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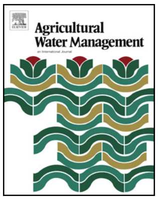

The role of groundwater trading in spatial water management

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ABSTRACT

Agricultural groundwater use is increasingly being restricted to address the negative impacts of pumping on instream flows for downstream users, endangered species habitat, and recreation. Understanding the spatial heterogeneity of the costs of water use restrictions to farmers is critical to evaluating the effectiveness of current and alternative water management policies. We use a geospatial population dataset of irrigation wells in the Republican River Basin of Nebraska and model the simultaneous crop choice, land and water use decisions at a well level. We estimate the magnitude and distribution of costs of current groundwater restrictions as well as cost savings from alternative market-based policies that allow trading of permits between farmers. Our analysis highlights the importance of the initial distribution of permits and the institutional context in which trading occurs. Both allocated but unused permits and land estimated to move from irrigated to dryland crops provide important trading volume into the water rights market. The results show that the cost savings from allowing trading of groundwater pumping rights are distributed unevenly between wells, counties, and groundwater management institutions.

1. Introduction

Groundwater resources are an important source of water to agricultural and urban users, and represent about a quarter of freshwater withdrawals. There may be negative consequences of groundwater use on neighboring wells, on groundwater-dependent ecosystems, on adjacent stream flow, and on the future availability of water supplies for growing populations (Young et al., 1986; Sophocleous, 2002; Brozović et al., 2010). Groundwater pumping is often unmonitored and unregulated. However, major policy concerns about the impact of groundwater pumping externalities on agricultural and environmental sustainability are reflected by rapidly-changing water management institutions and ongoing litigation over water resources. In the United States, restrictions on agricultural groundwater use to protect stream flow have been implemented or considered in several western states, including Colorado (Young et al., 1986), Nebraska (Thompson et al., 2009), and Texas (Keplinger et al., 1998; McCarl et al., 1999).

In order to evaluate the economic impacts of current groundwater management policies on farmers, as well as the potential effectiveness of alternative water allocation policies, it is necessary to analyze the variability of agricultural water use and the economic benefits that farmers obtain from using water across the region of interest. When uniform regulations are used to restrict heterogeneous farmers, the marginal values of applied water vary between farmers and such uniform restrictions are second best. Market-based water reallocation schemes are predicated on the heterogeneity of marginal values of water in use. In general, studies model water use by representative producers at a scale of a county, sub-basin or sector (Sunding et al., 2002; Jaeger, 2004; Thompson et al., 2009), or extrapolate from small samples to the population of water users (Pujol et al., 2006). To understand the distribution of *individual* benefits from water trading as well as the effectiveness of the water market as a whole, it is necessary to analyze the variability of individual potential traders. Only rarely are studies able to analyze data on populations of water users, and these are generally for small watersheds or portions of watersheds (Satti and Jacobs, 2004; Steward et al., 2009).

This study models and analyzes the costs of alternate spatial water management policies on individual groundwater users across a large agricultural watershed with existing water conflict and groundwater pumping restrictions in place. We use a unique population dataset of 11,000 agricultural irrigation wells and associated economic and hydrologic data in the Republican River Basin of Nebraska. We implement an optimization model of each irrigation well owner's crop choice, land use, and water use decisions. We extend previous research in several important

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ways. Although spatial data on populations of resource users have been used in evaluation of permit markets in an air quality setting (Muller and Mendelsohn, 2009), no previous study of water permit markets has used micro-level data on a large population of water users. By assembling and using a large geospatial population dataset we are able to characterize the broad variation of economic costs of water restrictions at a well level. When estimating the aggregate costs of reducing water available to farmers, most previous studies model the binary decision to irrigate each unit of land or not (Pujol et al., 2006; Jaeger, 2004). By modeling irrigation decision making at a field level, we are able to consider farmers' decisions not only whether to irrigate, but how much land to irrigate and how much water to apply to each irrigated area.

Our analysis demonstrates that the effectiveness of market-based schemes to reduce the costs of regulation to agricultural water users while maintaining instream flows is likely to vary within and between watersheds based on local institutions and geophysical conditions. Both allocated but unused permits and land estimated to move from irrigated to dryland crops provide important trading volume into the water rights market. In particular, we find that a relatively small portion of overall allocation is estimated to be unused, but that this slack plays a fundamental role in the market outcome. Results show a very large variation in estimated permit prices for groundwater markets from management district to management district, and from county to county. Importantly, in some markets, there are enough unused permits that the equilibrium permit price is indeterminate, as the supply of unused permits exceeds the demand for permits by constrained users.

The paper is laid out as follows. We present a model of a farmer's optimal choice of irrigated and dryland crops, land use, and water application. Next, we discuss the history of water conflict in the Republican River Basin of Colorado, Kansas, and Nebraska, and the institutional context in our study area, the Nebraska portion of the Basin. Following this, we describe model implementation and the data used in the analysis. In the next section the estimated economic impacts of the current and possible alternative water management policies are presented and analyzed. A discussion of policy implications and possible extensions concludes.

2. Model

We consider a model of a farmer with irrigated land who has no access to surface water rights and is dependent on groundwater. Each year, the farmer must decide simultaneously what dryland and irrigated crops to grow, the land allocated to each crop, and the water applied to each irrigated crop. Assume that there are J crops and that $Y_j^d(\theta_j)$ is the maximum per unit area yield possible for crop j when relying on rainfall alone, where θ_j is a vector of local characteristics that affect yield such as temperature, precipitation, and soil type. For each crop, the maximum irrigated crop yield per unit area is $Y_j^m(\theta_j)$, which is obtained when all inputs are unconstrained. Irrigation depth is defined as the amount of water delivered to the field per irrigation application. Then, for a given irrigation technology k, the maximum total irrigation depth, $I_{jk}^m(\theta_j)$, is defined as the total amount of water over an irrigation season that produces the maximum yield $Y_j^m(\theta_j)$ when other inputs are unconstrained. I_{jk}^m also varies with local characteristics such as climate and soil type. For total amounts of applied water I_j that are less than the maximum total irrigation depth, yields will be reduced below $Y_j^m(\theta_j)$. The per unit area yields for each crop $Y_j(I_j, \theta_j)$ are between $Y_j^d(\theta_j)$ and $Y_j^m(\theta_j)$ and are given by the following production function (Martin et al., 1984, 1989):

$$Y_j(I_j, \theta_j) = Y_j^d(\theta_j) + (Y_j^m(\theta_j) - Y_j^d(\theta_j))\left(1 - \left(1 - \frac{I_j}{I_{jk}^m(\theta_j)}\right)^{1/B_k}\right) \tag{1}$$

where the parameter B_k is the technical efficiency of the farmer's irrigation system with technology k, defined as the dimensionless ratio of the water consumed by the crop in producing yields to the water delivered to the field. Because not all water delivered to the field is usable by the crop due to inefficiency of the irrigation technology, irrigation management, and the infiltration process, $B_k < 1$ and the production function is concave in applied water. If a farmer chooses to irrigate a crop on a specific field, his optimal water use in the absence of any quantity restrictions will always be less than I_{jk}^m since pumping water from the ground entails a cost.

For each field that may be irrigated using groundwater from a single well, the farmer must decide which crops to grow, what area to allocate to each crop, and how much water to apply to irrigated crops. In the setting considered in this paper, each groundwater well and associated agricultural parcel have a quantified groundwater pumping right equal to $\bar{A}\bar{I}$, where $\bar{A}$ is the total possible land area accessible by water from the well and $\bar{I}$ is the regulatory limit on annual irrigation depth. Note that $\bar{I}$ is not an upper bound on allowable irrigation depth on the entire parcel. If the farmer is constrained below the optimal irrigation depth for his land, the optimal deficit irrigation strategy may be to increase irrigation depth above $\bar{I}$ on a subset of the irrigated area, while correspondingly reducing total irrigated area and increasing dryland area (English, 2006; Connor et al., 2006). This is the actual deficit irrigation strategy observed in our study area, and is specifically addressed in our model.

Assume that the output price for crop j is p_j. Per unit transportation costs may vary by location and crop type and are given by t_j, so that $(p_j - t_j)$ is the farm-gate price. Unit irrigation water cost is $c_j^w(\theta_j)$, and crop-specific per area fixed costs of production are $F_j^i(\theta_j)$ for irrigated crops and $F_j^d(\theta_j)$ for dryland crops; these costs also depend on local characteristics. A_j^i is the area used to grow crop j using groundwater irrigation and A_j^d is the area used to grow crop j with no supplemental irrigation. Then, dropping the θ_j and k parameters for ease of notation and given fixed irrigation technology, the farmer's maximization problem is

$$\begin{aligned} \max_{I_1,\ldots,I_J,A_1^i,\ldots,A_J^i,A_1^d,\ldots,A_J^d} \quad \pi = {} & \sum_{j=1}^{J} A_j^i[(p_j^i - t_j^i)Y_j^i(I_j) - c_j^w I_j - F_j^i] + \sum_{k=1}^{J} A_k^d[(p_k^d - t_k^d)Y_k^d - F_k^d] \\ \text{s.t.} \quad & A_1^i \geq 0; \ldots; A_J^i \geq 0 \\ & A_1^d \geq 0; \ldots; A_J^d \geq 0 \\ & \sum_{j=1}^{J} A_j^i + \sum_{k=1}^{J} A_k^d \leq \bar{A} \\ & 0 \leq I_1 \leq I_1^m; \ldots; 0 \leq I_J \leq I_J^m \\ & \sum_{j=1}^{J} A_j^i I_j \leq \bar{A}\bar{I} \end{aligned} \tag{2}$$