The Gains from Agricultural Groundwater Trade and the Potential for Market Power: Theory and Application*

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October 4, 2018

Abstract

This article models and estimates the efficiency gains from using market-based instruments relative to command and control to manage groundwater. A theoretical model of an imperfectly competitive groundwater market is developed to show how the magnitude and distribution of the gains from trade change as market structure varies. Market structure is a key consideration because future groundwater markets will likely feature geographic limitations to trade, large agricultural players, and a legal environment that is conducive to forming cartel-like coalitions. Application of the model to a groundwater-dependent agricultural region in southern California shows the existence of large gains from trade, despite the potential for market power. Distributional impacts, however, can be sizable even for small degrees of market power. Simulations that vary market conditions show that results likely generalize to other groundwater basins.

JEL codes: Q15, Q25
Keywords: water markets, market structure, market power, irrigation, groundwater

*The authors thank Katrina Jessoe, Pierre Mérel, Michael Hanemann, Richard Howitt, Daniel Sumner, Jeffrey Williams, Jim Wilen, Graham Fogg, Katherine Markovich, and Stephen Maples. Helpful comments and suggestions also came from seminar participants at the Agricultural and Applied Economics Association annual meeting, UC Berkeley, UC Riverside, Purdue, Resources for the Future, the EPA's National Center for Environmental Economics, the University of Western Australia, and the University of Adelaide. A special thanks goes to Ivory Reyburn and Robert Cheng at the Coachella Valley Water District. Funding for this research came from: The Giannini Foundation of Agricultural Economics, UC Water Security and Sustainability Research Initiative funded by the UC Office of the President (Grant No. MR-15-328473), and the National Science Foundation Climate Change, Water, and Society IGERT (DGE No. 1069333).

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Improved management of water resources is becoming increasingly important in the face of climate change. We expect to see higher temperatures and more variable precipitation, with droughts and other extreme climate events occurring more frequently (Kunkel et al. 2013, Swain et al. 2018). Shortages of surface water during times of drought are often met by increased groundwater pumping (Howitt et al. 2015). However, many groundwater basins worldwide have seen declines in groundwater storage over time as groundwater is extracted at a rate faster than it can be replenished (Rodell, Velicogna, and Famiglietti 2009). Because groundwater serves as a buffer to fluctuations in surface water supplies, its management is critical for reducing the costs of climate change for agriculture.

Groundwater management is at the forefront of water policy debates in California. Groundwater accounts for 40% of the agricultural water supply on average (CA DWR 2016) and several areas throughout the state have seen significant declines in groundwater storage (Faunt, Belitz, and Hanson 2009; Famiglietti 2014). In recognition of the value in maintaining a reliable groundwater supply, California passed legislation in 2014 that provides a statewide framework for local agencies to manage groundwater. The Sustainable Groundwater Management Act (SGMA) requires overdrafted basins throughout California to reach and maintain long-term stable groundwater levels. However, SGMA is silent as to how groundwater agencies should achieve sustainability, even though the cost effectiveness of different policy instruments may vary substantially. This paper evaluates the efficiency and distributional impacts of groundwater markets relative to a command-and-control regime for managing agricultural groundwater.

Economists have espoused the merits of market-based instruments to manage the environment (e.g., Goulder and Parry 2008), and growing empirical work points to substantial cost savings from the deployment of market-based instruments relative to command-and-control policies for air pollution (e.g., Fowlie, Holland, Mansur 2012; see Schmalensee and Stavins (2017) for a review). Less is known, however, about the performance of economic instruments for managing water. Previous literature has focused on the gains from surface water transfers, suggesting that there exist large benefits from the reallocation of water from low-value to high-value users (e.g., Vaux and Howitt 1984; Hearne and Easter 1997; Howitt 1994; Sunding et al. 2002; Jenkins et al. 2004). However, these conclusions are often drawn from programming models that rely upon strong assumptions regarding competition, information, and the availability of substitutes, and have yet to be empirically corroborated. Few studies have discussed groundwater trading, in part because groundwater use has remained unregulated, with notable exceptions of Australia (Gao et al. 2013) and Nebraska (Kuwayama and Brozović 2013; Palazzo and Brozović 2014).

Prior to the widespread implementation of groundwater markets, it will be important to understand the magnitude of the potential gains from trade and how these gains are influenced by market conditions, including market structure. The limited history of surface water trading is unlikely to provide much insight into how groundwater markets will evolve. Surface-water trading has, to date, been largely bilateral, involving exchanges among water-supply organizations operating on behalf of their membership (Brown 2006; Hagerty 2018). Groundwater markets, however, are likely to be localized in nature and involve participants pumping water from a given basin. These water rights are not shared collectively, and instead under legal doctrine inure to landowners within the geographic bounds of the basin.

Market structure is likely to be a key consideration in these settings because of the geographic limitations to the markets, presence of large agricultural operations, and a legal environment that is conducive to forming cartel-like coalitions. Our model imposes minimal assumptions on pumping permit market structure to evaluate the efficiency and distributional consequences of either buyer or seller market power in a trading regime.

The model begins with unconstrained groundwater demand functions for heterogeneous farmers. Then property rights for pumping are allocated such that the aggregate use is restricted relative to open access. We then derive excess pumping permit demand and supply functions, which are used to derive trading equilibria and quantify the gains from trade. Using a flexible model framework that can reflect any degree of buyer or seller market power in the permit market for groundwater, we identify the relationship between market power and the efficiency and distributional impacts of water trading.

Results show how the total efficiency gains and the distribution of benefits between buyers and sellers changes with market structure. Although the efficiency impacts of market power are relatively small even for substantial market power, the distributional impacts are large even for moderate levels of market power; traders with market power (whether as buyers or sellers) may be able to capture large shares of the gains from trade. Such impacts are important from a policy perspective because they may influence the political feasibility of implementing groundwater markets.

The contribution of the theoretical model is twofold. First, this work extends a branch of literature that evaluates the impacts of market power in permit markets to include groundwater. Stemming from the seminal paper by Hahn (1984), this literature considers the initial distribution of property rights, strategic behavior of competitors, role of storable permits, and impacts in the final product market, with applications to fisheries and pollution (e.g., Misiolek and Elder 1989; Montero 2009; Liski and Montero 2011; Hintermann 2011, 2017) and surface water (Chakravorty et al. 2009; Ansink and Houba 2012). Second, this analysis relaxes assumptions of prior work regarding market structure to more broadly characterize the impacts of imperfect competition. Whereas previous literature has made rigid assumptions on market structure, such as Cournot competition or dominant firms with a competitive fringe (e.g., Westskog 1996; Montero 2009; Ansink and Houba 2012), we use a flexible framework for imperfect competition in the permit market, allowing the model to depict the entire range of possible market power settings for either buyer or seller power.

The model is then applied to a groundwater basin in southern California that underlies the Coachella Valley, a major production region for citrus, dates, grapes, and vegetable row crops. We contribute to the literature on water markets by estimating the gains from groundwater trade for the water district serving this area. An essential feature of this application is that all model parameter are either constructed or estimated econometrically from observational data for the Coachella Valley. Results show that the economic surplus with competitive trade is almost 50% greater than under command and control, given a 20% reduction in basin-wide use that is needed for it to attain the sustainability requirements specified under SGMA. As the first model of California groundwater trade, this work brings new evidence and a new perspective on the cost-effectiveness of incentive-based instruments for groundwater management.

Background

Groundwater constitutes a significant component of California's water supply, but has historically been unmeasured and unmanaged by the state. Prompted by years of severe drought, the California legislature passed SGMA in 2014, a landmark groundwater law that provides a statewide framework for local groundwater agencies to coordinate data management and organize basin management plans to eliminate overdraft. The law applies to 127 of 515 basins in California, which account for 96% of the groundwater pumping in the state (CASGEM 2014). SGMA gives local agencies the authority and flexibility to correct overdraft conditions in a variety of ways.

Water agencies governing overdrafted basins will need to reduce basin-wide pumping to achieve groundwater sustainability targets. A logical means to achieve this goal is to establish individual property rights for groundwater that restrict aggregate pumping volumes below open-access outcomes and meter pumping. However, the assignment of property rights for groundwater use will cause efficiency losses in the absence of water trading, if the regulating agency lacks perfect information and/or faces legal restrictions to setting allocations.[1] Thus, groundwater trading represents an avenue for reaching basin sustainability targets while minimizing efficiency losses.

[1] California's correlative rights doctrine gives landowners the right to use the groundwater underneath their land, making it likely that land ownership will determine how property rights are allocated under the SGMA. For cases that clarified the legal ties of groundwater to the land, see City of Barstow v. Mojave Water Agency, 23 Cal. 4th 1224, 1253 (2000) and City of Pasadena v. City of Alhambra, 33 Cal. 2d 908, 925, 926 (1949).

Given that trading will likely be restricted to the boundaries of a given hydrologic region (Green Nylen et al. 2017), the structure of California agricultural production and marketing and the legal environment regarding coalition formation may give rise to consolidation of groundwater rights when they become properly defined under the SGMA, making market power an important dimension to consider in the evaluation of groundwater markets. First, it seems likely that these markets will evolve in settings where buyer or seller coalitions can emerge without legal impediments. For example, in many groundwater basins in California, multiple groundwater agencies are emerging to jointly manage the groundwater on a shared basin (Conrad et al. 2018). These agencies may be able to operate as joint buyers or sellers on behalf of farmers in their jurisdictions (Rosen and Sexton 1993).

Second, grower-shippers may themselves be large enough to exercise market power as either buyers or sellers. Especially in California, the agricultural sector has seen significant structural change over the last several decades, leading to fewer and larger vertically integrated farming-shipping operations (Rogers 2001). As noted in footnote 1, most groundwater rights in California are overlying rights based on ownership of the land above the aquifer. Permits for pumping based on land size may cause the concentration of permits in the hands of the large players.

Lastly, the likely absence of restrictions regarding the formation of coalitions among buyers or sellers may lead to groups of players coordinating interests in cartel-like fashion. These coalitions could take the form of growers' associations, cooperatives, or large downstream processors who purchase inputs on behalf of their growers. The horizontal coordination of farmers through such coalitions is common in agriculture. For example, dairy cooperatives have been shown to exercise market power by coordinating interests of dairy producers (Çakir and Balagtas 2012). Downstream processing or packing firms also commonly provide inputs to farmers supplying raw products to their operations. Such vertical coordination could easily be extended to the purchase or sale of groundwater, meaning that in such settings, concentration of buyers and sellers for a water market would be better measured at the processing/packing/shipping stage than at the farm production stage of the market chain.

The Coachella Valley is an ideal setting for an application of our model because it is both subject to mandates under SGMA and exhibits structural elements that may give rise to imperfectly competitive groundwater trade. In particular, the Valley is home to large grower-shippers and growers' organizations, suggesting the potential for market power in an emergent permit market.

Modeling Framework

We develop a theoretical model for studying agricultural groundwater use and trading. The groundwater basin defines the geographic scope of the market, and permit trading occurs among farmers. We investigate the magnitude of the gains from trade, the distribution of benefits among traders, and how both are affected by market power. Our model has the advantage that, when expressed in its linear form, the impacts of groundwater trade can be revealed via a few pure-number parameters that can be estimated with commonly available data for any groundwater basin.

We begin with an unmanaged, open-access groundwater setting and then introduce tradable property rights for pumping. For simplicity, we assume there are two types of farmers pulling from a common aquifer, low (L) and high (H), who are homogeneous within their type. Each produces a single output. Farmers of type L grow a low-value crop, such as rice or cotton, with individual (j) production functions denoted $q_{Lj} = f_{Lj}(x_{Lj}, y_{Lj})$. Farmers of type H grow a high-value crop, e.g., a produce commodity or tree nut, with individual production functions denoted $q_{Hj} = f_{Hj}(x_{Hj}, y_{Hj})$.[2] Production functions are assumed to exhibit diminishing marginal productivity to variable inputs. The variable x represents applied groundwater and

[2]This formulation assumes farmers have already preselected into producing certain crops, e.g., based on heterogeneous ability levels or land quality. Changes in cropping patterns or landholdings that might occur over time due to alternative groundwater management regimes are not considered in this model.

y represents a composite of other inputs to production, such as labor or fertilizer.

There are N_i identical farmers within each type $i \in H, L$. H-type growers have a higher willingness to pay at any given quantity of groundwater. To account for system distributional losses, pumped groundwater is distinguished from the amount of water applied to the crop. Aggregate water quantities are denoted by X and x, 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 $X_i = \sum_{j=1}^{N_i} X_j$, and $x_i = \sum_{j=1}^{N_i} x_j$ for $i \in H, L$. The relationship between pumped and applied water is given by the efficiency parameter δ, with $0 < \delta < 1$ such that $x_i = \delta X_i$.

The marginal pumping cost of water is denoted by $c(X) > 0$. Marginal pumping costs are assumed to be increasing and differentiable, i.e., $c'(X) > 0$; marginal pumping costs increase due to reduction in the water table as more water is pumped. 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.[3]

Open-Access Groundwater Use

Consider the profit maximization problem for farmers in the unmanaged, open-access case. In this setting, the price of groundwater equals the marginal pumping cost, which individual users regard as constant, and is denoted by c. Firms choose inputs (x_i, y_i) to maximize farm profits, where p_i is the output price for the crop produced by type i, $i \in L, H$, and w_y is price of the composite input, y. Farmers of type i face the following profit maximization problem:

$$\max_{x_i \geq 0, y_i \geq 0} \pi_i = p_i f_i(x_i, y_i) - c\frac{x_i}{\delta} - w_y y_i. \tag{1}$$

[3] One extension of this work is to expand on this farm-level groundwater optimization problem by allowing individual firms to account for their influence on their own pumping costs, e.g., 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 (Theis 1940).

The first-order conditions are $p_i \frac{\partial f_i(x_i, y_i)}{\partial x_i} = \frac{c}{\delta}$ and $p_i \frac{\partial f_i(x_i, y_i)}{\partial y_i} = w_y$. Optimizing farmers equate the marginal value product of an additional unit of groundwater to its price, which under open access is the marginal pumping cost adjusted by the efficiency parameter. Solving for x_i and y_i yields the input demand curves for each farmer as functions of crop output price, y_i input price, and the marginal pumping cost of groundwater: $x_H(p_H, w_y, \frac{c}{\delta})$, $x_L(p_L, w_y, \frac{c}{\delta})$.

Open-Access Equilibrium

The open-access equilibrium comes from equating the aggregate water demand relationship, attained by summing demands across both types, with the aggregate water supply relationship, which is simply the marginal pumping cost function, $c(X)$, adjusted by system distributional losses. If we define equilibrium pumping quantities and costs by writing $x_H^* = x_H(p_H, w_y, \frac{c^*}{\delta})$, $x_L^* = x_L(p_L, w_y, \frac{c^*}{\delta})$, and c^*, respectively, then the equilibrium condition is given by $c(X^*) = c(\frac{x_H^*(c^*)}{\delta} + \frac{x_L^*(c^*)}{\delta}) = c^*$.

To obtain analytical solutions and enable quantification of gains from establishment of groundwater markets requires explict functions, so we assume aggregate demands of H and L types for applied water are linear and parallel such that the H type demand curve is greater than that of the L type by a constant amount for all quantities of applied water. Although this approach entails some loss of generality, it has the advantage that we can define differences in H and L demands in terms of a single parameter α, $0 < \alpha < 1$, which measures the vertical difference between H and L water demands at any quantity. Given these assumptions, we can express aggregate demands as $x_H = \gamma - \frac{\beta}{2}c$ and $x_L = \alpha\gamma - \frac{\beta}{2}c$. Aggregate applied water demand is the sum of the total water demands from each type: $x = x_H + x_L = (\alpha + 1)\gamma - \beta c$.

We also assume marginal pumping costs are linear and increasing in X: $c(X) = \theta + \mu X$, with $\theta, \mu > 0$. The intersection of the aggregate demand function with the supply relationship for applied water, $c(x) = \theta + \frac{\mu}{\delta}x$, reveals the competitive, open-access equilibrium price (c^*)

and quantity (x^*) for the linear model:

$$x^* = \frac{\delta\gamma(\alpha+1) - \delta\beta\theta}{\delta+\beta\mu}, c^* = \theta + \mu(\frac{\gamma(\alpha+1) - \beta\theta}{\delta+\beta\mu}). \tag{2}$$

In what follows, we invoke normalizations for price and water quantity such that the competitive market equilibrium price (i.e., marginal pumping cost) and quantity are each equal to one: $(c^*, x^*) = (1, 1)$. 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 parameters that are pure numbers: 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, $\delta \in (0, 1)$. Restating aggregate high and low water demands and inverse groundwater supply with respect to these normalizations yields:

$$x_H = \frac{1+\eta}{1+\alpha} - \frac{\eta}{2}c \text{ and } x_L = \alpha(\frac{1+\eta}{1+\alpha}) - \frac{\eta}{2}c, \tag{3}$$

$$c(x) = (1 - \frac{1}{\varepsilon}) + \frac{1}{\varepsilon}x. \tag{4}$$

Establishing Property Rights for Groundwater

Now assume that a regulatory agency establishes non-tradable property rights for pumping. To induce conservation, the agency must set an aggregate endowment that is less than the amount pumped in the open-access scenario. Without the ability to trade, farmers of both

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

types must limit pumping to no more than their assigned allocations. 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 it would pump in the socially optimal setting, we logically assume the regulator lacks necessary information, political ability, or legal right to implement such an allocation. Instead we assume that allocations are based on some simple rule, such as on a pro-rata basis by land holdings, rendering it highly unlikely that the allocation equates marginal value products across types.

Suppose each farmer receives an initial groundwater allocation, denoted A_i^0, that is the same across homogeneous farmers within each farmer type. In the absence of markets, each farmer is constrained to choose $x_i(\cdot) \leq \delta A_i^0$. An individual of type i faces the following constrained optimization problem, where λ_i is the Lagrange multiplier associated with the constraint:

$$\max_{x_i \geq 0, y_i \geq 0, \lambda_i \geq 0} \pi_i = p_i f_i(x_i, y_i) - c\frac{x_i}{\delta} - w_y y_i - \lambda_i(x_i - \delta A_i^0). \tag{5}$$

The Kuhn-Tucker conditions for the inequality-constrained problem are:

$$p_i \frac{\partial f_i(x_i, y_i)}{\partial x_i} - \frac{c}{\delta} - \lambda_i \leq 0 \text{ and } x_i(p_i \frac{\partial f_i(x_i, y_i)}{\partial x_i} - \frac{c}{\delta} - \lambda_i) = 0 \tag{6}$$

$$p_i \frac{\partial f_i(x_i, y_i)}{\partial y_i} - w_y \leq 0 \text{ and } y_i(p_i \frac{\partial f_i(x_i, y_i)}{\partial y_i} - w_y) = 0 \tag{7}$$

$$x_i - \delta A_i^0 \leq 0 \text{ and } \lambda_i(x_i - \delta A_i^0) = 0. \tag{8}$$

Given that the aggregate endowment is less than the open-access pumping volume, the allocation must bind on pumping for at least one type, i.e. $x_i^* = \delta A_i^0$. Therefore, in equilibrium we must have a strictly positive shadow price, $\lambda_i^* > 0$, for at least one type. Whether the constraint binds for either type depends both on demand and on the initial allocation of permits.

In what follows, we focus on the case where the allocation is binding for both types and where both types apply some portion of their allocation to their farming operation.[5] The subsequent application to Coachella Valley, CA relaxes both of these assumptions.

In this case we get the following equilibrium expression for the shadow prices:

$$\lambda_i^* = p_i \frac{\partial f_i(\delta A_i^0, y_i^*)}{\partial x_i} - \frac{c^0}{\delta} > 0 \text{ for } i \in (H, L) \tag{9}$$

where $c^0 = c(X_H^0 + X_L^0)$ and $X_i^0 = N_i A_i^0$ for $i \in (H, L)$.

A necessary condition for water markets to emerge is that the shadow prices for the H and L types differ at the constrained equilibrium. Applying functional forms to equation (9), we characterize the necessary condition in terms of aggregate demands for each type. The shadow prices become $\lambda_H^* = \frac{2}{\eta}(\frac{1+\eta}{1+\alpha} - \delta X_H^0) - \frac{c^0}{\delta}$ and $\lambda_L^* = \frac{2}{\eta}(\frac{\alpha(1+\eta)}{1+\alpha} - \delta X_L^0) - \frac{c^0}{\delta}$, where $c^0 = (1 - \frac{1}{\varepsilon}) + \frac{\delta}{\varepsilon}(X_H^0 + X_L^0)$ is marginal pumping cost at the constrained equilibrium.

Equation (10) expresses the difference in shadow values between types to yield the necessary condition for trading to occur:

$$|\lambda_H^* - \lambda_L^*| = |MVP_H(\delta X_H^0) - MVP_L(\delta X_L^0)| = |\frac{(1-\alpha)(1+\eta)}{1+\alpha} + \delta X_L^0 - \delta X_H^0| = \Omega > 0. \tag{10}$$

Ω defines the differences in shadow values of applied water at the constrained optimum, $x_i^* = \delta X_i^0$. When equation (10) holds, a set of positive permit prices exists where trading will occur. In the subsequent analysis we assume (10) is satisfied and focus on the case were $\lambda_H^* > \lambda_L^*$, so that H types are net demanders, which requires

$$x_H^*(c^0) - x_L^*(c^0) = \frac{(1-\alpha)(1+\eta)}{1+\alpha} > \delta(X_H^0 - X_L^0), \tag{11}$$

[5] This assumption avoids unenlightening complexities that emerge if the allocation does not bind for one type or if one type idles its acreage and markets its entire allocation. In particular, the supply of permits follows the horizontal axis up to the point where the allocation starts to bind and then becomes vertical at the fixed allocation quantity, creating kinks (and non-differentiability at the kink point(s)) in the excess supply function.

i.e., the difference in equilibrium quantity demanded between the two types, given marginal pumping cost c^0, exceeds the difference in their initial endowments.

Tradable Property Rights

We now introduce trade by using the groundwater demand functions and the exogenous allocation of pumping rights to create excess demand and excess supply functions for pumping permits. Selling or supplying groundwater in this context is simply agreeing not to pump up to one's allocation of groundwater. Let P denote the full groundwater price in a trading regime, which consists of permit price, ρ, plus marginal extraction costs, c^0.

Each farmer's input demand for water is related to his allocation to formulate excess demand/excess supply functions. We define the excess function for each farmer in type i, denoted $E_i(P)$, as the difference between his demand for pumped water at price P and water allowance, A_i^0:

$$E_i(P) \equiv \frac{x_i(P)}{\delta} - A_i^0. \tag{12}$$

$E_i(P) > 0$ indicates a farmer with excess demand at groundwater price $P = \rho + c^0$, while $E_i(P) < 0$ indicates excess supply. Given that (11) holds, the H types will be net demanders and the L types will be net suppliers in the water market in this model. Applying functional forms to equation (12) obtains the following excess demand and excess supply curves as functions of the demand elasticity and other parameters from the profit-maximization problems:

$$\text{Excess Demand: } X_H(\rho) = \sigma_H - X_H^0 - \frac{\eta}{2\delta}\rho \tag{13}$$

where $\sigma_H = \frac{1}{\delta}(\frac{1+\eta}{1+\alpha}) - \frac{\eta}{2\delta}c^0$,

$$\text{Excess Supply: } X_L(\rho) = X_L^0 + \sigma_L + \frac{\eta}{2\delta}\rho \tag{14}$$

where $\sigma_L = \frac{\eta}{2\delta}c^0 - \frac{1}{\delta}\frac{\alpha(1+\eta)}{1+\alpha}$.

Trading Market Equilibrium with Possible Buyer or Seller Market Power

We focus on within-basin market power for two cases: (1) sellers exercise oligopoly power over competitive buyers, and (2) buyers exercise oligopsony power over competitive sellers. Either case encompasses perfect competition as a limiting case.[6]

We introduce buyer or seller market power through market-power parameters—ξ to measure seller power, and θ to measure buyer power. Both ξ and θ lie on the unit interval and are interpreted as indexes of market competitiveness. Several papers have used this approach to study market power for trade of agricultural products (e.g. Suzuki et al. 1994; Alston, Sexton, and Zhang 1997; Zhang and Sexton 2002; Çakir and Balagtas 2012). It allows for the complete range of competitive outcomes among buyers and sellers to be represented. For example, $\xi = \theta = 0$ gives the perfectly competitive solution, while $\xi = 1, \theta = 0$ depicts seller monopoly, and $\theta = 1, \xi = 0$ depicts buyer monopsony. Various degrees of oligopoly power can be described by $0 < \xi < 1, \theta = 0$ and various degrees of oligopsony power by $0 < \theta < 1, \xi = 0$.

These market-power parameters can also be related to conjectural variations models of oligopoly or oligopsony and are sometimes interpreted as conjectural elasticities, which capture firms' expectation about how rivals will react to a change in the firm's purchases (θ) or sales (ξ) (Kaiser and Suzuki, 2006; Perloff, Karp, and Golan 2007).[7]

The market power parameters can also be related to perceived marginal revenue (PMR) and perceived marginal factor cost ($PMFC$) curves. PMR is relevant to seller power and is

[6]We do not consider bilateral oligopoly power. This type of market structure involves multilateral bargaining, a problem that is fundamentally intractable without imposing strong assumptions on the bargaining environment.

[7]The market power parameters ξ and θ can be interpreted simply as summary measures of market competitiveness, i.e., as the realizations at any point in time of an unobserved game among players in the groundwater market; we do not need to rely on the concept of firms forming conjectures.

expressed as a linear combination of the monopoly marginal revenue curve, $MR(X_H)$, and the market inverse excess demand curve $ED^{-1}(X_H)$ for H types (i.e., the marginal revenue curve under perfect competition) with weights given by ξ:

$$PMR(X_H) = \xi MR(X_H) + (1 - \xi)ED^{-1}(X_H). \quad (15)$$

Similarly, $PMFC(X_L)$ applies in settings of buyer power and is a linear combination of the perfect competitor's marginal factor cost curve, i.e., the inverse supply curve ($ES^{-1}(X_L)$), and the monopsonist's marginal factor cost curve $MFC(X_L)$, with weights given by θ:

$$PMFC(X_L) = \theta MFC(X_L) + (1 - \theta)ES^{-1}(X_L). \quad (16)$$

Figure 1 illustrates the model for the case of seller oligopoly ($0 < \xi < 1, \theta = 0$). The intersection of the sellers' PMR and excess supply curves determines the equilibrium permit market volume, X^{SP}, which yields equilibrium groundwater permit price, ρ^{SP}. Relative to price and traded quantity (ρ^T, X^T) at the competitive equilibrium (i.e., $\xi = \theta = 0$), seller market power reduces trading, increases the permit price, and causes a deadweight loss equal to the shaded area in Figure 1.

Seller Market Power

To provide a benchmark for comparison to market-power solutions, we solve first for the perfectly competitive trading equilibrium by equating L types' excess supply functions with H types' excess demand functions to yield $(X^T, \rho^T) = (\frac{\Omega}{2\delta}, \frac{\delta}{\eta}[\sigma_H - \sigma_L - (X_H^0 + X_L^0)])$. The gains from trade under perfect competition, calculated as the sum of consumer and producer surplus in the permit market, is equal to $\frac{\Omega^2}{2\delta\eta}$.

From the excess demand and excess supply curves for permits in equations (13) and (14), we next derive the perceived marginal revenue curve, as shown in Figure 1, for the linear version

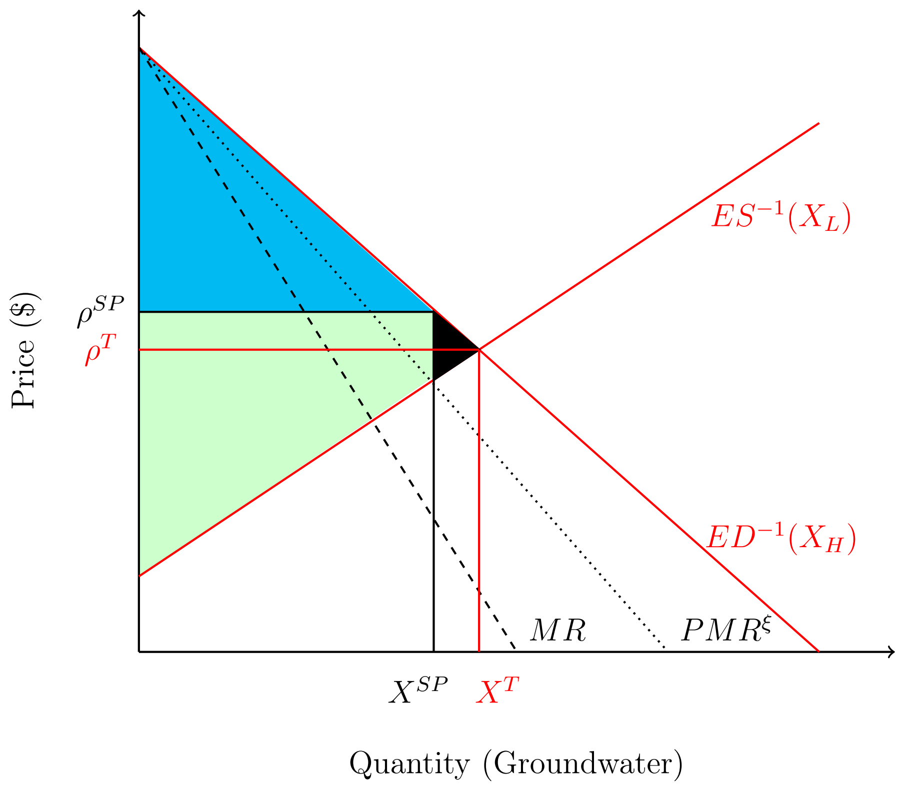

Figure 1: Groundwater permit market with seller market power

Notes: $PMR^{\xi}(X_H)$ represents the perceived marginal revenue when sellers exercise market power, ξ. (X^{SP}, ρ^{SP}) denote the equilibrium outcomes under seller power. The figure depicts consumer surplus, producer surplus, and deadweight loss relative to the perfectly competitive case when suppliers exercise market power, ξ.

of the model:

$$PMR(X_H) = \frac{2\delta}{\eta}(\sigma_H - X_H^0) - (1+\xi)\frac{2\delta}{\eta}X_H. \tag{17}$$

Then equating $PMR(X_H)$ with the sellers' excess inverse supply, we derive the equilibrium quantity of permits under seller power and express it as a function of the equilibrium quantity under perfect competition, $X^{SP} = \frac{1}{\delta}\frac{\Omega}{2+\xi} = (\frac{2}{2+\xi})X^T$. Plugging that result back into excess demand curve reveals the equilibrium permit price, ρ^{SP}, which can be written as a function of the perfectly competitive groundwater price, $\rho^{SP} = \frac{2\delta}{\eta}(\sigma_H - X_H^0 - [\frac{\sigma_H+\sigma_L+X_L^0-X_H^0}{2+\xi}]) = \rho^T + (1 - \frac{2}{2+\xi})\frac{\Omega}{\eta}$.

These results are completely summarized in terms of the demand elasticity parameter, the demand shift and distributional efficiency parameters, the initial assignment of property rights, plus the degree of competition on the seller side (ξ). If $\xi = 0$, the equilibrium outcome reverts to the perfect competition solution. For $\xi > 0$, the equilibrium quantity traded is lower and equilibrium price higher than under perfect competition, consistent with Figure 1. Differentiating with respect to ξ reveals how seller market power affects market outcomes:

$$\frac{\partial X^{SP}}{\partial \xi} = -\frac{1}{\delta}\frac{\Omega}{(2+\xi)^2} < 0, \frac{\partial \rho^{SP}}{\partial \xi} = \frac{2}{\eta}(\frac{\Omega}{(2+\xi)^2}) > 0. \tag{18}$$

The greater the market power exercised by the sellers, the fewer the permits that are traded and the higher the groundwater price.[8] This creates an inefficiency relative to a competitive permit market, with the deadweight loss (DWL) due to the exercise of market power expressed as:

$$DWL = \int_{X^{SP}(\xi)}^{X^T} ED^{-1}(\tau) - ES^{-1}(\tau)d\tau = \frac{\Omega^2}{2\delta\eta}(\frac{\xi}{2+\xi})^2 > 0. \tag{19}$$

Since $\frac{1}{2\delta\eta} > 0$, DWL is strictly positive for $\xi > 0$ and increases in ξ at an increasing rate.

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

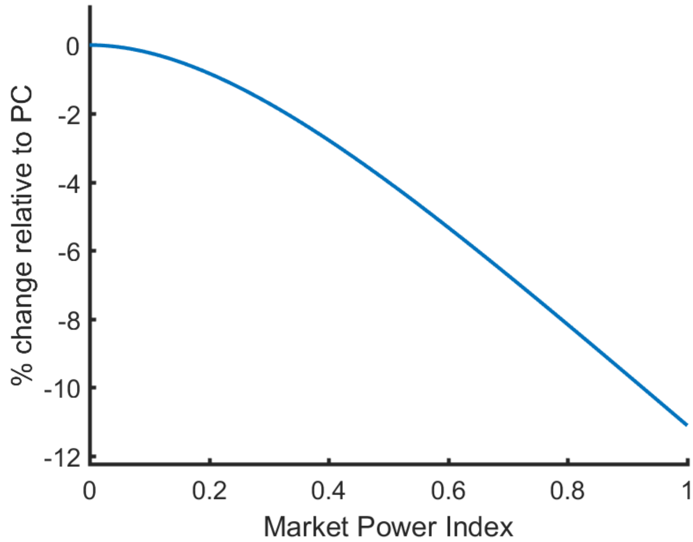

Figure 2: The effect of seller market power ($\xi \in (0, 1)$) on total gains from trade

Notes: The figure shows how the gains from trade, expressed as a percentage change from the benefits under perfect competition, change as market structure varies.

We can use the expression for DWL to characterize the gains from trading under seller market power, $G^{SP} = (1 - (\frac{\xi}{2+\xi})^2)\frac{\Omega^2}{2\delta\eta}$. Gains to trading are a decreasing function of seller market power: $\frac{\partial G^{SP}}{\partial \xi} = -\frac{2\Omega^2}{\delta\eta}\frac{\xi}{(2+\xi)^3} < 0$. We can also express the welfare loss due to seller power in the permit market relative to perfect competition in percentage form, $\% \triangle G^{SP}$, as follows:

$$\% \triangle G^{SP} = -(\frac{\xi}{2+\xi})^2 * 100, \tag{20}$$

i.e., the relative welfare change is solely a function of ξ, making the result robust to assumptions on parameters $\alpha, \delta, \eta, X^0$. Figure 2 shows how equation (20) varies over the range of possible market power values. As ξ converges to 1 (monopoly case), the surplus from trading is 11% smaller than under perfect competition.

Buyer Market Power

In the same way, we can alternatively introduce buyer market power ($\xi = 0, \theta > 0$) into the framework. The perceived marginal factor cost curve for the linear version of the model is:

$$PMFC(X_L) = -\frac{2\delta}{\eta}(X_L^0 + \sigma_L) + (1+\theta)\frac{2\delta}{\eta}X_L. \tag{21}$$

Equilibrium quantity, denoted X^{BP}, is determined by the intersection of $PMFC(X_L)$ with buyers' excess demand, and can be expressed as a function of the perfectly competitive outcome: $X^{BP} = \frac{1}{\delta}\frac{\Omega}{2+\theta} = (\frac{2}{2+\theta})X^T$. The equilibrium groundwater permit price, ρ^{BP}, is determined where X^{BP} intersects the excess supply curve: $\rho^{BP} = \frac{2\delta}{\eta}(\frac{\sigma_H+\sigma_L+X_L^0-X_H^0}{2+\theta} - X_L^0 - \sigma_L) = \rho^T + (\frac{2}{2+\theta} - 1)\frac{\Omega}{\eta}$. These equilibrium outcomes show that buyer power will depress trade in the water market and reduce price relative to the competitive equilibrium, with both effects increasing as a function of θ.

The solutions to the buyer market power case are symmetric 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 and transfer of substantial portions of the gains to trade into the hands of the entities exercising market power.

Application to the Coachella Valley, CA

We now apply the model to estimate the gains from groundwater trade for the Coachella Valley in Riverside County, CA under pumping restrictions likely to be imposed under SGMA. The structure of agriculture in Coachella exhibits features that could induce market power in groundwater trading, making it an ideal setting for application of the groundwater trading model.

The Coachella Valley receives only four inches of rain a year on average, making its agriculture dependent on groundwater and imported Colorado River surface water for irrigation.

The region has roughly 65,000 acres in crop production with an annual value of over half a billion dollars. In addition to producing 95% of the nation's dates, the area also produces table grapes, citrus fruits, bell peppers, and other vegetables (ACO 2016).

The model characterizes the gains from groundwater trade as a function of six market parameters: the heterogeneity of demand for groundwater across users (α), the price elasticity of groundwater demand (η), the total allowable extraction (X^0), the irrigation efficiency (δ), the price elasticity of groundwater supply (ϵ), and the degree of buyer (θ) or seller (ξ) market power. All except X^0 are pure numbers, but X^0 is converted to that form by expressing it as a percentage reduction from the open-access solution required to achieve sustainability of the aquifer. In addition, a rule for apportioning X^0 among users is needed. Given California's legal history (see footnote 1), an allocation of pumping permits that is proportional to land holdings is the most likely scenario and the one we assume for purposes of this application.

All model parameters in this application are estimated using data from the Coachella Valley. This section first describes the methods used to establish the model parameters, followed by estimation of the gains from groundwater trade and a sensitivity analysis. Results show that the economic surplus with competitive trade is almost 50% larger than under the no-trade equilibrium. Furthermore, the gains remain large in the presence of market power and over a reasonable range of other model parameter values, indicating that results are likely to generalize to other basins where trading might occur.

Simulation Model Parameters

Table 1 outlines the parameters used to simulate the gains from groundwater trade in the Coachella Valley, including either the data source for the parameter or a brief summary of how the parameter was estimated.

The demand-shift index, α, captures the degree of heterogeneity of water demands among groundwater users. It is the ratio of marginal value products (MVP) between low- and high-value crops for any quantity of groundwater. This parameter was calculated with data from

Table 1: Coachella Valley Parameter Estimates

Parameter	Symbol	Estimate	Source
Demand Shift Index	$0 < \alpha < 1$	.26	Estimated by comparing intercepts of H and L type water demands, which were proxied with estimates of water demands for Coachella's top ten crops.
Demand Elasticity	η	-.17	Bruno and Jessoe (2018)
Total Allowable Extraction	$X_L^0 + X_H^0$	.8	Calculated by comparing average annual basin total pumping with CVWD's annual overdraft estimates.
Irrigation Efficiency	δ	.85	Rogers et al. (1997)
Supply Elasticity	ε	1.03	Calculated with a point on the supply curve, an engineering formula that relates costs to depth to the water table, and an estimate of aquifer storativity.

Riverside County's 2016 Crop Report for Coachella Valley and University of California Cooperative Extension (UCCE) Cost and Return Studies.[9] We focus on the ten leading crops, which are listed by total acreage in Table 2, along with information on total production value and average applied water per acre.

To estimate α, we first obtained a point on the average product curve of irrigation water for each crop by dividing per acre production by applied water per acre. Given the assumption of linear demands, this point can then be related to a point on irrigation water's MVP curve with information on the per-unit output price as shown in Bruno (2018).

We extrapolated this point to the MVP intercept or "choke point" with the demand elasticity estimate described below, and compared these functions across crops.[10] In this fashion, the demand shift index can be computed for any pair of crops. For consistency with the conceptual model, we conducted the simulation with H and L demand types and a single value for α. To this end, based on Table 2 we bundled dates, sweet corn, carrots, watermelon, and broccoli as

[9]UCCE Cost and Return Studies for all available commodities can be accessed here: https://coststudies.ucdavis.edu/en/current.

[10]This elasticity is assumed to be the same across Coachella crops. The data used to estimate the Coachella water demand elasticity do not enable crop-specific elasticities to be estimated.

Table 2: Top Ten Crops Grown in the Coachella Valley, CA

Crop	Acreage	Revenue	Revenue per acre	Applied Water	Revenue per AF	Type
Dates	7,964	$40,110,000	$5,036	8.0	$630	Low
Grapes	7,379	$143,222,000	$19,409	3.0	$6,470	High
Bell Peppers	5,288	$77,700,000	$14,693	2.0	$7,347	High
Lemons	5,200	$110,605,000	$21,270	2.9	$7,334	High
Carrots	4,777	$28,700,000	$6,007	2.5	$2,403	Low
Broccoli	2,475	$14,561,000	$5,883	1.7	$3,461	Low
Sweet Corn	1,883	$11,174,000	$5,934	5.0	$1,187	Low
Lettuce	1,600	$12,480,000	$7,800	1.2	$6,500	High
Watermelon	1,525	$14,860,000	$9,744	3.0	$3,248	Low
Mandarins	1,475	$19,721,000	$13,370	2.5	$5,348	High

Notes: Revenue and acreage data come from the Coachella Valley 2016 Acreage and Agricultural Crop Report. Applied water by crop in acre-feet per year is from UCCE Cost and Return Studies. Revenue per acre-foot of water is calculated by dividing per-acre revenues by the average acre-feet of applied water.

the L crops and generated an H crop bundle consisting of table grapes, lemons, bell peppers, romaine lettuce, and mandarins. We calculated an acreage-weighted average of the intercept for each crop's water demand to arrive at an intercept value for the bundle. The ratio of the MVP intercepts between the H and L bundles serves as the estimate of α. The sensitivity analysis explores different combinations for the H and L bundles.

The largest water agency in the Valley, the Coachella Valley Water District (CVWD), meters extraction at each groundwater well within its service area and charges volumetric prices for groundwater pumping known as "Replenishment Assessment Charges" or RAC. These plausibly exogenous prices were utilized by Bruno and Jessoe (2018) to estimate a price elasticity of groundwater demand for agricultural users in the Coachella region based on monthly panel data on well-level groundwater extraction and prices. Their research design exploits the deployment of three location-based pricing regimes within the Coachella Valley. They find that demand is inelastic, with a preferred point estimate of -0.17 that is statistically significant and robust to alternative specifications.

The total endowment of groundwater pumping rights, $X_H^0 + X_L^0$, was estimated to be 80% of Coachella's open-access groundwater extraction, implying that a 20% reduction in water use is needed to correct for basin overdraft. This figure was calculated by comparing the average annual groundwater extraction within the service area of the CVWD to that which would be allowed if it were to eliminate its reported 70,000 AF/year of groundwater overdraft (CVWD 2016). Proportional to acreage held by each type, 53% of this cap is allocated to the H types in our simulation.

Drip technology is used for many crops in the Coachella Valley, including grapes, lemons, bell peppers, mandarins, and watermelon. An irrigation efficiency of 85% was chosen for δ because it is the reported average distribution efficiency for drip technology (Rogers et al. 1997) and is also the efficiency rate used in UCCE Cost and Return Studies for drip irrigation systems (O'Connell et al. 2015).

Estimating ε requires specifying the function for marginal groundwater extraction costs, $c(X)$, for Coachella. These costs consist of the sum of the incremental energy extraction costs and the volumetric pumping charge (i.e., the RAC) imposed by CVWD. From 2000 to 2016, the RAC has ranged from \$0 to \$129 across three subregions, with an average over this time period of \$65/AF, making up a large share of total pumping costs. Energy extraction costs are an increasing function of total pumping, X, and a reduction in basin-wide groundwater use under SGMA will decrease the marginal pumping costs faced by users on the basin.[11]

[11] We assume for simplicity that marginal extraction costs are the same across all users despite users in different regions of Coachella facing location-based volumetric groundwater charges. This assumption impacts the gains from trade only if H or L types are concentrated in one region. However, examination of the cropping patterns indicates no concentration by type in any single region.

To specify marginal energy extraction costs, let $h(X)$ represent the depth to the water table from the surface, p^e the electricity price per kwh, and ϕ the kwh requirement to raise an acre foot (AF) of water one foot. The marginal energy cost for groundwater extraction can then be expressed as $\phi p^e h(X)$ (Rogers and Alam 2006), thereby yielding the following expression for $c(X)$ for the Coachella Valley: $c(X) = \phi p^e h(X) + RAC$. Imperial Irrigation District, the local energy provider, reports $p^e = \$0.0618$ as the 2016 per kwh electricity price faced by irrigated agriculture in the Coachella area. The kwh requirement to lift 1 AF of water 1 foot is $\phi = 1.551$ (Rogers and Alam 2006) .

We assume $h(X) = \frac{X}{s}$, so that $h'(X) > 0$, which implies $c'(X) > 0$. Here s represents the storativity of the aquifer, defined as the volume of water released from groundwater storage per unit decline in the depth to water in a well (Fetter 2001). Thus, the inverse storativity can be interpreted as the change in the depth to the water table due to a change in groundwater extraction. Storativity is a pure number that is equal to the specific yield of an aquifer if groundwater is unconfined (Fetter 2001). Although both confined and unconfined groundwater conditions are present in the Indio subbasin beneath the Coachella Valley (DWR 2015), we focus on the storativity for an unconfined aquifer for simplicity. Tyley (1974) estimated specific yields ranging from 0.06 to 0.15 for the unconfined parts of the Indio basin. We take the simple average of these values for a baseline storativity value of 0.11.

The inverse of the supply elasticity in terms of applied water ($x = \delta X$) evaluated at the open-access equilibrium quantity and price, normalized to $(x^*, c^*) = (1, 1)$, is thus $\frac{1}{\varepsilon} = \frac{\partial c(x)}{\partial x} \frac{x^*}{c^*} = \frac{\phi p^e}{\delta s} = 1.03$, given $s = 0.11$, $\phi = 1.551$, $p^e = \$0.062$, and $\delta = 0.85$. We use this supply elasticity to parameterize the marginal cost function defined in equation (4) to estimate the marginal pumping costs given a 20% reduction in basin-wide groundwater extraction, $c(x = .8) = (1 - \frac{1}{\varepsilon}) + \frac{1}{\varepsilon}(.8) = .806$, i.e., marginal pumping costs under the constrained allocation are estimated to be 80.6% of their value under open-access.

The final parameter needed to estimate gains to groundwater trade in the Coachella Valley is the level of either buyer or seller market power. Since groundwater trading is only on the horizon, there exist no data from actual trades to estimate values for θ or ξ using, for example, methods of the new empirical industrial organization, as discussed, e.g., in Kaiser and Suzuki (2006) and Perloff, Karp, and Golan (2007). Our approach is to first solve for the market equilibrium price, trade volumes, and surplus measures under perfect competition and then show their sensitivity to alternative magnitudes of seller market power, as measured by ξ, recognizing that buyer power ($\theta > 0$) will yield a symmetric impact based on the theoretical model.

We encounter two complications relative to the framework presented in the conceptual model in applying the model to Coachella Valley based on the parameter estimates summarized in Table 1. First is that the measures of gains to trade derived in the conceptual model reflect the case when permit allocations constrain pumping for both types. However, for the baseline parameter values and allocation based on land holdings, the allocation constraint is not binding for the L types in Coachella. In this case, the inverse excess supply curve is flat ($ES^{-1}(X_H) = 0$) up to the sales volume, $\bar{X} = X_L^0 - \frac{1}{\delta}\frac{\alpha(1+\eta)}{1+\alpha}$, where the allocation binds for the L types, so they are only willing to sell quantities in excess of this amount at a positive price. Second is that under the baseline parameters, L types sell their entire allocations, which corresponds to the case where acreage is idled in favor of rights holders becoming exclusively water marketers.[12] For settings when this condition holds, $ES^{-1}(X_H)$ is vertical at the level of rights allocated to L types. $ES^{-1}(X_H)$ is thus a piecewise linear function for L types in Coachella, as depicted in Figure 3, which illustrates the gains from perfectly competitive trade under the aforementioned conditions.

Results for Coachella Valley, California

Equation (22) expresses the percentage change in economic surplus from allowing trade for the baseline groundwater-allocation scenario assuming perfect competition in the groundwater

[12]This outcome would represent a groundwater case of the land-fallowing equilibrium for surface-water trades discussed, for example, in Howitt and Sunding (2003).

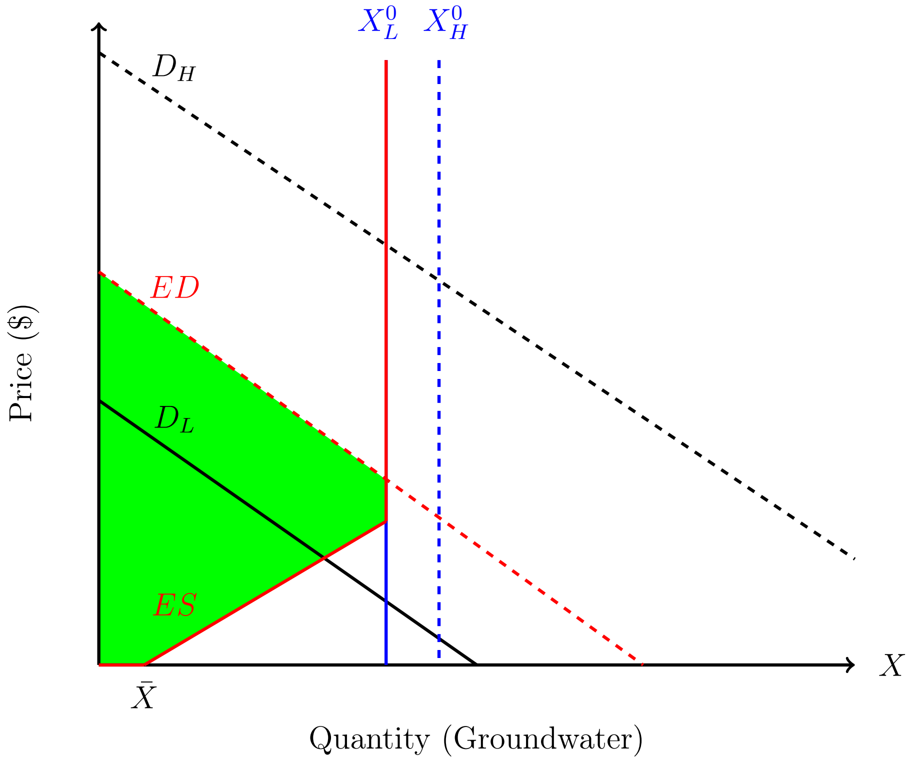

Figure 3: Market-level gains from trade (constraint non-binding for L types)

Notes: The figure denotes excess supply and excess demand curves when α is small, allocations differ between types, and the constraint is non-binding for the L types at the initial endowment, X_L^0. $\bar{X}$ denotes the point where sellers are willing to supply groundwater at a positive price. The shaded area illustrates the gains from trade. In equilibrium, the L types sell their entire allocation of pumping rights.

market. $D_i^{-1}(X)$ denotes the aggregate inverse demand curves for pumped water for type i, and $ED^{-1}(X)$ and $ES^{-1}(X)$ denote inverse excess demand and supply functions for the H and L types, respectively. The numerator of (22) expresses total surplus gains as the difference between $ED^{-1}(X)$ and $ES^{-1}(X)$ of the H and L types (i.e., the shaded area in Figure 3), while the denominator represents economic surplus generated from groundwater pumping in the no-trade setting when the initial allocation is non-binding for the L-type producers, who would, in the absence of trading, continue to apply their unconstrained optimum, X_L^*:

$$\%\triangle = \frac{\int_0^{X^T} \left(ED^{-1}(\tau) - ES^{-1}(\tau)\right) d\tau}{\int_0^{X_H^0} \left(D_H^{-1}(\tau) - c^0\right) d\tau + \int_0^{X_L^*} \left(D_L^{-1}(\tau) - c^0\right) d\tau} * 100. \tag{22}$$

Given the aforementioned model parameters, the percent change in surplus from groundwater trading in Coachella Valley relative to command and control is 45% or $39.7 million. In equilibrium, 88,315 AF of groundwater would be traded at $383 per AF. Details of these calculations can be found in the appendix.

The Effect of Market Power on the Gains from Trade

We lean on the theoretical model for insight regarding the impacts of market power in the Coachella Valley. As illustrated in Figure 2, the gains from trade can be reduced by at most 11% when $\xi = 1, \theta = 0$ or $\theta = 1, \xi = 0$, regardless of the initial allocation of permits or the specific estimates for the other parameters. In this extreme case, the gains from trade can still be as large as $35.2 million, assuming permits are allocated based on acreage. Thus, the efficiency gains of groundwater markets relative to command and control remain large even in the presence of market power.

To assess the distributional impacts of market power, we study how the gains from groundwater trade change as a function of ξ. Equation (23) depicts the percent change in consumer, i.e., buyer, surplus due to seller market power relative to that under perfect competition:

$$(23) \qquad \% \triangle CS = \frac{\int_0^{X^{SP}(\xi)}(ED^{-1}(\tau) - P^{SP}(\xi))d\tau - \int_0^{X^T}(ED^{-1}(\tau) - P^T)d\tau}{\int_0^{X^T}(ED^{-1}(\tau) - P^T)d\tau} * 100.$$

The percentage change in consumer surplus is decreasing in ξ because fewer permits are traded and at a higher price, meaning buyers are increasingly worse off with increasing seller power. Sellers' relative surplus gains from trade, $\% \triangle PS$, are, conversely, increasing in their market power as equation (24) shows:

$$(24) \qquad \% \triangle PS = \frac{\int_0^{X^{SP}(\xi)}(P^{SP}(\xi) - ES^{-1}(\tau))d\tau - \int_0^{X^T}(P^T - ES^{-1}(\tau))d\tau}{\int_0^{X^T}(P^T - ES^{-1}(\tau)d\tau)} * 100.$$[13]

Figure 4 shows the percent change in buyer/consumer and seller/producer surplus relative to that under perfect competition as a function of ξ. Consumer surplus declines more rapidly than the overall gains to trade shown in Figure 2. At $\xi = 1$, consumer surplus is over 55.5% smaller than it would be under perfect competition, with most of the loss to buyers captured by sellers, given the relatively small deadweight loss. At $\xi = 1$, seller surplus is 54.1% greater than that under perfect competition.

Even a small degree of market power generates large distributional differences in surplus relative to competitive levels. Figure 4 shows that an oligopoly index of $\xi = 0.2$, which is equivalent to that produced in a five firm symmetric Cournot equilibrium, results in buyer surplus losses of 17.4% and seller surplus gains of 32.7% relative to perfect competition. A two firm symmetric Cournot equilibrium, which translates to an oligopoly index of $\xi = 0.5$, generates surplus changes of -36% and 47.7% for buyers and sellers, respectively.

These distributional impacts are important because relative winners and losers from a trading environment will help determine the political feasibility of implementing groundwater markets. While it is still the case that all are better off than under no trade, these distributional

[13]Equations (23) and (24), expressed as functions of parameters from the linear model, can be found in the appendix.

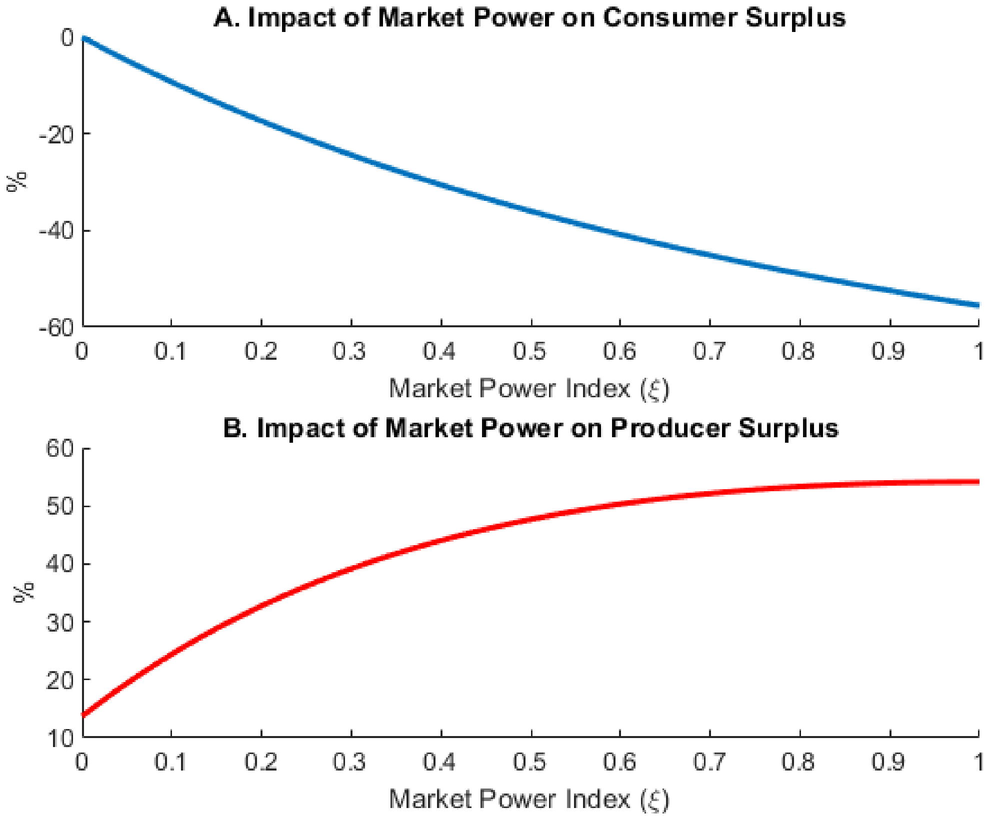

Figure 4: Distributional effects of market power

Notes: The top panel shows how buyers' gains from trade, expressed as a percentage change from consumer surplus under perfect competition, change as market structure varies. Likewise, the bottom panel shows how sellers' gains from trade change as market structure varies.

impacts may be undesirable from an equity perspective because a large share of the gains to trade accrue to those with market power, which are more likely to be large agribusiness enterprises with significant landholdings.

Sensitivity Analysis

We now perform a sensitivity analysis to gauge the robustness of results to plausible alternative values for the market parameters. This exercise also helps in understanding how the Coachella results might generalize to other groundwater trading environments. Agriculture fed by different groundwater basins will feature different crops and groundwater conditions than Coachella, meaning that their groundwater market environments will feature distinct values for most or all of the model parameters.

Figure 5 shows how the gains from groundwater trade change as market conditions vary, where the surplus with trade is expressed as a percentage change in surplus from the no-trade scenario. Panels A - E respectively show how the gains change as we vary the demand shift parameter, α, the demand elasticity η, the total allowable extraction on the basin relative to open access, X^0, the groundwater supply elasticity, ϵ, and the initial allocation between types. The base parameter values are shown with a vertical line in each panel of Figure 5.

The first panel of Figure 5 shows to no surprise that the gains to groundwater decrease substantially as α increases, making water demands more similar between types. The gains from trade converge to zero as $\alpha \to 1$. Coachella Valley grows a large diversity of crops, with no more than 15% of total acreage in any single crop, a level of cash crop diversification that is not uncommon in California. The estimate of α for Coachella remains small (and the gains to trade substantial) when different bundles of crops are considered for the H and L types. The α parameter ranges between .21 and .43 across five different plausible classifications of the crops into low and high crop bundles.

The second panel of Figure 5 shows the percentage increase in surplus from trade as a function of the demand elasticity. More elastic demands lead to a greater percentage increase

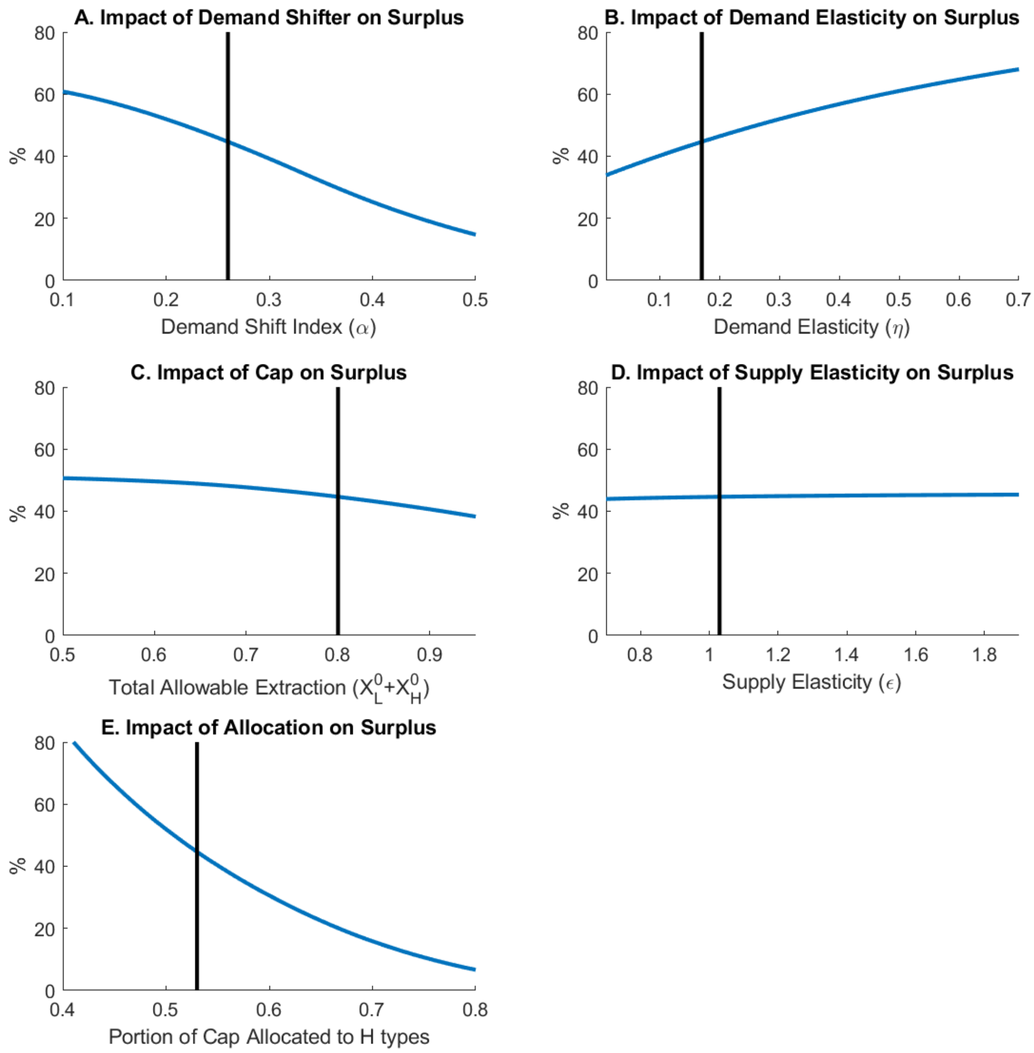

Figure 5: Gains from trade sensitivity analysis

Notes: This figure shows the sensitivity of the gains result to changes in five parameters: the demand shift index, the price elasticity of groundwater demand, the total allowable extraction (cap), the supply elasticity, and the allocation of permits between types. Each panel shows the gains from trade, expressed as a percent increase from the benefits under a no-trade regime. The vertical black lines denote the Coachella Valley parameter estimates of Table 1.

in the gains from trade. More trading occurs with more elastic demands. We see from panel B that the percent increase in benefits is large for a wide range of elasticity values.

Panel C depicts the gains with trade as a function of the total endowment of property rights for pumping, i.e., the total allowable extraction on the basin as a percentage of the open-access extraction. As expected, the percent gains with trade are decreasing as the endowment increases. However, even as the total allowable extraction approaches the aggregate quantity pumped in open-access (i.e., $X_L^0 + X_H^0 \to 1$), there are gains from trade because we retain an inefficient allocation of permits between types. 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 reduce economic surplus relative to a trading scenario that enables an efficient allocation.

Panel D of Figure 5 shows the percentage change in surplus from trade as a function of the groundwater supply elasticity. We consider a range for ε that corresponds with the potential storativity values for the Coachella groundwater basin estimated by Tyley (1974). The percentage change in surplus is increasing in ε, but at a small rate, showing that the gains result is very insensitive to our storativity assumption of $s = .11$. The pumping supply elasticity is a relatively unimportant parameter because pumping costs are fixed by the allowed pumping volume, X^0. The main role of ϵ in the trading model is to calibrate reduced pumping costs relative to open access.

Finally, panel E shows the percentage change in surplus from trade as a function of the allocation of permits between types. Holding all other parameters fixed, this figure varies the allocation between types to show the sensitivity of the gains measure to changes in the initial allocation. Clearly, the benefits from trade are strongly influenced by the initial allocation. Given the significant legal, political, and information barriers preventing a discriminatory allocation of pumping rights that would lead to an efficient result, this figure shows the importance of allowing trade in this situation. The change in surplus relative to command and control can change substantially depending on the initial allocation of the cap between types. In our

Coachella application an efficient allocation would put most of the permits in the hands of H-type growers, so an initial allocation that skews in the opposite direction produces even greater gains to trade relative to the baseline solution.

Overall, the efficiency gains of groundwater markets relative to the no-trade scenario are large on a percentage basis for a broad range of the model parameters. Since these parameter ranges represent a wide spectrum of market conditions, they suggest that our results for Coachella are likely to hold more generally, i.e., the gains from groundwater trade can be quite large for many groundwater-dependent agricultural regions.

Conclusion

Regulation of groundwater is on the near-term horizon for California and likely for many other jurisdictions as well, as climate change makes rainfall and surface-water supplies more variable and in many cases less bountiful (e.g., with reduced snow pack in California's Sierra Nevada range). Due to informational, legal, and political impediments regulators will have little opportunity to assign property rights to groundwater in an economically efficient manner, opening the door to groundwater markets as a device to achieve allocative efficiency and increase returns to agricultural stakeholders operating on a restricted basin.

The existing literature on surface water trading (e.g., Sunding et al. 2002, Hagerty 2018) provides little guidance to regulators and stakeholders in understanding how groundwater markets may operate, as most surface water trades have been through bilateral negotiations between water-supply organizations, whereas groundwater rights are likely to be in the hands of individual landowners. This paper has been devoted to understanding the essential economic factors that will impact emergent groundwater markets. Our theoretical model, when expressed in its linear form, described a groundwater trading equilibrium in terms of six market parameters that can be expressed as pure numbers: the heterogeneity of demand for groundwater across users (α), the price elasticity of groundwater demand (η), the total allowable extraction defined relative to the open-access equilibrium (X^0), the irrigation efficiency (δ), the price elasticity of groundwater supply (ϵ), and the degree of buyer (θ) or seller (ξ) market power.

We argued that buyer or seller market power could be a key consideration in many groundwater trading markets due to their restricted geographic coverage and barriers to entry, high and increasing concentration among producers and processor-shippers for many industries, and relative lack of impediments to formation of buyer or seller coalitions. Results from applying a flexible oligopoly-oligopsony model to groundwater trading showed that either buyer or seller power had limited impacts on the overall gains to trade, but that even relatively modest buyer or seller power could tilt the gains from trade significantly in the direction of the entities exercising the power.

We applied the model to the Coachella Valley in California where we were able to obtain Coachella-specific estimates for each of the model's parameters. Given the basin-wide reduction in groundwater pumping of 20% needed to achieve sustainability of the basin, we estimated that the economic benefits with perfectly competitive trade are 45% greater than that under a "command-and-control" scenario where pumping is restricted but trade is not allowed. Simulations that varied market conditions showed that the gains from trade remained large over a reasonable range of parameter values, meaning results are likely to generalize to other basins where trading might occur.

Although buyer or seller power has only a minor impact on the overall gains from trade, it, as noted, has significant distributional impacts. Thus, concerns about market power should not constitute a compelling argument to avoid trades, but its impacts on distribution may impact some stakeholders' incentives to support a trading regime. The majority of the gains from trade accrue to the players with market power; these will tend to be large operations that may also wield considerable political influence. Nonetheless, both buyers and sellers will benefit overall from trade even with severe market power. Concerns about market power may be better directed at the initial allocation of permits among players, because the closer the initial allocation is to the efficient outcome, the less are the impacts of market power.

References

[ACO] Agricultural Commissioner's Office. 2016. "Coachella Valley Acreage and Agricultural Crop Report." Riverside County, CA. Available at: http://www.rivcoawm.org/Resources/Publications.aspx.

Alston, J.M., R.S. Sexton, M. Zhang. 1997. "The Effects of Imperfect Competition on the Size and Distribution of Research Benefits." *American Journal of Agricultural Economics* 79.4: 1252-1265.

Ansink, E., and H. Houba. 2012. "Market Power in Water Markets." *Journal of Environmental Economics and Management* 64.2: 237-252.

Brown, T.C. 2006. "Trends in Water Market Activity and Price in the Western United States." *Water Resources Research* 42.9:1-14.

Bruno, E.M. 2018. "An Evaluation of Policy Instruments for Sustainable Groundwater Management." Ph.D. dissertation, University of California, Davis.

Bruno, E.M. and K.K. Jessoe. 2018. "Water Markets and Climate Change Adaptation: Micro-level Evidence on Agricultural Water Demand." Working Paper, Department of Agricultural and Resource Economics, University of California, Berkeley.

Çakir, M., and J.V. Balagtas. 2012. "Estimating Market Power of U.S. Dairy Cooperatives in the Fluid Milk Market." *American Journal of Agricultural Economics* 94.3: 647-658.

[CA DWR] California Department of Water Resources. 2016. "California's Groundwater: Working Toward Sustainability." Bulletin 118 Interim Update 2016. Available at: https://www.water.ca.gov/Programs/Groundwater-Management/Bulletin-118.

[CA DWR] California Department of Water Resources. 2015. "Coachella Valley Groundwater Basin, Indio Subbasin" California's Groundwater, Bulletin 118. Available at: https://www.water.ca.gov/Programs/Groundwater-Management/Bulletin-118.

[CASGEM] California Statewide Groundwater Elevation Monitoring Program. 2014. "CASGEM Groundwater Basin Prioritization." Available at: https://www.water.ca.gov/Programs/

Groundwater-Management/Bulletin-118/Basin-Prioritization.

Chakravorty, U., E. Hochman, C. Umetsu, and D. Zilberman. 2009. "Water Allocation Under Distribution Losses: Comparing Alternative Institutions." *Journal of Economics Dynamics and Control* 33.2: 463-476.

Coachella Valley Water District. 2016. "Coachella Valley Water District Engineer's Report on Water Supply and Replenishment Assessment for the Mission Creek Subbasin Area of Benefit, West Whitewater River Subbasin Area of Benefit, and East Whitewater River Subbasin Area of Benefit 2016-2017." Available at: http://www.cvwd.org/Archive.

Coachella Valley Water District. 2012. "Coachella Valley Water Management Plan 2010 Update." Available at: http://www.cvwd.org/Archive.

Conrad, E., J. Martinez, T. Moran, M. DuPraw, D. Ceppos, W. Bloomquist. 2016. "To Consolidate or Coordinate? Status of the Formation of Groundwater Sustainability Agencies in California." Working Paper, Water in the West, Stanford University.

——. 2018. "Diverse Stakeholders Create Collaborative, Multilevel Basin Governance for Groundwater Sustainability." *California Agriculture* 72.1: 44-53.

Famiglietti, J.S. 2014. "The Global Groundwater Crisis." *Nature Climate Change* 4: 945-948.

Faunt, C.C., K. Belitz, and R.T. Hanson. 2009. "Groundwater Availability in California's Central Valley" in *Groundwater Availability of the Central Valley Aquifer, California.*, ed. Claudia C. Faunt. Reston, VA: U.S. Geological Survey.

Fetter, C. W. 2001. *Applied Hydrogeology.* 4th edition. Prentice-Hall, New Jersey.

Fowlie, M.L., S. Holland and E. Mansur. 2012. "What Do Emissions Markets Deliver and to Whom? Evidence from Southern California's NOx Trading Program." *American Economic Review* 102.2: 1-29.

Gao, L., J. Connor, R. Doble, R. Ali, D. McFarlane. 2013. "Opportunity for Peri-urban Perth Groundwater Trade." *Journal of Hydrology* 496: 89-99.

Goulder, L.H., and I.H. Parry. 2008. "Instrument Choice in Environmental Policy." *Review of Environmental Economics and Policy* 2.2: 307-322.

Green Nylen, N., M. Kiparsky, K. Archer, K. Schneir, and H. Doremus. 2017. "Trading Sustainably: Critical Considerations for Local Groundwater Markets under the Sustainable Groundwater Management Act." Working Paper, University of California Berkeley School of Law.

Hagerty, N. 2018. "Liquid Constrained: Estimating the Potential Gains from Water Markets" Working Paper, Department of Agricultural and Resource Economics, University of California, Berkeley.

Hahn, R.W. 1984. "Market Power and Transferable Property Rights." *The Quarterly Journal of Economics* 99.4: 753-765.

Hearne, R.R. and K.W. Easter. 1997. "The Economic and Financial Gains from Water Markets in Chile." *Agricultural Economics* 15.3: 187-199.

Hintermann, B. 2011. "Market Power, Permit Allocation and Efficiency in Emission Permit Markets." *Environmental and Resource Economics* 49.3: 327-349.

Hintermann, B. 2017. "Market Power in Emission Permit Markets: Theory and Evidence from the EU ETS." *Environmental and Resource Economics* 66.1: 89-112.

Howitt, R.E. 1994. "Empirical Analysis of Water Market Institutions: The 1991 California Water Market." *Resource and Energy Economics* 16.4: 357-371.

Howitt, R.E., D. MacEwan, J. Medellín-Azuara, J.R. Lund, D.A. Sumner. 2015. "Economic Analysis of the 2015 Drought for California Agriculture." Center for Watershed Sciences, University of California, Davis.

Howitt, R. and D. Sunding. 2003. "Water Infrastructure and Water Allocation in California" in J. Siebert ed. California Agriculture: Dimensions and Issues, University of California Giannini Foundation of Agricultural Economics, Division of Agriculture and Natural Resources, pp. 181 - 90.

Jenkins, M.W., J.R. Lund, R.E. Howitt, A.J. Draper, S.M. Msangi, S.K. Tanaka, R.S. Ritzema, G. F. Marques. 2004. "Optimization of California's Water Supply System: Results and Insights." *Journal of Water Resources Planning and Management* 130.4: 271-280.

Kaiser, H.M., and N. Suzuki. 2006. *New Empirical Industrial Organization and the Food System.* New York: Peter Lang Publishing, Inc.

Kunkel, K.E., T.R. Karl, H. Brooks, J. Kossin, J.H. Lawrimore, D. Arndt, L. Bosart. 2013. "Monitoring and Understanding Trends in Extreme Storms: State of Knowledge." *Bulletin of the American Meteorological Society* 94.4: 499-514.

Kuwayama, Y., and N. Brozović. 2013. "The Regulation of a Spatially Heterogeneous Externality: Tradable Groundwater Permits to Protect Streams." *Journal of Environmental Economics and Management* 66.2: 364-382.

Liski, M., and J.-P. Montero. 2011. "Market Power in an Exhaustible Resource Market: The Case of Storable Pollution Permits." *The Economic Journal* 121.551: 116-144.

Misiolek, W.S., and H.W. Elder. 1989. "Exclusionary Manipulation of Markets for Pollution Rights." *Journal of Environmental Economics and Management* 16.2: 156-166.

Montero, J-P. 2009. "Market Power in Pollution Permit Markets." *The Energy Journal* 30.2: 115-142.

MWH Global. 2015. "Technical Memorandum No. 2 Ambient Water Quality" prepared for the Coachella Valley Salt and Nutrient Management Plan Technical Group. Available at https://www.cvwd.org/DocumentCenter.

Palazzo, A., and N. Brozović. 2014. "The Role of Groundwater Trading in Spatial Water Management." *Agricultural Water Management* 145: 50-60.

Perloff, J.M., L. Karp, and A. Golan. 2007. *Estimating Market Power and Strategies.* Cambridge: Cambridge University Press.

Rodell, M., I. Velicogna, and J.S. Famiglietti. 2009. "Satellite-based Estimates of Groundwater Depletion in India." *Nature* 460.7258: 999-1002.

Rogers, D.H., F.R. Lamm, M. Alam, T.P. Trooien, G.A. Clark, P.L. Barnes, and K. Mankin. 1997. "Efficiencies and Water Losses of Irrigation Systems." Irrigation Management Series MF-2243. Kansas State University.

Rogers, D.H., and M. Alam. 2006. "Comparing Irrigation Energy Costs." Irrigation Management Series MF-2360. Kansas State University.

Rogers, R.T. 2001. "Structural Change in US Food Manufacturing." *Agribusiness* 17.1: 3-32.

Rosen, M.D., and R.J. Sexton. 1993. "Irrigation Districts and Water Markets: An Application of Cooperative Decision-making Theory." *Land Economics* 69.1: 39-53.

Scanlon, B.R., C.C. Faunt, L. Longuevergne, R.C. Reedy, w.M. Alley, V.L. McGuire, P.B. McMahon. 2012. "Groundwater Depletion and Sustainability of Irrigation in the U.S. High Plains and Central Valley." *Proceedings of the National Academy of Sciences* 109.24: 9320-9325.

Scheierling, S.M., J.B. Loomis, and R.A. Young. 2006. "Irrigation Water Demand: A Meta-analysis of Price Elasticities." *Water Resources Research* 42: W01411.

Schmalensee, R., and R.N. Stavins. 2017. "The Design of Environmental Markets: What Have we Learned from Experience with Cap and Trade?" *Oxford Review of Economic Policy* 33.4: 572–588.

Sunding, D.L., D. Zilberman, R. Howitt, A. Dinar, and N. MacDougall. 2002. "Measuring the Costs of Reallocating Water from Agriculture: A Multi-model Approach." *Natural Resource Modeling* 15.2: 201-225.

[SGMA] Sustainable Groundwater Management Act. 2014. California Water Code. §10720.1. Available at: https://www.water.ca.gov/Programs/Groundwater-Management/SGMA-Groundwater-Management.

Suzuki, N., H.M. Kaiser, J.E. Lenz, K. Kobayashi, and O.D. Forker. 1994. "Evaluating Generic Milk Promotion Effectiveness with an Imperfect Competition Model." *American Journal of Agricultural Economics* 76.2: 296-302.

Swain, D.L., B. Langenbrunner, J.D. Neelin, A. Hall. 2018. "Increasing Precipitation Volatility in Twenty-first-century California." *Nature Climate Change* 1: in press.

Theis, C.V. 1940. "The Source of Water Derived from Wells." *Civil Engineering* 10.5: 277-280.

Tyley, S.J. 1974. "Analog Model Study of the Groundwater Basin of the Upper Coachella Valley, California." U.S. Geological Survey Water Supply Paper 2027.

U.S. Department of Agriculture. 2017. "Percent Area in U.S. Drought Monitor Categories." Available at: http://droughtmonitor.unl.edu/CurrentMap/StateDroughtMonitor.aspx?CA.

U.S. Department of the Interior, Bureau of Reclamation. 2017. "Colorado River Accounting and Water Use Report: Arizona, California, and Nevada." Calendar Years 2000-2016.

Vaux, H.J., and R.E. Howitt. 1984. "Managing Water Scarcity: An Evaluation of Interregional Transfers." *Water Resources Research* 20.7: 785-792.

Westskog, H. 1996. "Market Power in a System of Tradeable C02 Quotas." *The Energy Journal* 17.3: 85-103.

Zhang, M., and R.J. Sexton. 2002. "Optimal Commodity Promotion when Downstream Markets Are Imperfectly Competitive." *American Journal of Agricultural Economics* 84.2: 352-365.

Appendix: Simulation Details

Recall $ES^{-1}(X)$ and $ED^{-1}(X)$ functions:

$$ED^{-1}(X) = \frac{2}{\eta}(\frac{1+\eta}{1+\alpha}) - \frac{2}{\eta}\delta X_H^0 - \frac{2}{\eta}\delta X \tag{25}$$

$$ES^{-1}(X) = \begin{cases} 0 & 0 \leq X \leq \bar{X} \\ \frac{2}{\eta}(\frac{\alpha(1+\eta)}{1+\alpha}) - \frac{2}{\eta}\delta X_L^0 + \frac{2}{\eta}\delta X & \bar{X} \leq X \leq X_L^0 \end{cases}$$

where $\bar{X} = X_L^0 - \frac{1}{\delta}\frac{\alpha(1+\eta)}{1+\alpha}$. And, recall inverse demand functions for H and L types:

$$D_H^{-1}(X) = \frac{2}{\eta}(\frac{1+\eta}{1+\alpha}) - \frac{2}{\eta}\delta X, \tag{26}$$

$$D_L^{-1}(X) = \frac{2}{\eta}(\frac{\alpha(1+\eta)}{1+\alpha}) - \frac{2}{\eta}\delta X. \tag{27}$$

We showed this expression in the text for gains from trade as a percentage of surplus under command and control:

$$\%\triangle = \frac{\int_0^{X^T}\big(ED^{-1}(\tau) - ES^{-1}(\tau)\big)d\tau}{\int_0^{X_H^0}\big(D_H^{-1}(\tau) - c^0\big)d\tau + \int_0^{X_L^*}\big(D_L^{-1}(\tau) - c^0\big)d\tau} * 100. \tag{28}$$

We know that for Coachella, the constraint in non-binding for the L types for a range of prices, and we know that in equilibrium the L types sell all their water (on vertical portion of supply) as show in Figure 3. Plugging in the above functional forms for ES, ED, D_i, and reducing yields the following expression:

(29)

$$\%\triangle = \frac{\int_0^{\bar{X}} \left(\frac{2}{\eta}(\frac{1+\eta}{1+\alpha}) - \frac{2}{\eta}\delta X_H^0 - \frac{2}{\eta}\delta\tau\right)d\tau + \int_{\bar{X}}^{X^T} \left[\frac{2}{\eta}\left(\frac{(1-\alpha)(1+\eta)}{1+\alpha}\right) + \frac{2}{\eta}(\delta X_L^0 - \delta X_H^0) - \frac{4}{\eta}\delta\tau\right]d\tau}{\int_0^{X_H^0} \left(\frac{2}{\eta}(\frac{1+\eta}{1+\alpha}) - \frac{2}{\eta}\delta\tau - c^0\right)d\tau + \int_0^{X_L^*} \left(\frac{2}{\eta}(\frac{\alpha(1+\eta)}{1+\alpha}) - \frac{2}{\eta}\delta\tau - c^0\right)d\tau} * 100.$$

Performing the integration and simplifying yields:

(30)

$$\%\triangle = \frac{\left(\frac{2}{\eta}(\frac{1+\eta}{1+\alpha})\tau - \frac{2}{\eta}\delta X_H^0\tau - \frac{1}{\eta}\delta\tau^2\right)\Big|_0^{\bar{X}} + \left(\frac{2}{\eta}\left(\frac{(1-\alpha)(1+\eta)}{1+\alpha}\right)\tau + \frac{2}{\eta}(\delta X_L^0 - \delta X_H^0)\tau - \frac{2}{\eta}\delta\tau^2\right)\Big|_0^{X^T}}{\left(\frac{2}{\eta}(\frac{1+\eta}{1+\alpha})\tau - \frac{1}{\eta}\delta\tau^2 - c^0\tau\right)\Big|_0^{X_H^0} + \left(\frac{2}{\eta}(\frac{\alpha(1+\eta)}{1+\alpha})\tau - \frac{1}{\eta}\delta\tau^2 - c^0\tau\right)\Big|_0^{X_L^*}} * 100.$$

(31)

$$\%\triangle = \frac{\frac{2}{\eta}(\frac{1+\eta}{1+\alpha})\bar{X} - \frac{2}{\eta}\delta X_H^0\bar{X} - \frac{1}{\eta}\delta(\bar{X})^2 + \frac{2}{\eta}\left(\frac{(1-\alpha)(1+\eta)}{1+\alpha}\right)X^T + \frac{2}{\eta}(\delta X_L^0 - \delta X_H^0)X^T - \frac{2}{\eta}\delta(X^T)^2}{\frac{2}{\eta}(\frac{1+\eta}{1+\alpha})X_H^0 - \frac{1}{\eta}\delta(X_H^0)^2 - c^0 X_H^0 + \frac{2}{\eta}(\frac{\alpha(1+\eta)}{1+\alpha})X_L^* - \frac{1}{\eta}\delta(X_L^*)^2 - c^0 X_L^*} * 100.$$

Where

$$X^T = \begin{cases} \frac{\Omega}{2\delta} & X^T < X_L^0 \\ X_L^0 & otherwise \end{cases}$$

is the equilibrium quantity traded. Plugging parameter values for Coachella (Table 1) yields $\%\triangle = 44.65\%$.

The numerator in equation (31) is the normalized monetary gains, G, from trade, i.e.,

(32)

$$G = \frac{2}{\eta}(\frac{1+\eta}{1+\alpha})\bar{X} - \frac{2}{\eta}\delta X_H^0\bar{X} - \frac{1}{\eta}\delta(\bar{X})^2 + \frac{2}{\eta}\left(\frac{(1-\alpha)(1+\eta)}{1+\alpha}\right)X^T + \frac{2}{\eta}(\delta X_L^0 - \delta X_H^0)X^T - \frac{2}{\eta}\delta(X^T)^2 = 1.37$$

We undo the normalization by multiplying G by the nominal values for (x^*, c^*) ($126/AF, 229,867 AF) to obtain the estimated monetary gains, G^* to groundwater trade in the Coachella

Valley in 2016 dollars, given the baseline parameter values:

(33)
$$G^* = 1.37 * \$126 * 229,867 = \$39.7 \text{ million.}$$

Recall the expressions for the percentage change in consumer and producer surplus as a function of the market power parameter, ξ, equations (23) and (24). We can express these as functions of the parameters for the linear model:

(34)
$$\% \triangle CS = \frac{\int_0^{X^{SP}(\xi)} \left(\frac{2\delta}{\eta}(\sigma_H - X_H^0 - \tau) - \rho^{SP})\right) d\tau - \int_0^{X^T} \left(\frac{2\delta}{\eta}(\sigma_H - X_H^0 - \tau) - \rho^T\right) d\tau}{\int_0^{X^T} (\frac{2\delta}{\eta}(\sigma_H - X_H^0 - \tau) - \rho^T) d\tau} * 100,$$

(35)
$$\% \triangle PS = \frac{\int_0^{X^{SP}(\xi)} \left(\rho^{SP}(\xi) - \frac{2\delta}{\eta}(\tau - X_L^0 - \sigma_L)\right) d\tau - \int_0^{X^T} \left(\rho^T - \frac{2\delta}{\eta}(\tau - X_L^0 - \sigma_L)\right) d\tau}{\int_0^{X^T} \left(\rho^T - \frac{2\delta}{\eta}(\tau - X_L^0 - \sigma_L)\right) d\tau)} * 100,$$

where $\rho^{SP} = \frac{2\delta}{\eta}(\sigma_H - X_H^0 - [\frac{\sigma_H + \sigma_L + X_L^0 - X_H^0}{2+\xi}])$, $\rho^T = \frac{\delta}{\eta}[\sigma_H - \sigma_L - (X_H^0 + X_L^0)]$, $X^{SP} = \frac{1}{\delta}\frac{\Omega}{2+\xi}$, and $X^T = \frac{\Omega}{2\delta}$. Plugging baselines parameter values from Table 1 and a choice for ξ yields changes in market surplus for buyers and sellers. These expressions are calculated for every value of ξ in Figure 4.