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

Ellen M. Bruno, and Richard J. Sexton

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, with benefits up to 36% greater than that under command and control. 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.

Key words: Groundwater, irrigation, market power, market structure, water markets.

JEL codes: Q15, Q25.

Improved management of water resources is becoming increasingly important in the face of climate change. Climate models predict 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 with 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). Declining groundwater levels increase pumping costs and reduce availability of the underground reserve in times of drought.

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 market-based instruments relative to command-and-control policies for air pollution (Fowlie, Holland, and Mansur 2012; Schmalensee and Stavins 2017). Less is known, however, about the performance of economic instruments for managing water. Previous

Ellen M. Bruno is an assistant cooperative extension specialist in the Department of Agricultural and Resource Economics at University of California, Berkeley (Email: ebruno@berkeley.edu). Richard J. Sexton is a distinguished professor in the Department of Agricultural and Resource Economics at University of California, Davis (Email: rich@primal.ucdavis.edu). The authors thank Graham Fogg, Michael Hanemann, Richard Howitt, Katrina Jessoe, Stephen Maples, Katherine Markovich, Pierre Mérel, Daniel Sumner, Jim Wilen, and Jeffrey Williams for helpful comments on this work. Valuable 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 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 was provided by The UC Giannini Foundation of Agricultural Economics, UC Water Security and Sustainability Research Initiative, and the National Science Foundation Climate Change, Water, and Society IGERT (DGE No. 1069333).
*Correspondence may be sent to: rich@primal.ucdavis.edu

Amer. J. Agr. Econ. 00(00): 1–27; doi:10.1111/ajae.12031

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 (Vaux and Howitt 1984; Howitt 1994; Hearne and Easter 1997; Sunding *et al.* 2002; Jenkins *et al.* 2004; Peterson *et al.* 2004; Grafton and Horne 2014; Grafton, Horne, and Wheeler 2016). 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.

This paper studies groundwater trading in an environment where pumping is restricted to achieve long-run sustainability of the groundwater basin. Relatively few studies have discussed groundwater trading, with notable exceptions focused on the handful of jurisdictions where groundwater is actively regulated. In the U.S., key examples include Thompson *et al.* (2009), Kuwayama and Brozović (2013), Brozović and Young (2014), and Palazzo and Brozović (2014) for Nebraska, and Guilfoos *et al.* (2017) for Kansas. Elsewhere, key examples include Gao *et al.* (2013) for Australia and Raffensperger, Milke, and Read (2009) for New Zealand. Unlike previous work, our model allows either buyers or sellers to exercise market power in the groundwater market. We contribute to this water markets literature by quantifying the efficiency gains to groundwater trading relative to a command-and-control regime and showing how the gains and the distribution of benefits from trading are influenced by the presence of market power. We apply our model to a groundwater basin in California that faces pumping restrictions in light of landmark legislation passed in California in 2014 to achieve sustainability of groundwater resources.

This analysis is important because, prior to the widespread implementation of groundwater markets, it will be necessary 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, often characterized by high transaction costs, and limited by physical conveyance infrastructure (Brown 2006; Hagerty 2019).

Groundwater markets, however, are likely to be localized in nature and involve participants pumping water from a shared groundwater basin. The rights to pump groundwater are not shared collectively and, instead, under most legal doctrines, accrue to landowners within the geographic bounds of the basin. These distinguishing features of groundwater trade have important implications for how well the market will function. Market structure in particular is likely to be a key consideration in these settings because of the geographic barriers to trade, presence in many instances of large-scale agricultural operations, and a legal environment that is conducive to forming cartel-like coalitions of sellers or buyers.

The economic literature on groundwater management has to date been dominated largely by studies that evaluate the difference in social welfare between open-access groundwater use and socially optimal groundwater use. Early research showed that high discount rates diminish the importance of higher future pumping costs caused by depletion of basin resources, and, when extraction is small relative to the total storage of an aquifer, the gains from management may be negligible (Gisser and Sanchez 1980; Brill and Burness 1994). More recent literature has found larger gains from management by developing spatially explicit models to capture aquifer heterogeneity and spatial pumping externalities between wells (Brovozić, Sunding, and Zilberman Brozović, Sunding, and Zilberman 2010; Pfeiffer and Lin 2012; Edwards 2016; Merrill and Guilfoos 2017) and by accounting for drought reserve value and avoided capital costs (MacEwan *et al.* 2017).

Our model abstracts from these dynamic and spatial dimensions to answer a different question: given a fixed cap on pumping, what are the price, quantity, and welfare impacts of trading conditional on any degree of buyer or seller market power? 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 that the efficiency impacts of market power are relatively small even for substantial market power, but 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, it 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, the role of storable permits, and impacts in the final product market, with applications to fisheries (Anderson 2008), pollution (e.g. Misiolek and Elder 1989; Montero 2009; Hintermann 2011, 2017; Liski and Montero 2011), 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. Hahn 1984; Westskog 1996; Montero 2009; Hintermann 2011, 2017; Ansink and Houba 2012), we use a flexible framework for imperfect competition in the permit market. This allows the model to depict the entire range of possible market power settings for either buyer or seller power and enables us to see how the gains from trade and distribution of benefits vary with market 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. Water supply organizations in California are charged to adopt regulations to correct groundwater overdraft and achieve sustainability of groundwater resources under the Sustainable Groundwater Management Act (SGMA) of 2014. The groundwater basin serving the Coachella Valley is among those designated as overdrafted and subject to SGMA. Moreover, the structure of agriculture in the Coachella Valley exhibits features that could induce market power in groundwater trading, making it an ideal setting for application of the groundwater trading model.

We estimate the gains from groundwater trade for the water district serving Coachella Valley. An essential feature of this application is that all model parameters are either constructed or estimated econometrically from observational data for this region. Results show that the economic surplus with competitive trade is almost 40% greater than under command and control, given a 20% reduction in basin-wide use that is needed for groundwater sustainability under SGMA. Either seller or buyer market power is shown to have a relatively small impact on the overall gains to trade, but even moderate market power can significantly skew the gains to trade in the direction of entities with market power, either as buyers or sellers. 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 water management.

Modeling Framework

We develop a theoretical model for studying agricultural groundwater use and trading, with the goal of understanding 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, most of which can be estimated with commonly available data for any groundwater basin. To sharpen focus on our objective of analyzing the gains from trade in a flexible setting regarding buyer or seller market power while maintaining tractability, the model necessarily abstracts from some of the dynamic and spatial characteristics of groundwater pumping.

Herein the groundwater basin defines the geographic scope of the market, and permit trading occurs among farmers. 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 production functions for an individual

j denoted $q_{Lj} = f_{Lj}(x_{Lj}, y_{Lj})$. Farmers of type H grow a high-value crop, for example a produce commodity or tree nut, with individual production functions denoted $q_{Hj} = f_{Hj}(x_{Hj}, y_{Hj})$.[1] The variable x represents applied groundwater, and y represents a composite of other inputs to production, such as labor or fertilizer. Production functions are assumed to be differentiable and exhibit diminishing marginal productivity to variable inputs.

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 irrigation efficiency, 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. We assume farmers face the same pumping costs and that individual pumping is small relative to the basin total, so farmers take the marginal pumping cost as given, but collectively their decisions determine basin-wide pumping costs.[2]

Open-Access Groundwater Use

Consider the profit-maximization problem for farmers in the unmanaged, open-access case. In this setting, the price of groundwater in any period 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, $i \in H, L$, and w_y is price of the composite input, y, both of which are taken as given. Farmers of type i face the following profit-maximization problem:

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

The first-order conditions are $p_i \frac{\partial f_i(x_i, y_i)}{\partial x_i} = \frac{c}{\delta}$ and $p_i \frac{\partial f_i(x_i, y_i)}{\partial y_i} = w_y$. In any period, 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, price for input y, and the marginal pumping cost of groundwater: $x_H\left(p_H, w_y, \frac{c}{\delta}\right), x_L\left(p_L, w_y, \frac{c}{\delta}\right)$.

The assumption that output prices are fixed implies that individual farmers are perfect competitors for the sale of their output. An extension of this work is to introduce the potential for pumpers to exercise market power in their output sales, in which case the parametric prices, p_L, p_H, are replaced with marginal revenue functions, $MR_{ij}(q_{ij})$, $MR_{ij}{}' \leq 0$, $i \in H, L$ that reflect a farmer's perceptions of the impact of her sales on the price received. Hintermann (2011, 2016) shows that seller power in the output market can impact a player's optimal behavior in a permit market by creating an incentive for the firm to inflate the permit price if those higher costs can be passed forward to consumers.[3]

Open-Access Equilibrium

The open-access equilibrium in a given time period 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

[1] This formulation assumes farmers have already preselected into producing certain crops, for example 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.

[2] 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, for example 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).

[3] Hintermann's extensions of Hahn's (1984) seminal results for market power in permit trading to account for a trader's seller power in its output market are important in the pollution permit context they each studied, wherein firms subject to cap-and-trade regulations are often large and powerful. For example, Hintermann applies his theory to European electric power generators. Conversely, groundwater trading will most often be among farmers who are unlikely to have market power as sellers of farm products.

(X), adjusted by irrigation efficiency. If we define equilibrium groundwater extraction, applied water quantities, and marginal pumping cost in this period by $\left(X^*, x_H^*, x_L^*, c^*\right)$, then the equilibrium conditions in any period are: $x_H^* = x_H\left(p_H, w_y, \frac{c^*}{\delta}\right)$, $x_L^* = x_L\left(p_L, w_y, \frac{c^*}{\delta}\right)$, $X^* = \frac{\left(x_L^* + x_H^*\right)}{\delta}$, and $c(X^*) = c^*$.[4]

To obtain analytical solutions and enable quantification of gains from establishment of groundwater markets requires explicit 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 and is useful for comparative statics purposes. 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: $c(X) = \omega + \mu X$, with ω, $\mu > 0$. The intersection of the aggregate demand function with the supply relationship for applied water, $c(x) = \omega + \frac{\mu}{\delta}x$, reveals the competitive, open-access equilibrium marginal pumping cost (c^*) and applied water quantity (x^*) in a given period for the linear model:[5]

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

In what follows, we invoke normalizations for pumping cost and water quantity such this open-access equilibrium price (i.e. marginal pumping cost) and quantity are each equal to one: (c^*, x^*) = (1, 1). Evaluated at this perfectly competitive equilibrium, the supply elasticity is given by $\varepsilon = \frac{\partial x^S}{\partial c}\frac{c}{x^S} = \frac{\delta}{\mu}$ where $x^S(c) = \frac{\delta}{\mu}c - \frac{\delta}{\mu}\omega$ is the direct form of the marginal pumping cost function. Similarly, the absolute value of the elasticity of demand is given by $\eta = \left|\frac{\partial x^D}{\partial c}\frac{c}{x^D}\right| = \beta$ evaluated at the equilibrium (1, 1), with $x^D(c) = \gamma(\alpha + 1) - \beta c$. These relations imply the following substitutions, which are used to rewrite the original slope and intercept parameters in terms of the pure-number elasticities: $\beta = \eta, \gamma = \frac{1+\eta}{1+\alpha}, \omega = 1 - \frac{1}{\varepsilon}, \mu = \frac{\delta}{\varepsilon}$.

Given these substitutions, the demands for L and H types and the aggregate supply relationship are expressed in terms of (a) the supply and demand elasticities evaluated at the perfectly competitive, open-access equilibrium, ε and η respectively, (b) the demand shift parameter, $\alpha \in (0, 1)$, reflecting differences in water demands between H and L types, and (c) the irrigation efficiency parameter, $\delta \in (0, 1)$. Restating aggregate H and L demands and inverse groundwater supply with respect to these pure-number parameters yields:

$$(3) \quad x_H = \frac{1+\eta}{1+\alpha} - \frac{\eta}{2}c, \; x_L = \alpha\left(\frac{1+\eta}{1+\alpha}\right) - \frac{\eta}{2}c,$$

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

Establishing Property Rights for Groundwater

Now assume that a regulatory agency establishes non-tradable property rights for pumping. To induce conservation, the regulator must set an aggregate endowment that is less than the amounts being pumped under open access. Without the ability to trade, farmers of both types must limit pumping to no more than their assigned allocations. Although in theory it is possible to arrive at the socially optimal solution through a discriminatory set of water allocations where each type is assigned the amount it would pump in the socially optimal setting, we assume the regulator lacks necessary information, political ability, and/or legal right to implement such an allocation.

To simplify the exposition and focus on the long-run sustainability of an aquifer within our static model framework, we assume that

---

[4] In the absence of regulation, a basin that is subject to overpumping would face higher pumping costs in subsequent periods, affecting pumping decisions. This dynamic path has been studied by Gisser and Sanchez (1980), Brill and Burness (1994), and others. Consistent with a static model, our strategy instead is to consider the implementation of regulations designed to put the basin on a sustainable path and compare results across the command-and-control and cap-and-trade regimes under different competition scenarios.

[5] One way to introduce dynamics into our formulation would be to make ω a function of net pumping (pumping less recharge) in prior periods. Thus, a basin subject to overdraft, defined by pumping exceeding recharge in any given period, would face higher pumping costs through time until a steady state was reached.

regulators set a constant allocation based on a rule, such as on a pro-rata basis by land holdings, that is designed on average to balance aquifer extractions and recharge over time.[6] Allocations set in this type of regulatory environment are highly unlikely to equate marginal value products across user types, opening the door to possible welfare improvements achieved through water markets.

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

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

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

$$(6) \quad p_i \frac{\partial f_i(x_i, y_i)}{\partial x_i} - \frac{c}{\delta} - \lambda_i \le 0 \text{ and } x_i\left(p_i \frac{\partial f_i(x_i, y_i)}{\partial x_i} - \frac{c}{\delta} - \lambda_i\right) = 0$$

$$(7) \quad p_i \frac{\partial f_i(x_i, y_i)}{\partial y_i} - w_y \le 0 \text{ and } y_i\left(p_i \frac{\partial f_i(x_i, y_i)}{\partial y_i} - w_y\right) = 0$$

$$(8) \quad x_i - \delta A_i^0 \le 0 \text{ and } \lambda_i\left(x_i - \delta A_i^0\right) = 0.$$

Given that the aggregate endowment is less than the open-access pumping volume, the allocation must bind on pumping for at least one type, that is, $x_i^* = \delta A_i^0$. Therefore, in equilibrium we must have a strictly positive shadow price, $\lambda_i^* > 0$, for at least one type. A constrained farmer must reduce pumping below the unconstrained optimum by, for example, fallowing acreage or applying water less intensively to crops.

Whether the constraint binds for either type depends both on demand and on the initial allocation of permits. In what follows, we assume the allocation is binding for both types and that both types apply some portion of their allocation to their farming operation. This assumption avoids analytical complexities that emerge if the allocation does not bind for one type or if one type idles its full acreage and markets its entire allocation.[7] The subsequent application to Coachella Valley, CA, relaxes both of these assumptions, and a complete exposition of the analytical model that accounts for nonbinding allocation constraints and the marketing of one type's total allocation is contained in the online appendix File S1.

When allocations bind for both types, we get the following equilibrium expressions for the shadow prices:

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

where $c^0 = c\left(X_H^0 + X_L^0\right)$ 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 equilibrium shadow prices are $\lambda_H^* = \frac{2}{\eta}\left(\frac{1+\eta}{1+\alpha} - \delta X_H^0\right) - \frac{c^0}{\delta}$ and $\lambda_L^* = \frac{2}{\eta}\left(\frac{\alpha(1+\eta)}{1+\alpha} - \delta X_L^0\right) - \frac{c^0}{\delta}$, where $c^0 = \left(1 - \frac{1}{\varepsilon}\right) + \frac{\delta}{\varepsilon}\left(X_H^0 + X_L^0\right)$ is the marginal pumping cost at the constrained equilibrium.

Equation (10) expresses the difference in shadow values between types (at the constrained optimum, $x_i^* = \delta X_i^0$), which yields the necessary condition for trading to occur:

$$(10) \quad |\lambda_H^* - \lambda_L^*| = \left|\frac{2}{\eta}\left[\frac{(1-\alpha)(1+\eta)}{1+\alpha} + \delta X_L^0 - \delta X_H^0\right]\right| > 0.$$

We define $\Omega = \frac{(1-\alpha)(1+\eta)}{1+\alpha} + \delta X_L^0 - \delta X_H^0$ for simplicity. When equation (10) holds, that is when $|\Omega| > 0$, a set of positive permit prices exists where trading will occur. In the

[6] A binding cap that is sustainable and consistent over time allows us to abstract away from aquifer dynamics due to year-to-year variations in economic and hydrologic conditions. This assumption is also consistent with the legislative intent of California's SGMA, which mandates implementation of policies to achieve long-run sustainability of groundwater resources.

[7] 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 nondifferentiability at the kink point[s]) in the excess supply function of permits.

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

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

that is, 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 derive excess demand and excess supply functions for pumping permits. Selling or supplying groundwater in this context does not rely on access to physical infrastructure to transmit water to buyers but, rather, 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, that are determined by the aggregate constrained pumping allocation. If the difference between input demand for pumped water at price P and individual water allowance, A_i^0, exceeds zero, then that farmer has excess demand at groundwater price $P = \rho + c^0$. Otherwise, that farmer has excess supply at price P.

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. We obtain the following excess demand and excess supply curves as functions of the demand elasticity and other parameters from the profit-maximization problems:

$$\text{Excess Demand}: X(\rho) = \frac{x_H(\rho)}{\delta} - X_H^0 = (\sigma_H - X_H^0) - \frac{\eta}{2\delta}\rho \text{ where } \sigma_H = \frac{1}{\delta}\left(\frac{1+\eta}{1+\alpha}\right) - \frac{\eta}{2\delta}c^0, \quad (12)$$

$$\text{Excess Supply}: X(\rho) = X_L^0 - \frac{x_L(\rho)}{\delta} = (X_L^0 - \sigma_L) + \frac{\eta}{2\delta}\rho \text{ where } \sigma_L = \frac{1}{\delta}\frac{\alpha(1+\eta)}{1+\alpha} - \frac{\eta}{2\delta}c^0. \quad (13)$$

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.[8]

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, whereas $\xi = 1$, $\theta = 0$ 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 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).[9] In this article, the market power parameters are related to perceived marginal revenue (*PMR*) and perceived marginal factor cost (*PMFC*) curves because these interpretations of θ and ξ are particularly conducive to graphical representations of the market equilibrium. $PMR(X)$ is relevant to seller power and is expressed as a linear combination of the monopoly marginal revenue curve, $MR(X)$, and the market inverse excess demand curve $ED^{-1}(X)$ for H

[8] We do not consider situations where both buyers and sellers may exercise market power. These cases of bilateral oligopoly power are most often studied in a setting of multilateral bargaining, a problem that is fundamentally intractable without imposing strong assumptions on the bargaining environment (e.g. Inderst and Wey 2003; Dobson and Waterson 2007).

[9] The market power parameters ξ and θ do not need to be interpreted within the conjectural variations framework. They can be interpreted simply as summary measures of market competitiveness, that is, as the realizations at any point in time of an unobserved dynamic game among players in the groundwater market.

types (i.e. the marginal revenue curve under perfect competition) with weights given by ξ:

$$(14) \quad PMR(X) = \xi MR(X) + (1-\xi)ED^{-1}(X).$$

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

$$(15) \quad PMFC(X) = \theta MFC(X) + (1-\theta)ES^{-1}(X).$$

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

Seller Market Power

From the excess demand curves for permits in equation (12), we derive the PMR curve for the linear version of the model:

$$(16) \quad PMR(X) = \frac{2\delta}{\eta}\left(\sigma_H - X_H^0\right) - (1+\xi)\frac{2\delta}{\eta}X.$$

Then equating $PMR(X)$ with the sellers' excess inverse supply from (13), we derive the equilibrium volume of permits traded under seller power and express it as a function of the equilibrium quantity under perfect competition, $X^{SP} = \frac{1}{\delta}\frac{\Omega}{2+\xi} = \left(\frac{2}{2+\xi}\right)X^T$. Plugging that result back into the excess demand curve reveals the equilibrium permit price, ρ^{SP}, which can be written as a function of the perfectly competitive groundwater price, $\rho^{SP} = \frac{2\delta}{\eta}\left(\sigma_H - X_H^0 - \left[\frac{\sigma_H - \sigma_L + X_L^0 - X_H^0}{2+\xi}\right]\right) = \rho^T + \left(1 - \frac{2}{2+\xi}\right)\frac{\Omega}{\eta}$. These results are completely summarized in terms of the demand elasticity, the demand shift and irrigation efficiency parameters, the initial assignment of property rights, and the degree of seller market power, 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.

Figure 1 illustrates the model for the case of seller oligopoly ($0 < \xi < 1$, $\theta = 0$). The intersection of the PMR curve with sellers' excess supply curve determines the equilibrium permit market volume, X^{SP}, which yields equilibrium groundwater permit price, ρ^{SP}. Relative to traded quantity and price (X^T, ρ^T) at the perfectly 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.

Differentiating X^{SP} and ρ^{SP} with respect to ξ reveals how seller market power affects market outcomes:

$$\frac{\partial X^{SP}}{\partial \xi} = -\frac{1}{\delta}\frac{\Omega}{(2+\xi)^2} < 0, \frac{\partial \rho^{SP}}{\partial \xi} = \frac{2}{\eta}\left(\frac{\Omega}{(2+\xi)^2}\right) > 0. \quad (17)$$

The greater the market power exercised by the sellers, the fewer the permits that are traded and the higher the groundwater price.[10] This creates an inefficiency relative to a competitive permit market, with the deadweight loss (DWL) due to the exercise of market power expressed as:

$$\begin{aligned} DWL(\xi) &= \int_{X^{SP}(\xi)}^{X^T} ED^{-1}(\tau) - ES^{-1}(\tau)d\tau \\ (18) \qquad &= \frac{\Omega^2}{2\delta\eta}\left(\frac{\xi}{2+\xi}\right)^2 = G^T\left(\frac{\xi}{2+\xi}\right)^2 > 0. \end{aligned}$$

Equation (18) shows that DWL is strictly positive for $\xi > 0$ and increases in ξ at an increasing rate. The expression also shows how the gains from competitive trade, G^T, are diluted by deadweight loss as ξ increases.

We can use the expression for DWL to characterize the gains from trading under seller market power, $G^{SP}(\xi) = G^T - DWL(\xi) = \left(1 - \left(\frac{\xi}{2+\xi}\right)^2\right)\frac{\Omega^2}{2\delta\eta} = \left(1 - \left(\frac{\xi}{2+\xi}\right)^2\right)G^T$. Consistent with the result that DWL is increasing in ξ at an increasing rate, gains to trading are a decreasing function of seller market power, and they decrease at an increasing rate.

We can also express the welfare loss due to seller power in the permit market relative to

[10] These inequalities always hold because $\Omega > 0$ based on equation (10).

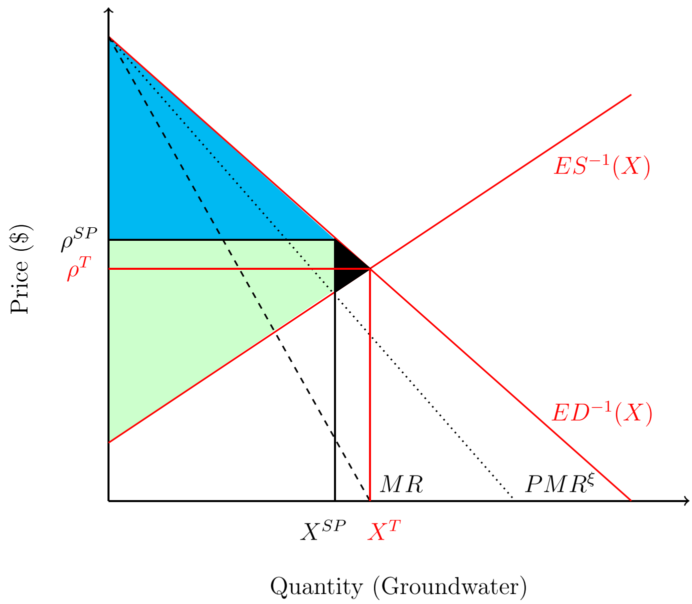

Figure 1. Groundwater permit market with seller market power.

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

perfect competition in percentage form, $\% \triangle G^{SP}$, as follows:

$$\%\triangle G^{SP} = -\left(\frac{\xi}{2+\xi}\right)^2 * 100, \tag{19}$$

that is, for the linear model the relative welfare change is solely a function of ξ, making the result robust to assumptions on parameters α, δ, η, X^0. Figure 2 shows how equation (19) varies over the range of possible market power values. As ξ converges to 1 (monopoly case), the surplus from trading is 11.1% smaller than under perfect competition.

To assess the distributional impacts of market power, we study how the gains from groundwater trade for buyers and sellers change as a function of ξ. Equation (20) depicts the percent change in consumer (buyer) surplus, $\% \triangle CS$, due to seller market power relative to that under perfect competition:

$$\%\triangle CS = \frac{\int_0^{X^{SP}(\xi)} \left(ED^{-1}(\tau) - \rho^{SP}(\xi)\right) d\tau - \int_0^{X^T} \left(ED^{-1}(\tau) - \rho^T\right) d\tau}{\int_0^{X^T} \left(ED^{-1}(\tau) - \rho^T\right) d\tau} * 100. \tag{20}$$

The percentage increase 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 (21) shows[11]:

$$\%\triangle PS = \frac{\int_0^{X^{SP}(\xi)} \left(\rho^{SP}(\xi) - ES^{-1}(\tau)\right) d\tau - \int_0^{X^T} \left(\rho^T - ES^{-1}(\tau)\right) d\tau}{\int_0^{X^T} \left(\rho^T - ES^{-1}(\tau) d\tau\right)} * 100. \tag{21}$$

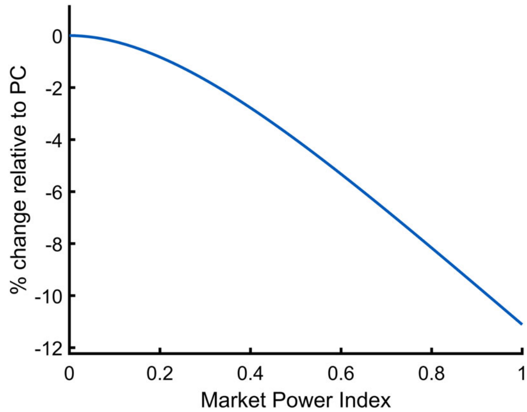

Figure 2. The effect of seller market power ($\xi > 0$) on total gains from trade.

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

Unlike the efficiency impacts of market power, the distributional impacts depend on all of the model parameters. To give a sense of these impacts, we set these parameter values at their levels for our Coachella application, with one exception. As we discuss in detail in the application, Coachella appears to represent a setting wherein L producers would sell their entire allocations in a water market primarily because the base value for α is only 0.26, thus conforming to the special case we discuss in detail in the online appendix File S1.[13]To generate model solutions consistent with the underlying assumption of this section that trading equilibria occur in the upward-sloping portion of L types' excess supply function, meaning that they apply some of their allocation to own crop production in the trading equilibrium, we adjust α above its base value in the Coachella case to $\alpha = .6$ for purposes of this simulation.

Figure 3 shows the percent change in buyer/consumer and seller/producer surplus relative to that under perfect competition as a function of ξ, given the adjusted Coachella parameter values. 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 33.3% greater than that under perfect competition.

Even a small degree of market power generates large distributional differences in surplus relative to competitive levels. Figure 3 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 15% 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 28% 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. Although all are absolutely better off than under no trade, these distributional impacts may be undesirable from an equity perspective because a large share of the gains to trade accrue to those with market power, either as buyers or sellers, which could be large agribusiness enterprises with significant landholdings.

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:

$$(22) \quad PMFC(X) = -\frac{2\delta}{\eta}\left(X_L^0 - \sigma_L\right) + (1+\theta)\frac{2\delta}{\eta}X.$$

Equilibrium traded quantity, denoted X^{BP}, is determined by the intersection of $PMFC(X)$ with buyers' excess demand and can be expressed as a function of the perfectly competitive outcome: $X^{BP} = \frac{1}{\delta}\frac{\Omega}{2+\theta} = \left(\frac{2}{2+\theta}\right)X^T$. The equilibrium groundwater permit price, ρ^{BP}, is determined where X^{BP} intersects the excess supply curve: $\rho^{BP} = \frac{2\delta}{\eta}\left(\frac{\sigma_H - \sigma_L + X_L^0 - X_H^0}{2+\theta} - X_L^0 + \sigma_L\right) = \rho^T + \left(\frac{2}{2+\theta} - 1\right)\frac{\Omega}{\eta}$. These equilibrium outcomes, which are

[11] Equations (20) and (21), expressed as functions of parameters from the linear model, can be found in Appendix B.

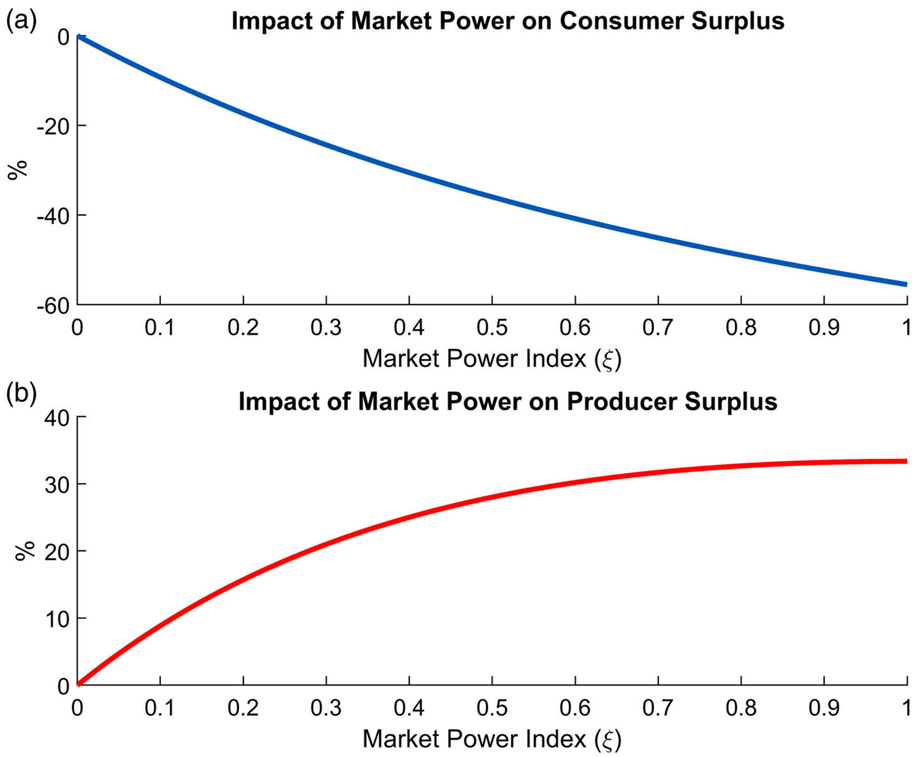

Figure 3. Distributional effects of market power.

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. Parameter values are from the Coachella application except for α as explained in the main text. Appendix A contains the linear model expressions for (20) and (21).

symmetric to the seller power scenario, show that buyer power will depress trade in the water market and reduce price relative to the perfectly competitive equilibrium, with both effects increasing as a function of θ. In a similar fashion, we can derive the welfare loss due to buyer power in the permit market relative to perfect competition in percentage form: $\%\triangle G^{BP} = -\left(\frac{\theta}{2+\theta}\right)^2 * 100$. Under either buyer or seller market power, a larger market power parameter implies fewer permits traded, efficiency loss relative to the perfectly competitive equilibrium, and transfer of substantial portions of the gains to trade into the hands of the entities exercising market power.

Application to California Agriculture

Groundwater management is at the forefront of water policy debates in California. Groundwater accounts for 40% of the agricultural water supply on average (DWR 2016), and several areas throughout the state have seen significant declines in groundwater storage (Faunt, Belitz, and Hanson 2009; Famiglietti 2014). In an effort to maintain a reliable groundwater supply, California's Sustainable Groundwater Management Act (SGMA) of 2014 provides a statewide framework for local agencies to manage groundwater. 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.

In what follows, we 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 Coachella Valley is an ideal setting for 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.

The Coachella Valley receives only four inches of rain a year on average, making its agriculture dependent on groundwater and imported surface water for irrigation. In the late 1940s, a concrete-lined aqueduct was constructed to transport surface water over 120 miles from the Colorado River to the Coachella Valley.[13] Enabled by irrigation, this region now exhibits 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).[14]

This section first provides background on SGMA and the specific mechanisms by which market power may arise under SGMA-inspired groundwater trading. We then present the model parameters for Coachella, which is followed by estimation of the gains from groundwater trade and a sensitivity analysis. Results show that the economic surplus with competitive trade is almost 40% 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.

Background

Under SGMA, groundwater agencies governing overdrafted basins must reduce basin-wide pumping to achieve groundwater sustainability targets. SGMA affects 127 of 515 basins in California, which account for 96% of the groundwater pumping in the state (DWR 2019). A logical means to achieve this goal is to meter pumping and establish individual property rights for groundwater that restrict aggregate pumping volumes below open-access outcomes. 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 political or legal restrictions to setting allocations. Thus, groundwater trading represents an avenue for reaching basin sustainability targets while minimizing efficiency losses.

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 SGMA, making market power an important consideration 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, which may lead to groups of players coordinating interests in cartel-like fashion. 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).

Other coalitions could take the form of growers' associations, cooperatives, or large downstream processors who purchase inputs on behalf of their growers. Both horizontal and vertical 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. If such vertical coordination were extended to the purchase or sale of groundwater, the relevant concentration of buyers and sellers for a water market would be the processing/packing/shipping stage rather than the farm production stage of the market chain.

Finally, in some instances grower-shippers themselves may be large enough to exercise market power as either buyers or sellers. Recent research points to some evidence of insider trading occurring among water market participants

---

[13] Although between 1/3 and 1/2 of the Coachella Valley's irrigation needs are met with Colorado River water in a given year, the fact that the valley has no natural surface water flow means groundwater pumping is unlikely to have a meaningful effect on surface water hydrology. A spatially explicit aquifer model could account for this physical groundwater-surface water interaction in settings where it is relevant. See, for example, Kuwayama and Brozović (2013) for an illustration.

[14] Although the Valley produces most of the nation's dates, the Coachella production is only about 0.3% of world production based on UN Food and Agriculture Organization (FAO) statistics (FAO 2019). The relevant geographic market for dates appears to be worldwide; for example, the U.S. is both an importer and exporter of dates. Given its tiny share in the world market, Coachella producers as individual sellers or as a group have no influence on world date prices, meaning impacts on the output market of the type considered by Hintermann (2011, 2017) are not an issue. Our analysis suggests that this conclusion also applies to the other commodities produced in Coachella.

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	Absolute value of estimate from 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.
Portion of cap to H types	-	.53	Assumed to be equivalent to the proportion of acreage in H-type crops.

in Australia's Murray-Darling Basin, suggesting that individual players can have impacts on market outcomes (de Bonviller, Zuo, and Wheeler 2019). 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). Most groundwater rights in California are overlying rights based on ownership of the land above the aquifer,[15] so permits for pumping based on land holdings may directly concentrate permits in the hands of a relatively few large landowners.

Model Parameters

Our 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, and 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. 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. Table 1 outlines the parameters, all of which were estimated using data from the Coachella Valley, and includes either the data source for the parameter or a brief summary of how the parameter was estimated. A detailed discussion of the methods used to estimate each parameter is provided in Appendix B.

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, the allocation constraint is not binding for the L types in Coachella for some positive quantity range. In this case, the inverse excess supply curve is flat ($ES^{-1}(X) = 0$) up to the sales volume, $\bar{X} = X_L^0 - \sigma_L$, 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 in equilibrium, which corresponds to the case where acreage is idled in favor of rights holders becoming exclusively water marketers.[16] $ES^{-1}(X)$ is vertical at the level of rights, X_L^0, allocated to L types. $ES^{-1}(X)$ is

[15] 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 (2000) and City of Pasadena v. City of Alhambra (1949).

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

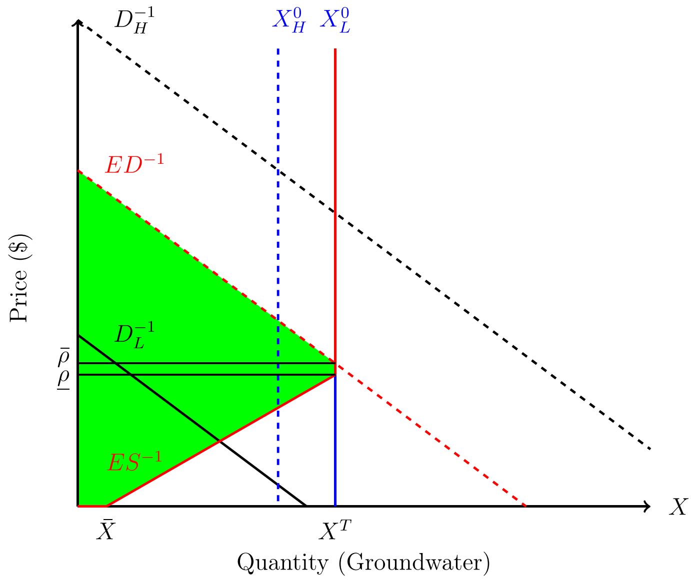

Figure 4. Market-level gains from trade (constraint non-binding for L types).

Notes: The figure denotes excess supply and excess demand curves when α is small, allocations differ between types, $c^0 = 0$, and the constraint is nonbinding for the L types at the initial endowment, X_L^0. ES^{-1} and ED^{-1} are derived according to Equations (12) and (13). $\bar{X}$ denotes the trade volume when sellers' allocation constraint binds. The shaded area illustrates the gains from trade. Here, the L types sell their entire allocation of pumping rights, that is, $X_L^0 = X^T$, and the market-clearing price resides between $\underline{\rho}$ and $\bar{\rho}$.

thus a piecewise linear function for L types in Coachella, as shown in figure 4, which depicts the competitive equilibrium when $ED^{-1}(X)$ intersects $ES^{-1}(X)$ in its vertical portion. The gains from perfectly competitive trade under these conditions are depicted by the green-shaded area. An interesting aspect of the case where the competitive equilibrium occurs on the vertical portion of $ES^{-1}(X)$ is that a range of prices clears the market, making it impossible to render a sharp prediction as to the market-clearing price. This range is illustrated in figure 4 by $\rho \in \left[\underline{\rho}, \bar{\rho}\right]$.

Results for Coachella Valley, California

Equation (23) expresses the percentage change in economic surplus from allowing trade assuming perfect competition in the groundwater 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 (23) 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 4), whereas the denominator represents economic surplus generated from groundwater pumping in the no-trade setting when the initial allocation is nonbinding for the L-type producers, who would, in the absence of trading, apply their unconstrained optimum, X_L^*:[17]

$$\text{(23)} \quad \%\triangle = \frac{\int_0^{X^T} \left(ED^{-1}(\tau) - ES^{-1}(\tau)\right) d\tau}{\int_0^{X_H^0} \left(D_H^{-1}(\tau) - c^0\right) d\tau + \int_0^{X_L^*} \left(D_L^{-1}(\tau) - c^0\right) d\tau} * 100.$$

Given the aforementioned model parameters, the percent change in surplus due to groundwater trading in Coachella Valley relative to command and control is 36% or $30.42 million annually. In equilibrium, 86,430 AF of groundwater would be traded at a price between $\underline{\rho}$=$227 and $\bar{\rho}$ =$235 per acre-foot. Details of these calculations can be found in

[17] X_L^* is computed to reflect reduced pumping costs caused by H types' pumping being constrained by their binding allocations.

Appendix A. The quantity traded is 47% of the total water available for trade (or 37.6% of open-access equilibrium quantity), and the market-clearing price is more than twice as large as the average marginal extraction costs prior to the regulation.[18]

Dividing the estimated gains of $30.42 million by the quantity traded reveals an annual average value per acre-foot traded of $352. These average gains to trade are larger than the $0-148/AF gains from groundwater trade in the Republican Basin, Nebraska, estimated by Thompson *et al.* (2009), with the disparity due in large part to the heterogeneity of crops grown in Coachella and differences in their value relative to the cropping pattern in the Republican Basin, which consists primarily of corn and wheat. Our estimate falls near the midpoint of the range of values reported by Hagerty (2019) of $88-697/AF for the statewide wholesale surface water market in California.

The Effect of Market Power on the Gains from Trade

The theoretical model lends insight regarding the efficiency and distributional impacts of market power in a water market for the case when equilibrium occurs along the upward-sloping portion of sellers' excess supply function. In this case, as illustrated in figure 2, the gains from trade in the linear model can be reduced by at most 11% under monopoly ($\xi = 1$, $\theta = 0$) or monopsony ($\theta = 1$, $\xi = 0$), regardless of the initial allocation of permits or the specific estimates for the other parameters.

This result is not directly relevant to the Coachella application because, given our base parameters, the competitive equilibrium occurs in the vertical portion of excess supply, with L types selling their entire allocations to H types. This means that there is a range of seller market power, $\xi > 0$, where $PMR(X|\xi)$ intersects $ES^{-1}(X)$ along its vertical portion. For this range, there is no deadweight loss from the exercise of seller power because the trade volume remains at X_L^0. A similar conclusion holds for buyer power. Buyers' $PMFC(X|\theta)$ function becomes vertical at X_L^0, meaning that a range of values exist for $\theta > 0$ where $PMFC$ intersects buyers ED^{-1} function in its vertical portion. Magnitudes of buyer power in this range do not cause a deadweight loss. Further, predictions regarding the impacts of market power on the distribution of welfare are not sharp, given that the competitive model does not yield a clear prediction for price, as discussed earlier and as illustrated in figure 4.[19]

We can solve for the range of values of ξ and θ for which the trading equilibrium remains on the vertical portion of excess supply to determine the range of market power realizations for which some positive DWL occurs. For both seller and buyer market power, values of θ and $\xi \in [0, 0.0223]$ result in a trading equilibrium that remains on the vertical portion of excess supply, given other parameter values estimated for Coachella. Market power realizations of ξ or θ greater than 0.0223 will result in reduced trade volumes and positive DWL. Thus, any significant exercise of market power in Coachella (i.e. ξ, $\theta > 0.0223$) will reduce trading below the competitive equilibrium and cause a DWL, with the result from the general model of a maximum 11.1% surplus reduction from pure monopoly or monopsony representing a close approximation for Coachella.

Sensitivity Analysis

We 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

[18] These estimates assume that trading is costless. In reality, a trading platform would need to be established, which would likely involve both fixed and variable (per trade) costs. Variable costs to trading would create a wedge between sellers' price paid and buyers' price received and decrease trading volume and surplus to trading below the estimates reported here. Other costs that might be associated with water markets, such as means to monitor extraction and enforce compliance are already in place for Coachella and, in general, will need to be implemented under SGMA whether or not an agency establishes a trading mechanism.

[19] In online appendix File S1 where this case is studied in detail, we argue that the presence of seller power makes it likely that equilibrium price is set where the trade volume, X_L^0 intersects buyers' inverse excess demand. Conversely the presence of buyer power makes it more likely that equilibrium price is set at the kink point where ES^{-1} becomes vertical.

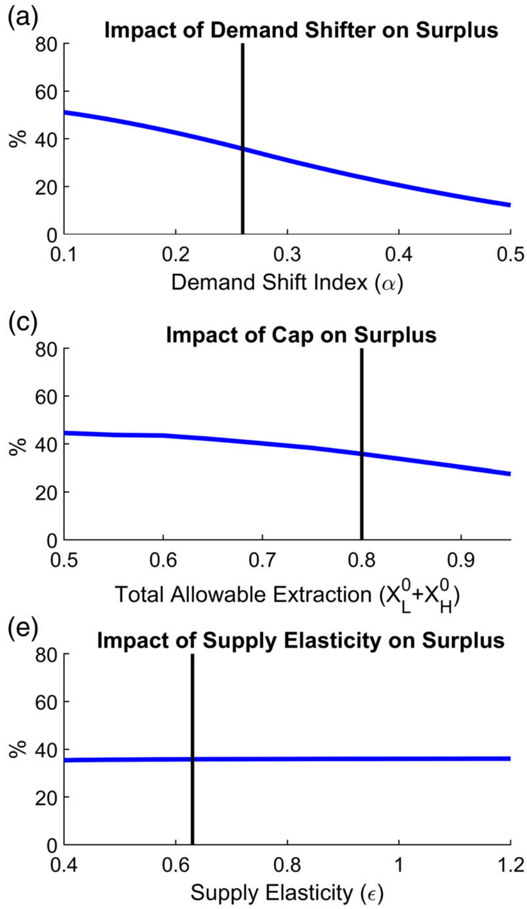

Figure 5. Gains from trade sensitivity analysis.

Notes: Panels A through E in this figure show, respectively, the sensitivity of the surplus gains result to changes in five parameters: the demand shift index, the price elasticity of groundwater demand, the total allowable extraction, the allocation of permits between types, and the supply elasticity. 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.

feature distinct values for most or all of the model parameters.

Figure 5 shows for the perfectly competitive markets case how the gains from groundwater trade change as other conditions of the market vary, where the surplus with trade is expressed as a percentage change in surplus from the no-trade (command-and-control) 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 as α increases, making water demands more similar between types. The gains from trade converge to zero as $\alpha \rightarrow 1$. 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 but is rarer elsewhere. 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

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

Crop	Acreage	Revenue	Revenue per acre	Applied water (AF)	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 (AF) per year comes 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.

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.

Notably, the demand elasticity plays an additional role in determining economic surplus to trade in the presence of seller market power because the distortion from a given exercise of market power as measured by ξ depends on the demand elasticity, with more inelastic demands increasing the distortion for a given ξ. This effect reinforces the impact shown in panel B because more inelastic demands will exacerbate the surplus lost for a given value of ξ.

Panel C depicts the gains with trade as a function of the total endowment of property rights for pumping, that is, 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. $X_L^0 + X_H^0 \rightarrow 1$), 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

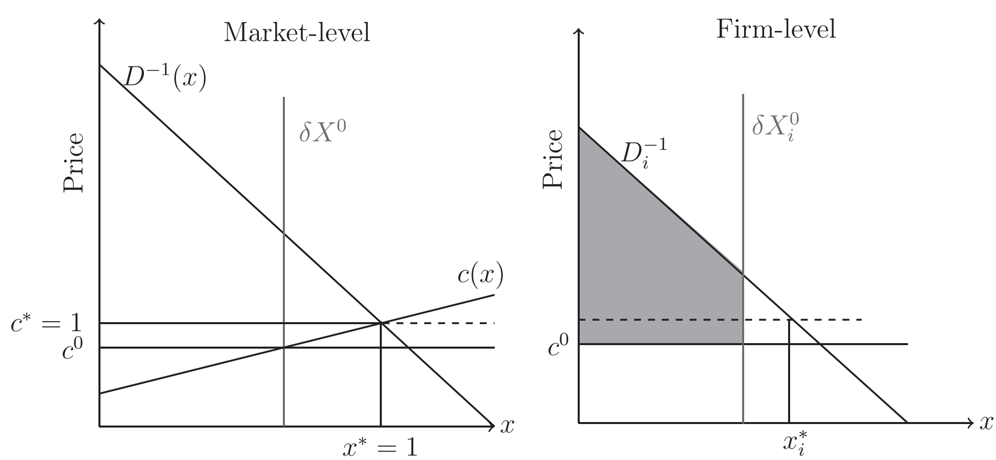

Figure 6. Surplus under command and control.

Notes: The right figure depicts the aggregate surplus for farmers of type i under command and control with a binding constraint of δX_i^0. Surplus is shown by the shaded area. The left figure depicts the market-level outcomes, where $D^{-1}(x)$ represents aggregate inverse demand. Open-access equilibrium quantity and price (x^*, c^*) were normalized to (1, 1). Marginal extraction costs at the binding constraint are represented by c^0. Individual farmers are assumed to take costs as given.

of the allocation of permits between types. 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. 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.

Finally, panel E shows the percentage change in surplus from trade as a function of the groundwater supply elasticity. We consider a range for ε that encompasses 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 very small rate, showing that the gains result is extremely insensitive to our storativity assumption of $s = 0.11$. 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. The value of ε, however, assumes increased importance in the presence of buyer power because, analogous to the seller power case, the distortion from a given value of θ and the resulting surplus loss is magnified the more inelastic is supply.

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.[20] Because these parameter ranges represent a wide spectrum of market conditions, they suggest that our results for Coachella are likely to hold more generally, that is, the gains from groundwater trade can be quite large for many groundwater-dependent agricultural regions.

[20] If we adjust α above its base value in Coachella to evaluate sensitivity of model parameters when the trading equilibria occur in the upward-sloping portion of the excess supply function (instead of the vertical portion as in the base Coachella case), we observe that higher α values shift the curves downward, reflecting lower gains to trade with more similar demands but with negligible impact on their shape. These results are available upon request from the authors.

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, thereby placing increased demands on the available groundwater supplies. 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 2019) 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 and limited by the hydrologic connectivity of the basin over which they operate. This article 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 except for market power. 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 36% 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.

Given evidence that the presence of buyer or seller power has only a minor impact on the overall gains from trade, concerns over market power should not constitute a compelling argument to avoid trading. However, distributional impacts, which may be considerable, may impact some stakeholders' incentives to support or oppose 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.

Our framework quantified the gains from trade in the short-run, given fixed cropping patterns and irrigation technologies. One compelling area for future research is the identification of market impacts over a long-run horizon, whereby all potential margins of adjustment, including cropping pattern and irrigation efficiency, are considered. A second and highly challenging potential area for further research is to consider trading in an environment of bilateral oligopoly. A fuller understanding of the potential of groundwater markets will be important as many agricultural regions continue to grapple with changes to groundwater and climate in the years to come.

Supplementary Material

Supplementary material are available at *American Journal of Agricultural Economics* online.

References

[ACO] Agricultural Commissioner's Office. 2016. Coachella Valley Acreage and Agricultural Crop Report. Riverside County, CA. Available at: www.rivcoawm.org/Resources/Publications.aspx. Accessed June 20, 2017.

Alston, Julian M, Richard J Sexton, and Mingxia Zhang. 1997. The Effects of Imperfect Competition on the Size and Distribution of Research Benefits. *American Journal of Agricultural Economics* 79 (4): 1252–65.

Anderson, Lee G. 2008. The Control of Market Power in ITQ Fisheries. *Marine Resource Economics* 23(1): 25–35.

Ansink, Erik, and Harold Houba. 2012. Market Power in Water Markets. *Journal of Environmental Economics and Management* 64(2)): 237–52.

Brill, Thomas C, and H Stuart Burness. 1994. lanning Versus Competitive Rates of Groundwater Pumping. *Water Resources Research* 30(6)): 1873–80.

Brown, Thomas C. 2006. Trends in Water Market Activity and Price in the Western United States. *Water Resources Research* 42(9): 1–14.

Brozović, Nicholas, David L Sunding, and David Zilberman. 2010. On the Spatial Nature of the Groundwater Pumping Externality. *Resource and Energy Economics* 32(2): 154–64.

Brozović, Nicholas, and Richael Young. 2014. Design and Implementation of Markets for Groundwater Pumping Rights. In *Water Markets for the 21st Century: What Have We Learned?* ed. K William Easter and Qiuqiong Huang, 283–303. Dordrecht: Springer Netherlands.

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

Bruno, Ellen M., and Katrina 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, Metin, and Joseph V Balagtas. 2012. Estimating Market Power of U.S. Dairy Cooperatives in the Fluid Milk Market. *American Journal of Agricultural Economics* 94(3): 647–58.

Chakravorty, Ujjayant, Eithan Hochman, Chieko Umetsu, and David Zilberman. 2009. Water Allocation under Distribution Losses: Comparing Alternative Institutions. *Journal of Economics Dynamics and Control* 33(2): 463–76.

City of Barstow v. Mojave Water Agency. 2000. Vol. 23 Cal. 4th 1224, 1253. Superior Court of Riverside County.

City of Pasadena v. City of Alhambra. 1949. Vol. 33 Cal. 2d 908, 925, 926.

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. Accessed June 20, 2017.

Conrad, Esther, Janet Martinez, Tara Moran, Marcelle E DuPraw, David Ceppos, and William Bloomquist. 2018. Diverse Stakeholders Create Collaborative, Multilevel Basin Governance for Groundwater Sustainability. *California Agriculture* 72(1): 44–53.

de Bonviller, Simon, Alec Zuo, and Sarah A Wheeler. 2019. Is There Evidence of Insider Trading in Australian Water Markets? *Australian Journal of Agricultural and Resource Economics* 63: 307–27.

Dobson, Paul W, and Michael Waterson. 2007. The Competition Effects of Industry-Wide Vertical Price Fixing in Bilateral Oligopoly. *International Journal of Industrial Organization* 25: 935–62.

[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. Accessed June 18, 2017.

———. 2016. California's Groundwater: Working Toward Sustainability. Bulletin 118 Interim Update 2016. Available at: https://www.water.ca.gov/Programs/Groundwater-Management/Bulletin-118. Accessed June 18, 2017.

———. 2019. Groundwater Monitoring (CASGEM). Available at: https://water.ca.gov/Programs/Groundwater-Management/Groundwater-Elevation-Monitoring–CASGEM. Accessed April 22, 2019.

Edwards, Eric C. 2016. What Lies Beneath? Aquifer Heterogeneity and the Economics of Groundwater Management. *Journal of the Association of Environmental and Resource Economists* **3** (2): 453–491.

Famiglietti, JS. 2014. The Global Groundwater Crisis. *Nature Climate Change* 4: 945–8.

[FAO] Food and Agriculture Organization of the United Nations. 2019. Available at: http://www.fao.org/faostat. Accessed May 20, 2019.

Faunt, Claudia C, Kenneth Belitz, and Randall T Hanson. 2009. Groundwater Availability in California's Central Valley. In *Groundwater Availability of the Central Valley Aquifer, California*, ed. Claudia C Faunt. Reston, 59–120, VA: U.S. Geological Survey.

Fetter, CW. 2001. *Applied Hydrogeology*, 4th ed. Upper Saddle River, NJ: Prentice-Hall.

Fowlie, Meredith L, Stephen P Holland, and Erin T 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, Lei, Jeff Connor, Rebecca Doble, Riasat Ali, and Don McFarlane. 2013. Opportunity for Peri-Urban Perth Groundwater Trade. *Journal of Hydrology* 496: 89–99.

Gisser, Micha, and David A Sanchez. 1980. Competition Versus Optimal Control in Groundwater Pumping. *Water Resources Research* 16(4): 638–42.

Gonzalez-Alvarez, Yassert, Andrew G Keeler, and Jeffrey D Mullen. 2006. Farm-Level Irrigation and the Marginal Cost of Water Use: Evidence from Georgia. *Journal of Environmental Management* 80(4): 311–7.

Goulder, Lawrence H, and Ian WH Parry. 2008. nstrument Choice in Environmental Policy. *Review of Environmental Economics and Policy* 2(2): 307–22.

Grafton, R Quentin, and James Horne. 2014. Water Markets in the Murray-Darling Basin. *Agricultural Water Management* 145: 61–71.

Grafton, R Quentin, James Horne, and Sarah A Wheeler. 2016. On the Marketisation of Water: Evidence from the Murray-Darling Basin, Australia. *Water Resources Management* 30: 913–26.

Green Nylen, Nell, Michael Kiparsky, Kelly Archer, Kurt Schneir, and Holly 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.

Guilfoos, Todd, Cloé Garnache, Jordan F. Suter, and Nathaniel H. Merrill. 2017. Efficiency Gains Arising from Dynamic Groundwater Markets. Working Paper, 2017 Annual Meeting, July 30–August 1, Chicago, Illinois, Agricultural and Applied Economics Association.

Hagerty, Nick 2019. Liquid Constrained: Estimating the Potential Gains from Water Markets. Working Paper, Department of Agricultural and Resource Economics, University of California, Berkeley.

Hahn, Robert W. 1984. Market Power and Transferable Property Rights. *Quarterly Journal of Economics* 99(4): 753–65.

Hearne, Robert R, and KWilliam Easter. 1997. The Economic and Financial Gains from Water Markets in Chile. *Agricultural Economics* 15(3): 187–99.

Hendricks, Nathan P, and Jeffrey M Peterson. 2012. Fixed Effects Estimation of the Intensive and Extensive Margins of Irrigation Water Demand. *Journal of Agricultural and Resource Economics* 37(1): 1–19.

Hintermann, Beat. 2011. Market Power, Permit Allocation and Efficiency in Emission Permit Markets. *Environmental and Resource Economics* 49(3): 327–49.

———. 2016. Pass-Through of CO2 Emission Costs to Hourly Electricity Prices in Germany. *Journal of the Association of Environmental and Resource Economists* 3(4): 857–91.

———. 2017. Market Power in Emission Permit Markets: Theory and Evidence from the EU ETS. *Environmental and Resource Economics* 66(1): 89–112.

Howitt, Richard E. 1994. Empirical Analysis of Water Market Institutions: The 1991 California Water Market. *Resource and Energy Economics* 16(4): 357–71.

Howitt, Richard E, Duncan MacEwan, José Medellín-Azuara, Jay R Lund, and Daniel A Sumner. 2015. *Economic Analysis of the 2015 Drought for California Agriculture*. Davis: Center for Watershed Sciences, University of California.

Howitt, Richard, and David Sunding. 2003. Water Infrastructure and Water Allocation in California. In *California Agriculture: Dimensions and Issues*, ed. J Siebert, 181–90. Oakland, CA: University of California Giannini Foundation of Agricultural Economics, Division of Agriculture and Natural Resources.

Inderst, Roman, and Christian Wey. 2003. Bargaining, Mergers, and Technology Choice in Bilaterally Oligopolistic Industries. *RAND Journal of Economics* 34: 1, 19.

Jenkins, Marion W, Jay R Lund, Richard E Howitt, Andrew J Draper, Siwa M Msangi, Stacy K Tanaka, Randall S Ritzema, and Guilherme F Marques. 2004. Optimization of California's Water Supply System: Results and Insights. *Journal of Water Resources Planning and Management* 130(4): 271–80.

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

Kunkel, Kenneth E, Thomas R Karl, Harold Brooks, James P Kossin, Jay H Lawrimore, Derek Arndt, and Lance Bosart. 2013. Monitoring and Understanding Trends in Extreme Storms: State of Knowledge. *Bulletin of the American Meteorological Society* 94(4): 499–514.

Kuwayama, Yusuke, and Nicholas Brozović. 2013. The Regulation of a Spatially Heterogeneous Externality: Tradable Groundwater Permits to Protect Streams. *Journal of Environmental Economics and Management* 66(2): 364–82.

Liski, Matti, and Juan-Pablo Montero. 2011. Market Power in an Exhaustible Resource Market: The Case of Storable Pollution Permits. *Economic Journal* 121 (551): 116–44.

MacEwan, Duncan, Mesut Cayar, Ali Taghavi, David Mitchell, Steve Hatchett, and Richard Howitt. 2017. Hydroeconomic Modeling of Sustainable Groundwater Management. *Water Resources Research* 53(3): 2384–403.

Merrill, Nathaniel H, and Todd Guilfoos. 2017. Optimal Groundwater Extraction under Uncertainty and a Spatial Stock Externality. *American Journal of Agricultural Economics* 100(1): 220–38.

Misiolek, Walter S, and Harold W Elder. 1989. Exclusionary Manipulation of Markets for Pollution Rights. *Journal of Environmental Economics and Management* 16(2): 156–66.

Montero, Juan-Pablo. 2009. Market Power in Pollution Permit Markets. *Energy Journal* 30(2): 115–42.

O'Connell, Neil V., Craig E. Kallsen, Karen M. Klonsky, and Kabir P. Tumber. 2015. Sample Costs to Establish an Orchard and Produce Lemons. University of California Cooperative Extension Current Cost and Return Studies. University of California Agricultural Issues Center. Available at: https://coststudies.ucdavis.edu. Accessed June 20, 2017.

Palazzo, Amanda, and Nicholas Brozović. 2014. The Role of Groundwater Trading in Spatial Water Management. *Agricultural Water Management* 145: 50–60.

Perloff, Jeffrey M, Larry S Karp, and Amos Golan. 2007. *Estimating Market Power and Strategies*. Cambridge: Cambridge University Press.

Peterson, Deborah C., Gavin Dwyer, David Appels, and Jane M. Fry. 2004. Modelling Water Trade in the Southern Murray-Darling Basin. Productivity Commission Staff Working Paper, Productivity Commission, Melbourne.

Pfeiffer, Lisa, and C-Y Cynthia Lin. 2012. Groundwater Pumping and Spatial Externalities in Agriculture. *Journal of Environmental Economics and Management* 64(1): 16–30.

Raffensperger, John F, Mark W Milke, and EGrant Read. 2009. A Deterministic Smart Market Model for Groundwater. *Operations Research* 57(6): 1333–46.

Rodell, Matthew, Isabella Velicogna, and James S Famiglietti. 2009. Satellite-Based Estimates of Groundwater Depletion in India. *Nature* 460(7258): 999–1002.

Rogers, Danny H, and Mahbub Alam. 2006. Comparing Irrigation Energy Costs. In *Irrigation Management Series MF-2360*. Kansas State University. Available at: https://itc.tamu.edu/files/2018/05/MF2360.pdf. Accessed May 6, 2017.

Rogers, Danny H, Freddie R Lamm, Mahbub Alam, Todd P Trooien, Gary A Clark, Philip L Barnes, and Kyle Mankin. 1997. Efficiencies and Water Losses of Irrigation Systems. In *Irrigation Management Series MF-2243*. Kansas State University. Available at: https://www.bookstore.ksre.ksu.edu/pubs/MF2243.pdf. Accessed May 6, 2017.

Rogers, Richard T. 2001. Structural Change in U.S. Food Manufacturing. *Agribusiness* 17(1): 3–32.

Rosen, Michael D, and Richard J Sexton. 1993. Irrigation Districts and Water Markets: An Application of Cooperative Decision-Making Theory. *Land Economics* 69(1): 39–53.

Schmalensee, Richard, and Robert 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): 572–88.

[SGMA] Sustainable Groundwater Management Act. 2014. California Water Code. §10720.1. Available at: https://www.water.ca.gov/Programs/Groundwater-Management/SGMA-Groundwater-Management. Accessed April 15, 2017.

Smith, Steven M, Krister Andersson, Kelsey C Cody, Michael Cox, and Darren Ficklin. 2017. Responding to a Groundwater Crisis: The Effects of Self-Imposed Economic Incentives. *Journal of the Association of Environmental and Resource Economists* 4(4): 985–1023.

Sunding, David L, David Zilberman, Richard Howitt, Ariel Dinar, and Neal MacDougall. 2002. Measuring the Costs of Reallocating Water from Agriculture: A Multi-Model Approach. *Natural Resource Modeling* 15(2): 201–25.

Suzuki, Nobuhiro, Harry M Kaiser, John E Lenz, Kohei Kobayashi, and Olan D Forker. 1994. Evaluating Generic Milk Promotion Effectiveness with an Imperfect Competition Model. *American Journal of Agricultural Economics* 76(2): 296–302.

Swain, Daniel L, Baird Langenbrunner, JDavid Neelin, and Alex Hall. 2018. Increasing Precipitation Volatility in Twenty-First-Century California. *Nature Climate Change* 8: 427–33.

Theis, CV. 1940. The Source of Water Derived from Wells. *Civil Engineering* 10 (5): 277–80.

Thompson, Christopher L, Raymond J Supalla, Derrel L Martin, and Brian O McMullen. 2009. Evidence Supporting Cap and Trade as a Groundwater Policy Option for Reducing Irrigation Consumptive Use. *JAWRA Journal of the American Water Resources Association* 45(6): 1508–18.

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

Vaux, HJ, and Richard E Howitt. 1984. Managing Water Scarcity: An Evaluation of

Interregional Transfers. *Water Resources Research* 20(7): 785–92.
Westskog, Hege. 1996. Market Power in a System of Tradeable C02 Quotas. *Energy Journal* 17(3): 85–103.
Zhang, Mingxia, and Richard J Sexton. 2002. Optimal Commodity Promotion when Downstream Markets Are Imperfectly Competitive. *American Journal of Agricultural Economics* 84(2): 352–65.

Appendix

Simulation Details

Herein we provide detailed explanations of the methods for estimating model parameters, the total gains from trade, and the distributional impacts of market power.

Model Parameters

The demand-shift index, α, captures the degree of heterogeneity of water demands among groundwater users. This parameter was calculated with data from Riverside County's 2016 Crop Report for Coachella Valley and University of California Cooperative Extension (UCCE) Cost and Return Studies.[21] 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 marginal value product (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" using the demand elasticity estimate described below and compared these estimates across crops. 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 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 intercepts 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 Coachella Valley Water District (CVWD), the largest water agency in the valley, meters extraction at each groundwater well within its service area that pumps more than 25 acre feet (AF) per year and charges volumetric prices for groundwater pumping known as "replenishment assessment charges" or RAC. The RAC ranged from \$0 to \$129/AF across three subregions from 2000 to 2016, with an average over this time period of \$65/AF. 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.[22] 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.[23]

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

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

[22] The well pumping data do not indicate the crop(s) being fed from the well, precluding crop-specific elasticities from being estimated. Bruno and Jessoe (2018) estimate an average water demand elasticity across all Coachella crops.

[23] A handful of other recent papers have estimated a price elasticity of groundwater demand including Gonzalez-Alvarez, Keeler, and Mullen (2006) for Georgia, Hendricks and Peterson (2012) for Kansas, and Smith *et al.* (2017) for Colorado. The estimates are difficult to compare directly due to differences in crops produced, sources of price variation, and rainfall. Bearing this caveat in mind, the Bruno-Jessoe estimate lies about midway between the 0.1 base estimate of Hendricks and Peterson and the 0.27 base estimate of Gonzalez-Alvarez et al. The estimates of Smith et al. are somewhat more elastic, ranging from 0.5 to 0.77.

overdraft (CVWD 2016). Proportional to acreage held by each type, 53% of this cap was allocated to the H types in the base simulation.

Drip technology is widely used in the Coachella Valley. 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. Energy extraction costs are an increasing function of total pumping, X, and, thus, a reduction in basin-wide groundwater use under SGMA will decrease the marginal energy pumping costs faced by users on the basin.[24]

To estimate marginal energy extraction costs, let $h(X)$ represent the depth to the water table (in feet) from the surface, which depends on total basin pumping X (in acre feet). Let p^e represent the electricity price (\$ per kwh) and the constant ϕ denote the kwh requirement to raise an acre foot of water one foot (kwh per AF per foot). The marginal energy cost per AF of groundwater extracted 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 $p^e = \$0.0952$ as the 2016 per kwh electricity price faced by irrigated agriculture in the Coachella area and Rogers and Alam (2006) report $\phi = 1.551$ to be the kwh requirement to lift one AF of water one foot.[25] Assuming an average depth to the water table of 108 feet and average 2016 RAC rates of \$84.60, the imputed price of groundwater for 2016 would be \$100.50 per AF on average (DWR 2019).[26]

In order to capture how a cap on pumping would affect pumping costs, we need to specify a relationship for $h(X)$, that is, how the depth to the water table changes with basin-wide pumping. Informed by Fetter (2001), 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 $\frac{1}{\varepsilon} = \frac{\partial c(x)}{\partial x}\frac{x^*}{c^*} = \frac{\phi p^e}{\delta s} = 1.58$, given $s = 0.11$, $\phi = 1.551$, $p^e = \$0.095$, and $\delta = 0.85$. We use this inverse 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, $c(X = .8) = \left(1 - \frac{1}{\varepsilon}\right) + \frac{1}{\varepsilon}(.8) = .68$, that is, marginal pumping costs under the constrained allocation are estimated to be about 68% of their normalized 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. Because groundwater trading is only on the horizon, there exist no data from actual trades to estimate values for θ or ξ

[24] 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 of the three pricing regions. However, examination of the cropping patterns indicates no concentration by type in any single region.

[25] The constant $\phi = 1.551$ accounts for pump efficiency by assuming an electric pump output of 0.885 water horsepower-hour per kwh (Rogers and Alam 2006).

[26] Mean depth to the water table was calculated by averaging the depths in 2016 across the ten active irrigation wells in the Coachella Valley Indio sub-basin that are monitored and reported to the California Statewide Groundwater Elevation Monitoring (CASGEM) program. At pumping quantities, depths, and prices observed in Coachella in 2016, $c^* = (1.551) * (\$0.0952) * 108\,ft + \$84.60 = \$100.50$.

using, for example, methods of the new empirical industrial organization, as discussed in Kaiser and Suzuki (2006), Perloff, Karp, and Golan (2007), and elsewhere. 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 $\xi > 0$, recognizing that buyer power ($\theta > 0$) will yield a similar impact based on the theoretical model.

Gains from Trade

Recall the excess supply relationship defined by the set of all $(X, \rho) \in \mathrm{IR}^2$ and $X \geq 0$ such that:

$$\begin{cases} \rho = ES^{-1}(X) = 0, X \leq \bar{X} \\ \rho = ES^{-1}(X) = \dfrac{2}{\eta}\delta\sigma_L - \dfrac{2}{\eta}\delta X_L^0 + \dfrac{2}{\eta}\delta X, \bar{X} \leq X \leq X_L^0 \\ X(\rho) = X_L^0, \rho > \dfrac{2}{\eta}\left(\dfrac{\alpha(1+\eta)}{1+\alpha}\right), \end{cases}$$

where $\bar{X} = X_L^0 - \sigma_L$ and $\sigma_L = \frac{1}{\delta}\frac{\alpha(1+\eta)}{1+\alpha} - \frac{\eta}{2\delta}c^0$. Additionally, recall $ED^{-1}(X) = \frac{2\delta}{\eta}\left(\sigma_H - X_H^0 - X\right)$ where $\sigma_H = \frac{1}{\delta}\frac{1+\eta}{1+\alpha} - \frac{\eta}{2\delta}c^0$ and inverse demand functions for H and L types:

$$\text{(B.1)} \quad D_H^{-1}(X) = \frac{2}{\eta}\left(\frac{1+\eta}{1+\alpha}\right) - \frac{2}{\eta}\delta X,$$

$$\text{(B.2)} \quad D_L^{-1}(X) = \frac{2}{\eta}\left(\frac{\alpha(1+\eta)}{1+\alpha}\right) - \frac{2}{\eta}\delta X.$$

We solved the following expression in the main text for gains from trade as a percentage of surplus under command and control:

$$\text{(B.3)} \quad \%\triangle = \frac{\int_0^{X^T}\left(ED^{-1}(\tau) - ES^{-1}(\tau)\right)d\tau}{\int_0^{X_H^0}\left(D_H^{-1}(\tau) - c^0\right)d\tau + \int_0^{X_L^*}\left(D_L^{-1}(\tau) - c^0\right)d\tau} * 100$$

where $c^0 = c\left(X_H^0 + X_L^0\right)$ is the marginal pumping cost under the constrained equilibrium and $X_L^* = \frac{1}{\delta}\left(\frac{\alpha(1+\eta)}{1+\alpha} - \frac{\eta}{2}c^0\right) < X_L^0$ is defined as the quantity pumped by unconstrained L types, $D_L^{-1}\left(X_L^*\right) = c^0$. Figure 6 illustrates the surplus under command and control that is captured in the denominator of equation (B.3) and shows how basin-wide pumping costs change with a restriction on pumping at the basin level.

We know that for Coachella, the constraint is nonbinding 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 excess supply) as shown in figure 4. Plugging in the above functional forms for ES^{-1}, ED^{-1}, and $D_i^{-1}, i = H, L$, and simplifying yields the following expression:

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

Performing the integration and simplifying yields:

$$\text{(B.5)} \quad \%\triangle = \frac{\left(\frac{2}{\eta}\left(\frac{1+\eta}{1+\alpha}\right)\tau - \frac{2}{\eta}\delta X_H^0\tau - \frac{1}{\eta}\delta\tau^2\right)\Big|_0^{\bar{X}} + \left(\frac{2}{\eta}\left(\frac{(1-\alpha)(1+\eta)}{1+\alpha}\right)\tau + \frac{2}{\eta}\left(\delta X_L^0 - \delta X_H^0\right)\tau - \frac{2}{\eta}\delta\tau^2\right)\Big|_0^{X^T}}{\left(\frac{2}{\eta}\left(\frac{1+\eta}{1+\alpha}\right)\tau - \frac{1}{\eta}\delta\tau^2 - c^0\tau\right)\Big|_0^{X_H^0} + \left(\frac{2}{\eta}\left(\frac{\alpha(1+\eta)}{1+\alpha}\right)\tau - \frac{1}{\eta}\delta\tau^2 - c^0\tau\right)\Big|_0^{X_L^*}} * 100.$$

$$\text{(B.6)} \quad \%\triangle = \frac{\frac{2}{\eta}\left(\frac{1+\eta}{1+\alpha}\right)\bar{X} - \frac{2}{\eta}\delta X_H^0\bar{X} - \frac{1}{\eta}\delta\left(\bar{X}\right)^2 + \frac{2}{\eta}\left(\frac{(1-\alpha)(1+\eta)}{1+\alpha}\right)X^T + \frac{2}{\eta}\left(\delta X_L^0 - \delta X_H^0\right)X^T - \frac{2}{\eta}\delta\left(X^T\right)^2}{\frac{2}{\eta}\left(\frac{1+\eta}{1+\alpha}\right)X_H^0 - \frac{1}{\eta}\delta\left(X_H^0\right)^2 - c^0X_H^0 + \frac{2}{\eta}\left(\frac{\alpha(1+\eta)}{1+\alpha}\right)X_L^* - \frac{1}{\eta}\delta\left(X_L^*\right)^2 - c^0X_L^*} * 100.$$

Where

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

is the equilibrium quantity traded. Plugging parameter values for Coachella (table 1) yields $\%\triangle = 35.8\%$.

The numerator in equation (B.6) is the normalized monetary gains, G, from trade, that is,

$$\text{(B.7)} \quad G = \frac{2}{\eta}\left(\frac{1+\eta}{1+\alpha}\right)\bar{X} - \frac{2}{\eta}\delta X_H^0\bar{X} - \frac{1}{\eta}\delta\left(\bar{X}\right)^2 + \frac{2}{\eta}\left(\frac{(1-\alpha)(1+\eta)}{1+\alpha}\right)X^T + \frac{2}{\eta}\left(\delta X_L^0 - \delta X_H^0\right)X^T - \frac{2}{\eta}\delta\left(X^T\right)^2 = 1.32$$

We undo the normalization by multiplying G by the nominal values for (x^*, c^*) (229,867 AF, \$100.50/AF) in the open-access equilibrium to obtain the estimated monetary gains, G^*, to groundwater trade in the Coachella Valley in 2016 dollars, given the baseline parameter values:

$$\text{(B.8)} \quad G^* = 1.37 * \$100.50 * 229{,}867 = \$30.42\,\text{million}.$$

In equilibrium, L types sell their entire allocation, meaning 37.6% of the open-access 229,867 AF quantity is traded, which is 86,430 AF. The range of market-clearing prices, $\underline{\rho}$ to $\bar{\rho}$, is determined by the range between the point in which the excess supply curve becomes vertical and where ED^{-1} intersects the vertical ES^{-1}, as shown in figure 4:

$$\text{(B.9)} \quad \underline{\rho} = ES^{-1}\left(X_L^0\right) = \frac{2\delta}{\eta}\left(X_L^0 - X_L^0 + \sigma_L\right) = 2.16$$

$$\text{(B.10)} \quad \bar{\rho} = ED^{-1}\left(X_L^0\right) = \frac{2\delta}{\eta}\left(\sigma_H - X_H^0 - X_L^0\right) = 2.14$$

Multiplying by baseline marginal extraction costs of \$100.5 AF, we see $\underline{\rho}$=\$217 and $\bar{\rho}$ =\$225 per acre-foot. Thus, total price ($P = \rho + c^0$) paid for groundwater in this context would range between \$317 and \$325. Dividing the total gains by the quantity traded reveals an annual average value of about \$352 per AF traded.

A.1.1. Estimating Distributional Impacts

Expressions for changes in consumer and producer surplus shown in figure 3 are similarly expressed here as a function of parameters from the linear model. Recall the expressions for the percentage change in consumer and producer surplus as a function of the market power parameter, ξ, equations (20) and (21), which characterize the case where the constraint is always binding for the L types and in equilibrium the L types apply some portion of their water to their land (on the upward-sloping portion of excess supply). We can express these as functions of the parameters for the linear model:

$$\text{(B.11)} \quad \% \triangle CS = \frac{\int_0^{X^{SP}(\xi)} \left(\frac{2\delta}{\eta} \left(\sigma_H - X_H^0 - \tau \right) - \rho^{SP} \right) d\tau - \int_0^{X^T} \left(\frac{2\delta}{\eta} \left(\sigma_H - X_H^0 - \tau \right) - \rho^T \right) d\tau}{\int_0^{X^T} \left(\frac{2\delta}{\eta} \left(\sigma_H - X_H^0 - \tau \right) - \rho^T \right) d\tau} * 100,$$

$$\text{(B.12)} \quad \% \triangle PS = \frac{\int_0^{X^{SP}(\xi)} \left(\rho^{SP}(\xi) - \frac{2\delta}{\eta} \left(\tau - X_L^0 + \sigma_L \right) \right) d\tau - \int_0^{X^T} \left(\rho^T - \frac{2\delta}{\eta} \left(\tau - X_L^0 + \sigma_L \right) \right) d\tau}{\int_0^{X^T} \left(\rho^T - \frac{2\delta}{\eta} \left(\tau - X_L^0 + \sigma_L \right) \right) d\tau} * 100,$$

where $\rho^{SP} = \frac{2\delta}{\eta} \left(\sigma_H - X_H^0 - \left[\frac{\sigma_H - \sigma_L + X_L^0 - X_H^0}{2 + \xi} \right] \right)$, $\rho^T = \frac{\delta}{\eta} \left[\sigma_H + \sigma_L - \left(X_H^0 + X_L^0 \right) \right]$, $X^{SP} = \frac{1}{\delta} \frac{\Omega}{2 + \xi}$, and $X^T = \frac{\Omega}{2\delta}$. Plugging baseline parameter values from table 1 with an adjustment to α as explained in the main text, and a choice for ξ, yields changes in market surplus for buyers and sellers. These expressions are calculated for every value of ξ to obtain figure 3.