economic instruments to bring the water table in their basins to a long-run stable level. Prior to implementation of a voluntary groundwater trading program, it will be important to understand how groundwater markets will function, how they might be impacted by market power, and how market power influences other types of behavior.

In this paper, we formalize a groundwater permit market and investigate how groundwater markets will be impacted by market power. We model the decisions of heterogeneous farmers to buy or sell tradable permits where one side of the market has a market power. In the base model, there are two types of farmers extracting groundwater from a common aquifer that are homogenous within their type. Farmers of type L grow a low-value crop and farmers of type H grow a high-value crop such that growers of the high-value crop have a higher willingness to pay for water at any given quantity. The firms with market power account for the effect of their permit trading on the permit price via a conjectural elasticities framework.

We show that the presence of market power in the permit market causes inefficiency—fewer permits are traded than under perfect competition. Calibrating this model with elasticity estimates, a demand shift parameter, and an irrigation efficiency estimate for the Coachella Valley, CA, allows us to see how large of an issue this is in a real-world setting. Simulations that vary market conditions show how these results may change in other settings.

Imperfect competition is likely to be an important characteristic of future groundwater markets in California. Rights for use will likely be allocated by land size in a state characterized by large, vertically integrated farming operations. Additionally, in areas where trading occurs on the level of the water districts and agencies jointly governing a basin, there is a small-numbers problem that will influence trading. Despite the likely presence of market power in future groundwater trading, we have shown that the associated deadweight loss is small relative to the magnitude of potential gains from trading.

Overall, we have shown that there are significant net benefits from a groundwater trading regime. Results from simulations based on linear groundwater demand curves show that the potential gains relative to a no-trade baseline are positive and significant for all reasonable ranges of the model parameters. These results are robust to variations in the demand elasticity, the pumping restrictions or endowment of property rights, and the demand shift index, which captures the degree to which marginal value products differ between buyers and sellers. To evaluate the role of market power, we showed how gains from trade decrease relative to the perfectly competitive baseline; the reduction in the gains from trade due to market power is relatively small. Considering the magnitude of the potential gains from trade, this welfare loss should not be used as an argument against the formation of groundwater markets.

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Figure 1: Excess Supply and Demand for Water

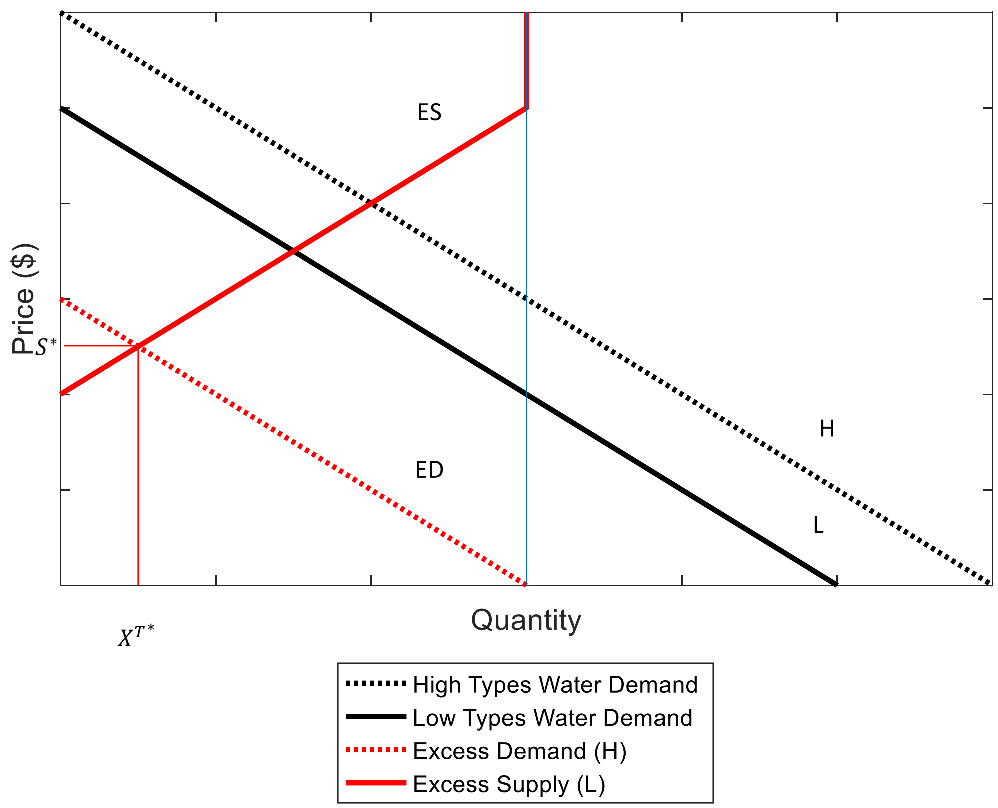

Figure 2: Water Permit Market with Seller Market Power

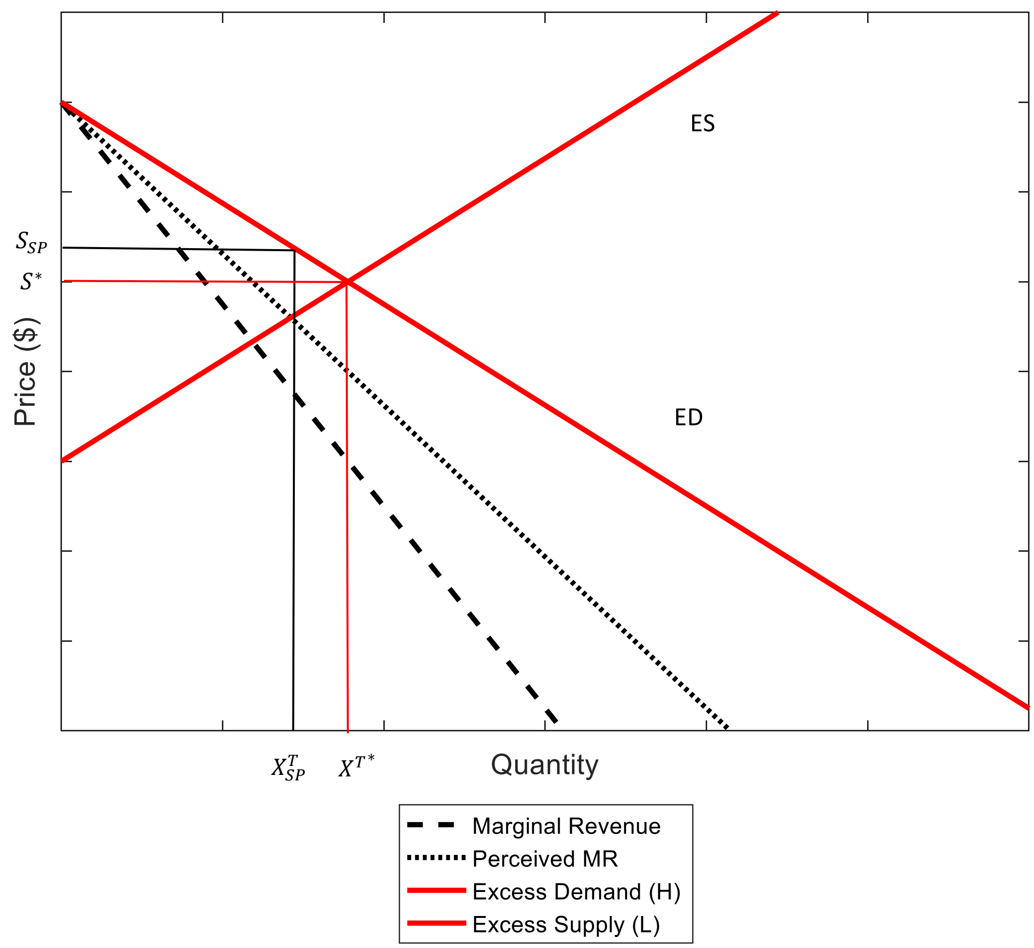

Figure 3: Gains from Trade

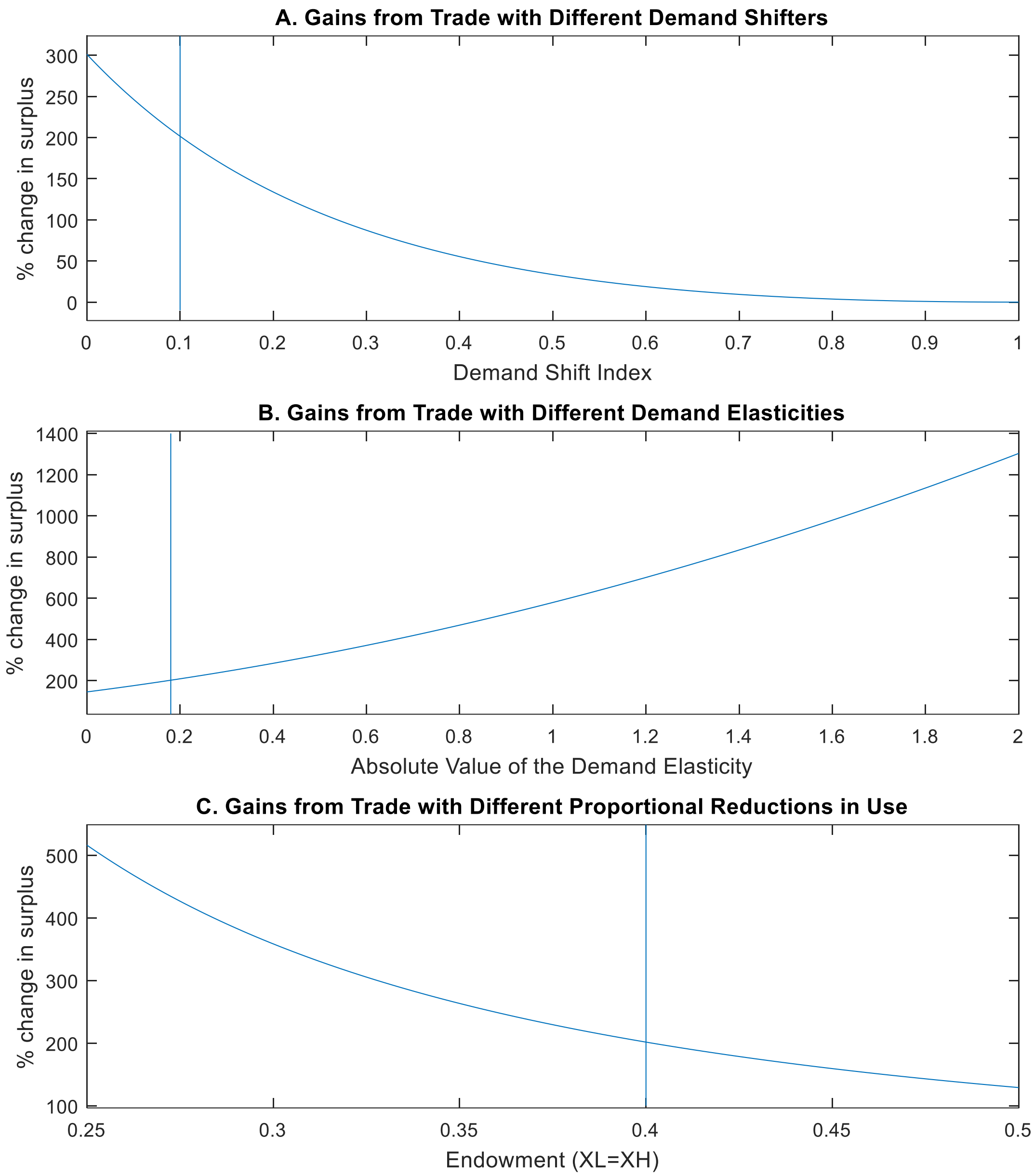

Figure 4: Gains from Trade with Seller Market Power

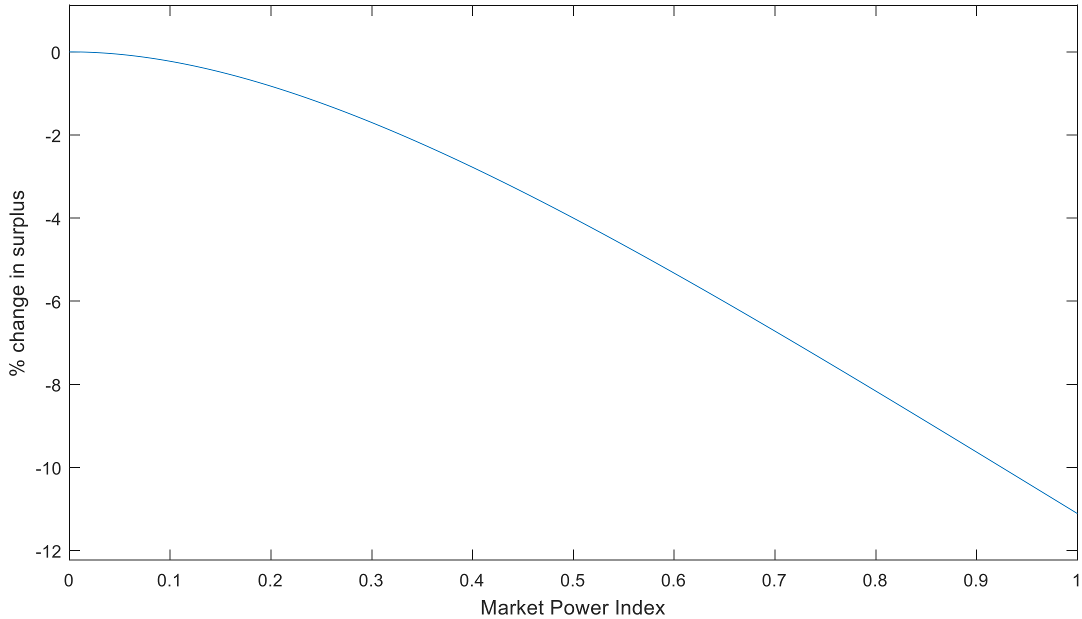

Table 1: Top Four Crops Grown in the Coachella Valley, CA

Crop	Value	Acreage	Estimated Marginal Value Product	Value Type
Grapes	$131,852,825	7802	$1,608	High
Lemon/lime	$93,824,406	3887	$1,819	High
Bell Peppers	$87,891,750	4490	$1,930	High
Dates	$36,184900	7765	$167	Low

Source: Coachella Valley Water District 2014 Crop Report and Authors' calculations

Table 2: Parameter Estimates

Parameter	Description	Parameter Value	Source
α	Demand shift index	0.1	Calculated using University of California Cooperative Extension Cost and Return Studies for the top four crops by acreage in the Coachella Valley. Production value data by crop came from the Riverside County Agricultural Commissioner's 2015 Acreage and Agricultural Crop Report for Coachella Valley.
η	Price elasticity of demand for groundwater	0.18	Bruno and Jessoe (2017) performed a fixed effects estimation using monthly, well-level pumping and price data from the Coachella Valley Water District spanning 2000-2016.
δ	Irrigation efficiency	0.85	This is the average distribution efficiency for drip technology (Rogers et al., 1997).
$X_L^0 + X_H^0$	Aggregate endowment of pumping rights	0.8	Calculated by comparing average annual groundwater extraction in Coachella to that which would be allowed on the basin if it were to eliminate its 70,000 AF/year of groundwater overdraft (Coachella Valley Water District, 2016).