GOVERNING A GROUNDWATER COMMONS: A STRATEGIC AND LABORATORY ANALYSIS OF WESTERN WATER LAW

ROY GARDNER, MICHAEL R. MOORE, and JAMES M. WALKER*

We examine strategic behavior in groundwater depletion within the setting of state governance of groundwater resources in the American West. Solving a dynamic common-pool resource model for its optimal solution and its subgame perfect equilibrium provides benchmarks for behavior observed in laboratory experiments. Three forms of legal rules—common-pool depletion with a "rule-of-capture" to establish ownership (absolute ownership doctrine), entry restrictions (prior appropriation doctrine), and stock quotas (correlative rights doctrine)—are examined in terms of their impact on individual strategic behavior in laboratory experiments. (*JEL* Q25, C72, C92)

I. INTRODUCTION

Between the poles of rent maximization and complete rent dissipation, wide latitude exists for institutions to manage or allocate common pool resources (CPRs) with reasonable economic performance. Two topics addressed in previous research are salient. One concerns the role of limiting entry by users into a commons. In the seminal article on the economics of CPRs, Gordon [1954] described how monopolist ownership would internalize CPR externalities, thereby creating incentives for rent maximization. Eswaran and Lewis [1984], applying a model of a CPR as a time-dependent repeated game, derived a related analytical result that the degree of rent accrual depends inversely on the number of users depleting the resource. In the context of groundwater, Brown [1974] and Gisser [1983] reasoned that existing laws restricting entry into groundwater CPRs would improve rent accrual. Empirical experience with more than five users, however, reached pessimistic conclusions in two cases. Libecap and Wiggins [1984] found that cooperative behavior in oil pool extraction occurred only with fewer than five firms. Otherwise, state law was required to coerce cooperation with roughly 10–12 firms. Indeed, with hundreds of firms operating in the East Texas oil fields there was no cooperation and, apparently, complete rent dissipation. Walker, Gardner, and Ostrom [1990] and Walker and Gardner [1992] reached a similar conclusion in analysis of data from laboratory experiments on noncooperative game CPRs. A high degree of rent dissipation or a high probability of resource destruction occurred even with access limited to eight users.[1]

The second topic concerns the ability of additional regulations or property rights, other than entry restrictions, to mitigate CPR externalities in light of noncooperative behavior. Forms of property rights, such as firm-specific fishing rights or quotas, are widely recognized as reducing or removing the incentive for a race to exploit a CPR, as in Levhari, Michener, and Mirman [1981]. Specific to groundwater, Smith [1977] recommended that rights

ABBREVIATIONS

CPR: Common pool resource
CRU: Coefficient of resource utilization

---

* Research support from USDA Cooperative Agreement #43-3AEM1-80078 and National Science Foundation Grant #SBR-9319835 is gratefully acknowledged.

Gardner: Professor, Department of Economics and Workshop in Political Theory and Policy Analysis, Indiana University, Bloomington, Ind., Phone 1-812-855-6383 Fax 1-812-855-3736, E-mail gardner@indiana.edu
Moore: Associate Professor, School of Natural Resources and Environment, University of Michigan, Ann Arbor Phone 1-313-647-4337, Fax 1-313-936-2195 E-mail micmoore@umich.edu
Walker: Professor, Department of Economics and Workshop in Political Theory and Policy Analysis, Indiana University, Bloomington, Ind., Phone 1-812-332-0466 Fax 1-812-855-3736, E-mail walkerj@indiana.edu

[1] The result that fewer than five firms are necessary for cooperation has received theoretical support from Selten [1971].

Economic Inquiry
(ISSN 0095-2583)
Vol. XXXV, April 1997, 218–234

to a share of the groundwater stock should replace Arizona's then-existing rule-of-capture, while Gisser [1983] noted that New Mexico's individual rights to annual water quantities, combined with a guaranteed time period of depletion, effectively define a share right in the stock. Both reasoned that this form of property right—stock quotas—would go far toward achieving optimal groundwater depletion.

State governance of groundwater resources in the western United States provides an institutional setting to study the effect of property rights and regulations on rent appropriation. Sax and Abrams [1986] and Smith [1989] write that, in the early- to mid-1900s, independent state authority over groundwater resulted in adoption of four distinct legal doctrines governing groundwater use in the 17 western states. Each doctrine established a set of principles directing entry and allocation rules. Further, concern about the pace of groundwater mining has spawned major legal reforms in five states within the last 25 years.[2] The reforms primarily involved adopting specific regulations that either limit entry into groundwater basins to the set of existing groundwater pumpers or define permit systems setting quotas on individuals' pumping levels, or both. The variety across states of general doctrinal principles and specific regulations creates a diverse set of groundwater property-right systems in the West.

This paper develops and empirically applies a modeling framework of governing a groundwater CPR. Section II qualitatively describes the groundwater property-right systems in the West in terms of externalities present in a groundwater commons. Following the literature on CPRs as dynamic games originating in Levhari and Mirman [1980], Eswaran and Lewis [1984], and Reinganum and Stokey [1985], section III develops a formal model in which depletion from a fixed stock is modeled as a noncooperative game. Solving the model for its optimal solution and subgame perfect equilibrium provides benchmarks for behavior observed in laboratory experiments. Section IV describes an experimental design that implements the modeling framework. The design involves three experimental treatments, all of which depict legal doctrines governing groundwater depletion. Section V presents evidence from laboratory experiments that apply the experimental design. Performance is judged by an efficiency measure, the ratio of rent earned to maximum possible rent. Given the high cost and imprecise measurement that confronts collection of field data, laboratory experiments offer a unique method for assessing the performance of various groundwater property rights and the applicability of game theory to behavior in such systems.

II. GROUNDWATER EXTERNALITIES AND WATER LAW: AN ANALYTICAL FRAMEWORK

This section develops an analytical framework to guide subsequent model development and empirical analysis.[3] It adopts the perspective that western water law developed as a response to the externality problems of a groundwater CPR. The framework isolates the key features of the major groundwater laws applied throughout the West, rather than replicating groundwater law in any particular state.

CPR Externalities

As described in Eswaran and Lewis [1984], Gardner, Ostrom, and Walker [1990], Negri [1990], and Reinganum and Stokey [1985], users depleting a CPR typically face three appropriation externalities: a strategic externality, a stock externality, and a congestion externality.[4] These externalities induce inefficiently rapid depletion or destruction of CPRs, commonly described by the adage "tragedy of the commons."

---

[2] The states are Arizona, Colorado, Kansas, Nebraska, and Oklahoma.

[3] Several previous studies also address issues related to the performance of groundwater institutions. The costliness of collecting data on groundwater use and the difficulty of applying game-theoretic models explains the overwhelming reliance in that research on analytical results (Dixon [1988]; Negri [1989]; Provencher and Burt [1993]), simulation methods (Dixon [1988]), or reasoned institutional arguments concerning the desirable properties of specific groundwater property-right systems (Anderson et al. [1983]; Gisser [1983]; Smith [1977]). For a more empirical approach, see Blomquist [1992] for an insightful investigation of groundwater institutions in southern California.

[4] Provencher and Burt [1993] also identified a risk externality that pertains to the case of agricultural irrigation using groundwater in conjunction with stochastic surface water supply. Study of the risk externality is beyond the scope of this paper.

Negri [1989] and Provencher and Burt [1993] show that groundwater depletion for irrigated agriculture creates the potential for all three CPR externalities.[5] Individual agricultural producers invest in deep wells drilled into aquifer formations, and pump groundwater from the wells for application in crop production. The strategic externality occurs because, under some legal doctrines governing groundwater depletion, water use offers the only vehicle to establish ownership. Ownership through use creates a depletion game. The stock externality occurs because, with groundwater pumping costs, individual water depletion reduces the aquifer's water-table level, thereby increasing pumping costs for all producers. The congestion externality occurs by spacing wells too closely together, with a subsequent direct loss in pumping efficiency. Thus, one producer's current effort can reduce the current output of another producer. The congestion externality, however, is not a focus of this study.[6]

Groundwater Law

A state's groundwater property-rights system consists of a general legal doctrine in combination with distinctive regulations adopted by the state when implementing the doctrine. In the authoritative source on water law, Sax and Abrams [1986] define the four legal doctrines applied to groundwater in the West:

> *Absolute Ownership Doctrine:* The "absolute ownership rule was that the landowner overlying an aquifer had an absolute right to extract the water situated beneath the parcel. No consideration was given to the fact that the groundwater extracted from one parcel might have flowed to that location from beneath a neighbor's property..." (p. 787).
>
> *Reasonable Use Doctrine*: As a minor modification of the absolute ownership rule, the "reasonable use rule may have curtailed some whimsical uses of groundwater that harmed neighbors, but it continued the basic thrust of the absolute ownership rule that treated groundwater as an incident of ownership of the overlying tract" (p. 792).
>
> *Correlative Rights Doctrine*: "The central tenets of the doctrine... are [that:] (1) the right to use groundwater stored in an aquifer is shared by all of the owners of land overlying the aquifer, (2) uses must be made on the overlying tract and must be reasonable in relation to the uses of other overlying owners and the characteristics of the aquifer, and (3) the groundwater user's property right is usufructuary" (p. 795).
>
> *Prior Appropriation Doctrine*: "As with surface streams, states that follow prior appropriation doctrine in regard to groundwater protect pumpers on the basis of priority in time... Most jurisdictions which employ the prior appropriation doctrine to groundwater protect only 'reasonable pumping levels' of senior appropriators" (p. 794). Further, again adopting a principle of the surface water appropriation doctrine, an appropriative right is established by demonstrating use of the water rather than being incidental to landownership.

Of the 17 western states, 12 apply the prior appropriation doctrine to establish basic principles of groundwater rights.[7] Texas is the only state to continue with the absolute ownership doctrine, the common-law doctrine adopted from English law. Nebraska (beginning 1982) and Oklahoma (beginning 1972) utilize general principles of the correlative rights doctrine. Arizona, a state that applied the reasonable use doctrine until recently, replaced existing law with the 1980 Arizona Groundwater Management Act. The Act primarily uses principles from the correlative rights doctrine because water scarcity is shared "equitably" among landowners. In California, groundwater management occurs at the local level, rather than at the state level. There, several local basins—including the region of the state reliant on groundwater for irrigated agriculture—operate without a legal structure to govern use.

---

[5] The model is developed for the case of irrigated agriculture because agriculture is the dominant water-consuming sector in the 17 western states. The sector commonly consumes 85% to 90% of total water consumption in those states. Groundwater provides roughly 37% of water withdrawn for irrigation, with surface water supplying the remainder (U.S. Department of the Interior [1993]). Groundwater pumping distances vary substantially depending on aquifer conditions. Over the Ogallala Aquifer in the Great Plains region, for example, average depth-to-water in the Great Plains states in 1988 ranged from 70 to 154 feet (U.S. Department of Commerce [1990]).

[6] Virtually every western state has a well-spacing statute to avoid this externality. Further, Negri [1989] notes that well spacing is less interesting in a modeling context because it does not require a dynamic model.

[7] The 12 states are Colorado, Idaho, Kansas, Montana, Nevada, New Mexico, North Dakota, Oregon, South Dakota, Utah, Washington, and Wyoming. See Grant [1981].

TABLE I
An Analytical Framework for Groundwater Law in the American West

Legal Doctrine	Analytical Element	States
Absolute Ownership	Common-pool depletion: fixed number of agents in commons	Texas; regions of California
Prior Appropriation	Entry restriction: reduced number of agents in commons	Colorado, Idaho, Kansas, Montana, Nevada, New Mexico, North Dakota, Oregon, South Dakota, Utah, Washington, Wyoming
Correlative Rights	Stock quota: property right to share of groundwater stock	Nebraska, Oklahoma

In addition to the general doctrinal principles, most western states created permit systems to administer groundwater law. Aiken [1980] and Jensen [1979] note that to implement the sharing rule of correlative rights, Nebraska and Oklahoma set annual permit levels based on an individual's share of the land overlying the aquifer. In the case of the prior appropriation doctrine, states set annual permit levels based on the pumper's historical use of water. Groundwater permits typically define an individual's maximum annual use rather than specifying a fixed level of use.

Several states with permit systems also define a planning horizon that specifies a minimum time period before exhaustion could occur. With information on the stock of water in an aquifer, individual permits can be specified to guarantee a minimum depletion period, i.e., a year through which water in the aquifer is guaranteed. For example, New Mexico designated a minimum 40-year life for some aquifers, while Oklahoma set a minimum 20-year period for its groundwater.[8]

Analytical Elements

CPR externalities in groundwater depletion lead to the problem of creating property rights that provide incentives for more efficient intertemporal depletion of stocks. As one conceivable property right, annual quotas could be assigned to users in a way that reproduces the optimal depletion path. This approach, however, is a planning solution; it requires perfect information on the part of a central planner to implement the optimal path. In contrast to the optimal program, features of existing groundwater law may partially remedy the externality problem.[9] A framework with three elements develops from the key features of groundwater law in the West (Table I). It is these three features that motivate the experimental design developed in section IV.

Common-pool depletion. The absolute ownership doctrine establishes a baseline for studying groundwater property rights. As applied in its pure form in Texas—and used implicitly in regions of California—the doctrine imposes no constraints on groundwater depletion by overlying landowners. This creates an environment for the rule-of-capture to prevail, providing depletion incentives to a fixed number of users. Rent dissipation is most likely to occur under the absolute ownership doctrine.

Entry restriction. The key feature of the widely-used prior appropriation doctrine is restricted entry of users into a groundwater commons. The doctrine gives chronologically senior pumpers security in the maintenance of "reasonable" depths-to-water. To effect this provision, in prior appropriation states, administrative agencies commonly close

---

[8] For details see Gisser [1983], Nunn [1985], and Jensen [1979].

[9] This paper does not address the role of water markets in achieving optimal groundwater allocation. Since we assume homogeneous users with stationary benefit functions, markets (or other forms of transaction) are not a necessary component of achieving optimality. Other research, such as Gisser [1983] and Smith [1977], emphasizes the importance of markets for groundwater rights.

groundwater basins to additional entrants. Moreover, groundwater users have successfully sued under the doctrine to block entry.[10] In contrast, the other legal doctrines grant entry to a groundwater CPR based solely on ownership of overlying land. Since the concept of monopolistic ownership or unitary behavior does not apply to groundwater, limited entry to the commons primarily should mitigate, as opposed to remove, the strategic and stock externalities.[11]

Stock quota. The key feature of the correlative rights doctrine is land-based apportionment of an aquifer, i.e., a user's share of the overlying land determines the share of the groundwater stock. We label this a *stock quota*: a water right that assigns an ownership share in the stock without specifying intertemporal use.[12] In practice, the states applying this doctrine—Nebraska and Oklahoma—also specify annual depletion permits. However, Smith [1989] cautions that these permits likely impose nonbinding constraints on annual use because they are based on historic use.

In terms of externalities creating CPR inefficiency, a stock quota removes the strategic externality but ignores the stock externality. That is, it ends the strategic race to capture a share of the stock, but continues the incentive to capture a *cheap* share. Nevertheless, Smith [1977][13] and Anderson, Burt, and Fractor [1983] speculate that, by removing incentives given by a rule-of-capture, a stock quota would significantly reduce the magnitude of CPR externalities in groundwater depletion.[14] This, of course, is an empirical question—one that this research addresses directly.

III. A NONCOOPERATIVE GAME MODEL OF CPR DEPLETION

In the following CPR model, we will refer to the CPR as a groundwater aquifer. Other interpretations are available, however, such as appropriation activities in forests, fisheries, and irrigation systems.

Consider an aquifer described by the state variable depth to water at time t, d_t. There are n users of the water, indexed by i. User i withdraws an amount of water x_{it} in period t. The depth to water evolves according to the following discrete time equation:

$$d_{t+1} = d_t + k\sum_i x_{it} - h. \tag{1}$$

The parameter k depends on the size and configuration of the aquifer; the parameter h represents a constant recharge rate. Here we examine the special case where $h = 0$.

We assume that water pumped to the surface is used in agricultural production. The instantaneous benefit accruing to user i at time t, B_{it}, is quadratic:

$$B_{it}(x_{it}) = ax_{it} - bx_{it}^2 \tag{2}$$

where a and b are positive constants. This implies diminishing returns to production at the surface, an assumption that accords with production experience from aquifers like the Ogallala (Kim et al. [1989]). Users are assumed to be homogeneous, so that equation (2) applies to each. Notice also that since the

---

[10] See Bagley[1961], Grant [1981], and Nunn [1985] for further discussion of these issues.

[11] With groundwater, irrigation development proceeded via settlement of arable cropland by individual farm families. The conceptual artifice of sole ownership thus lacks sufficient realism to be incorporated into this groundwater model except as a benchmark. Further, unlike oil or natural gas, the economic value of water in agriculture cannot support transportation of groundwater to distant markets. This feature, together with the high cost of negotiation relative to resource value, removes the incentive for unitization of aquifers developed for agriculture. In contrast, Libecap and Wiggins [1984] found that unitization is an incentive that operates successfully in many cases for oil fields.

[12] A second configuration of legal rules also resembles a stock quota. A permit specifying an annual limit on depletion, along with a guaranteed time horizon for use of the permit, combine to produce a stock quota. In literal terms, however, the stock quota is binding only if the annual permit is binding over the time period. Nonetheless, this configuration reinforces the need to analyze a stock quota.

[13] Smith [1977] recommended three elements to solve Arizona's groundwater mining problem: a stock quota to define a right to the groundwater stock; an annual quota to define a right to annual groundwater recharge; and water markets in which the rights could be transferred freely. The analysis here focuses on the first element. Notably, the direct connection between the correlative rights doctrine and a stock quota has not been made in the literature.

[14] A strength of a system of stock quotas is that annual depletion rates would not be specified; individual and aggregate intertemporal depletion paths would be determined endogenously. Thus, such a system would economize on an agency's information requirements relative to selecting the optimal depletion path.

parameters a and b are time independent, so is the benefit function.

The cost for user i to pump water to the surface at time t, C_{it}, depends on both water pumped to the surface and depth to water. For our purposes we use the following transformation of physical units into monetary units, measured in cents:

$$C_{it}(x_{it}, X_t, d_t) = [(d_t + AX_t + B)x_{it}], \tag{3}$$

where A and B are positive constants and X_t is the sum of all users' withdrawals from the aquifer at time t. Cost is proportional to water pumped to the surface. Cost is increasing in depth to water, and in total water pumped in a given period. The latter effect is due to the fact that depth to water increases within a period, as a function of current pumping. Given the common pool nature of groundwater, each user has an incentive to pump the relatively cheap water near the surface before others do.

Solve the depletion problem in equations (1) through (3) for its optimal solution. An authority with total control over pumping maximizes net benefits from groundwater depletion over a planning horizon of length T by solving the following optimization problem:

$$\text{maximize} \sum_i \sum_t [B_{it}(x_{it}) - C_{it}(x_{it}, X_t, d_t)]$$

subject to (1), (2), (3), the initial condition d_1, and the terminal time T. Notice that in this maximization, there is no discounting of future benefits. The solution can be easily amended if discounting is desired.

Solve this optimization by dynamic programming. Let $V_t(d_t)$ denote the optimal value of the resource at time t, given that the depth to water is d_t. The recursive equation defining the value function is given by

$$V_t(d_t) = \max \sum_i [B_{it}(x_{it}) - C_{it}(x_{it}, X_t, d_t)] + V_{t+1}(d_{t+1}). \tag{4}$$

The transversality condition for this problem is that the value of the resource after the terminal period is zero, regardless of the depth to water:

$$V_{T+1} = 0. \tag{5}$$

By varying the transversality condition (5), one can map out a variety of optimal paths.

In order for the resource to have a positive optimal value, it is necessary that the following condition on the parameters of the net benefit function (measured in cents) be satisfied:

$$a - d_T - B > 0. \tag{6}$$

It remains to find the form of the optimal value function $V_t(d_t)$. Consider the last period T. One can show, differentiating (4) and using (5), that the optimal decision in the last period is given by

$$\sum_i x_{iT} = (a - d_T - B) / (2b/n + 2A). \tag{7}$$

Further, the optimal value function (in cents) for the last period is given by

$$V_T(d_T) = 0.5(a - d_T - B)^2 / (2b/n + 2A). \tag{8}$$

One can show by mathematical induction that for any time t, the optimal decision function takes the form

$$\sum_i x_{it} = L_t(a - d_t - B), \tag{9}$$

and the optimal value function takes the form

$$V_t(d_t) = K_t(a - d_t - B)^2. \tag{10}$$

The proportionality factors L_t and K_t in equations (9) and (10) are given by the nonlinear recursive equations:

$$L_t = (1 - 2kK_{t+1}) / (2b/n + 2A - 2k^2K_{t+1}) \tag{11}$$

and

$$K_t = L_t - (b/n + A)L_t^2 + K_{t+1}(1 - kL_t)^2. \tag{12}$$

TABLE II
Backward Recursion and Optimal Solution $n = 10$

t	K_t	L_t	x_{it}	c_t	Cumulative Earnings
10	1/4	1/2	2.00	179.6	$219
9	2/6	1/3	2.00	159.6	$215
8	3/8	1/4	2.00	139.7	$207
7	4/10	1/5	2.00	119.7	$195
6	5/12	1/6	2.00	99.7	$179
5	6/14	1/7	2.00	79.8	$159
4	7/16	1/8	2.00	59.8	$136
3	8/18	1/9	2.00	39.9	$108
2	9/20	1/10	2.00	19.9	$ 76
1	10/22	1/11	2.00	0.0	$ 40

One derives the optimal solution by starting the recursion with (5), substituting into (11) to get L_T, substituting into (12) to get K_T, and working back from there to the beginning, $t = 1$. Equations (7) and (8) represent the first two steps of the solution process. For all values of the eight-dimensional parameter space $(a, b, n, A, B, k, d_1, T)$ satisfying inequality (6), one can show that the optimal solution path has each user withdrawing water at a uniform rate. This rate is such that the last unit of water withdrawn in the terminal period has zero net benefit.

For illustration, consider the parameter values chosen for our baseline design $(a, b, n, A, B, k, d_1, T) = (220, 5, 10, 0.5, 0.5, 1, 0, 10)$. For these parameters, Table II gives the backward recursion solution for the series L_t and K_t. The optimal aggregate withdrawal in the first period is given by

$$(13) \quad \sum x_{i1} = (1/11)(220 - 0.5) = 19.95,$$

whence the optimal withdrawal by each individual user is 19.95/10, or 1.995. The optimal value in cents of the entire resource, $V_1(d_1)$, from Table II, is

$$(14) \quad V_1(d_1) = (10/22)(220 - 0.5)^2 = 21900.$$

Any other withdrawal path will have a lower value. The coefficient of resource utilization, or CRU (Debreu [1951]) measures how efficiently a resource is being used. The CRU, which lies between 0% and 100%, can be expressed as the ratio of the value of the resource from any other withdrawal path to its optimal value.

Depletion patterns associated with game equilibria are important to establish benchmarks for behavior observed in the laboratory experiments. In a noncooperative game, each user maximizes his own net benefit without regard to the effect of this behavior on other users. This is the basis for the externality created when a rule-of-capture defines resource ownership. Analyze the game played by users in extensive form, and characterize its symmetric subgame perfect equilibrium. A strategy for user i, x_i, is a complete plan for the play of the game, given the history available to the player when he has to make a decision. At the beginning of the game, player i's decision, x_{i1}, is based on no history. Recall that X_t is the sum of all users' withdrawals at time t:

$$(15) \quad X_t = \sum x_{it}.$$

In the same period, user i's decision x_{i2} depends on depth to water d_2 which in turn depends on the previous period's water withdrawal. Write this dependence as $x_{i2}(X_1)$. Proceeding inductively, write a complete plan of play as

$$(16) \quad x_i = [x_{i1}, x_{i2}(X_1), \ldots, x_{iT}(X_1, \ldots, X_{T-1})].$$

Now solve the depletion game whose net benefit functions and transition equations are given by (1) through (3) for its symmetric subgame perfect equilibrium. Since the game is symmetric, it has such an equilibrium. User i

chooses his strategy x_i to maximize net benefits from groundwater depletion over a planning horizon of length T by solving the following optimization problem:

$$\text{maximize} \sum_t B_{it}(x_{it}) - C_{it}(x_{it}, X_t, d_t)$$

subject to (1), (2), (3), the initial depth to water d_1, and the terminal time T.

Solve this optimization problem by dynamic programming. Let $V_{it}(d_t)$ denote the optimal value of the resource to user i at time t, given that the depth to water is d_t. The recursive equation defining the value function is given by

$$V_{it}(d_t) = \max B_{it}(x_{it}) - C_{it}(x_{it}, X_t, d_t) + V_{it+1}(d_{t+1}). \tag{17}$$

The transversality condition for this problem is that the value of the resource to user i after time T is zero, regardless of the depth to water:

$$V_{iT+1} = 0. \tag{18}$$

It remains to find the form of the optimal value function $V_{it}(d_t)$. Consider the last period T. One can show, differentiating (17), and using (18), that the optimal decision in the last period is given by

$$x_{iT} = (a - d_T - B) / [2b + (n + 1)A)]. \tag{19}$$

Further, the optimal value function for the last period is given by

$$V_{iT}(d_T) = 0.5\,(2b + 2A)(a - d_T - B)^2 / [2b + (n + 1)A]^2. \tag{20}$$

One can show by mathematical induction that in each period, the equilibrium decision function takes the form

$$x_{it} = L_{it}(a - d_t - B), \tag{21}$$

and the equilibrium value function takes the form

$$V_{it}(d_t) = K_{it}(a - d_t - B)^2. \tag{22}$$

The proportionality factors L_{it} and K_{it} in equations (21) and (22) are given by the nonlinear recursive equations

$$L_{it} = (1 - 2kK_{it+1}) / [2b + (n + 1)A - 2k^2nK_{it+1}] \tag{23}$$

and

$$K_{it} = L_{it} - (b + nA)L_{it}^2 + K_{it+1}(1 - knL_{it})^2. \tag{24}$$

One derives the symmetric subgame perfect equilibrium by starting the recursion with (18), substituting (18) into (23) to get L_{iT}, substituting L_{iT} into (24) to get K_{iT}, and working back from there to the beginning, $t = 1$. Equations (20) and (21) represent the first two steps of the solution process.

Since this is a symmetric equilibrium, the solution for user i is the same for all users. Note that the recursive equations (23) and (24) are different from those defining the optimal solution. Thus, the subgame perfect equilibrium is not an optimum. Suppose that the program is one period long ($T = 1$). Then the equilibrium and the optimum both start at the initial depth to water d_1. Comparing (11) and (23), yields

$$nL_{i1} = 1 / \{2b / n + [(n + 1) / n]A\} > 1 / (2b / n + 2A) = L_t. \tag{25}$$

The subgame perfect equilibrium withdraws too much water. This continues to hold true more generally: the subgame perfect equilibrium path withdraws too much water in the first period regardless of the length of the game. Table III shows the subgame perfect equilibrium path using the same parameters as for Table II. The subgame perfect path is virtually exponential, thus differing markedly from the optimal path's constant depletion rate. The first two periods have high depletion rates, while later periods have almost no depletion. At this equilibrium, each user has the incentive to deplete the relatively cheap water at the top of the aquifer before other users capture it. This equilibrium naturally pro-

TABLE III

Backward Recursion and Symmetric Subgame Perfect Equilibrium $n = 10$

t	K_t	L_t	x_{it}	c_t	Cumulative Earnings
10	0.0229	0.0645	0.00	219.5	$130
9	0.0263	0.0634	0.00	219.4	$130
8	0.0268	0.0633	0.01	219.3	$130
7	0.0269	0.0632	0.04	218.9	$130
6	0.0269	0.0632	0.09	218.0	$130
5	0.0269	0.0632	0.25	215.5	$130
4	0.0269	0.0632	0.70	208.5	$130
3	0.0269	0.0632	1.90	189.5	$130
2	0.0269	0.0632	5.07	138.8	$127
1	0.0269	0.0632	13.88	0.0	$112

duces a lower payoff from the water resource. In particular (from Table III), the aggregate value in cents at the subgame perfect equilibrium is

$$(26) \qquad nK_{iT}(a - d_1 - B)^2$$

$$= 10(0.0269)(219.5)^2 = 12960.$$

Compared to the optimum, the subgame perfect equilibrium has an efficiency of 12960/21900 = 59%.

IV. EXPERIMENTAL DESIGN AND DECISION SETTING

The experimental design focuses on three conditions: (1) a baseline with no restrictions on individual levels of appropriation, group size equal to 10, and $T = 10$; (2) a treatment with no restrictions on individual levels of appropriation, but group size restricted to $n = 5$ with the terminal round extended to $T = 20$; and (3) a treatment imposing a stock quota restriction on each individual's total level of appropriation (see Table IV). The three conditions depict, respectively, common-pool depletion under the absolute ownership doctrine, an entry restriction under the prior appropriation doctrine, and a stock quota under the correlative rights doctrine.[15]

Subject i makes a decision x_{it} in each round t. The decision x_{it} is itself integer-valued with a lower bound of zero and an upper bound, if any, given by the institutions. The units of the decision are called "tokens." Payoffs according to the net benefit function are evaluated at integer values of the arguments of that function.[16]

All experiments satisfy the following net benefit function parameterizations, measured in cents:

$$a = 220,\ b = 5,\ A = .5,\ B = .5,\ d_1 = 0.$$

As discussed above, with the additional parameter $k = 1$ governing the depth to water transition equation (1), the optimal solution for the case $n = 10$ and $T = 10$ is

$$V_1(d_1) = \$219 \quad x_{it} = 2.$$

As shown in Table V, the treatment with $n = 5$ and $T = 20$ gives the same optimal value and individual withdrawal rate. The exhaustion condition is reached by half as many appropriators withdrawing the same amount of water per period for twice as many periods. Thus, holding the value of the resource con-

---

[15] The model and experiments contain a number of restrictive assumptions, including no resource recharge, no discounting, and a known finite horizon. These restrictions were made to make the model solvable and the experiment less complex. The simplicity of the design allows subjects to focus on the strategic and stock externalities without the further complexities associated with field settings. Relaxing the restrictions would allow for a richer, yet more complex, decision setting.

[16] It would have been preferable to have parameterized an experimental design with the subgame perfect equilibrium path and the optimal path each taking on integer values at each point at time. Given the complexity of this decision problem, meeting each of these criteria was impossible.

TABLE IV
Parameterization of Laboratory Experiments

	Number of Players	Number of Decision Periods	Water Use Quantity Constraints
Baseline ($n = 10$)	10	10	∞
Entry Restriction ($n = 5$)	5	20	∞
Stock Quota Rule[a]	10	10	$\sum x_{it} \leq 25$

[a]The quantity constraint for the stock quota states that accumulated multi-period water use cannot exceed a specified quantity.

stant, this parameterization allows us to investigate a pure "number of appropriators" effect.[17]

In contrast to the optimal value, the valuations generated by the subgame perfect equilibria are lower. As discussed above, for $n = 10$ and $T = 10$ the subgame perfect equilibrium reaches its maximum cumulative earnings, $130, by the fourth period, for an efficiency of 59%. For $n = 5$ and $T = 20$ the subgame perfect equilibrium reaches its maximum cumulative earnings, $136, by the sixth period, as shown in Table VI, with an efficiency of 62%. Thus, according to subgame perfection, restricting group size from ten to five players increases efficiency by only 3%.

For our parameterizations ($d_1 = 0$, $k = 1$), $d_{T+1} - d_1 = d_{T+1}$ represents the amount of groundwater ultimately pumped from the aquifer. A stock quota places an upper bound on the water an individual player can withdraw over the life of the resource. This type of quota mitigates the impact of especially high individual withdrawal paths.[18] In our experiments, the stock quota was 25 tokens per individual.[19] Note, this quota does not act as a constraint to subgame perfect equilibrium behavior, which requires only 22 tokens per individual. Placing the stock quota at a level below 22 tokens per person would artificially lead to improvements in efficiency. Our purpose was to investigate the role of a stock quota on behavior without disturbing potential equilibrium behavior.

All experiments were conducted at Indiana University. Volunteers were recruited from graduate and advanced undergraduate economics courses. These subjects were paid in cash in private at the end of the experiment. Subjects privately went through a series of instructions and had the opportunity to ask the experimenter a question at any time during the experiment. The decision problem faced by the subjects can be summarized as follows.

Each subject had a single decision to make each round, namely how many tokens to order. Each knew his/her own benefit function (expressed in equation and tabular form), and that every subject faced the same benefit function. A base token cost of $0.01 was stipulated for round 1. The instructions explained that token cost increased by $0.01 for each token ordered by the group and token cost for an individual in a given round would be the average token cost for that round times the number of tokens the individual ordered in that round. The base cost for the next round was computed by adding one to the aggregate number of tokens ordered in previous rounds, and then multiplying this total by $0.01. All subjects made purchasing decisions simultaneously. Subjects were explicitly informed of the maximum number of rounds in the experiment. After each decision round, subjects were informed of the total number of tokens ordered by the group, the cost per token for that round, the new base cost for tokens purchased in the next round, and their profits for

---

[17] Alternatively, we could have held $T = 10$ and merely reduced n to 5. This parameterization would yield an arbitrary reduction in the value of the resource. Thus, the design we investigate examines the impact of reducing the number of users in a situation where maximal resource value is held constant.

[18] Alternatively, one could investigate the impact of placing flow quotas on an individual user's per period withdrawals. Further, one could investigate an even more complex environment where flow or stock quotas are marketable. In fact, we intend to pursue these types of settings in future research.

[19] A stock quota of 20 would allow the players to follow the optimal path; 22 would allow players to follow the subgame perfect equilibrium path. In baseline experiments, subjects often ordered tokens in the last round that went beyond the economically valuable range. For comparisons, we chose a stock quota of 25 to allow this type of behavior in our stock quota design.

TABLE V

Backward Recursion and Optimal Solution $n = 5$

t	K_t	L_t	x_{it}	c_t	**Cumulative Earnings**
20	1/3	1/6	2.00	189.6	$219
19	1/4	2/8	2.00	179.6	$218
18	1/5	3/10	2.00	169.7	$216
17	1/6	4/12	2.00	159.7	$212
16	1/7	5/14	2.00	149.7	$207
15	1/8	6/16	2.00	139.7	$202
14	1/9	7/18	2.00	129.7	$195
13	1/10	8/20	2.00	114.7	$188
12	1/11	9/22	2.00	109.8	$179
11	1/12	10/24	2.00	99.8	$170
10	1/13	11/26	2.00	89.8	$160
9	1/14	12/28	2.00	79.8	$148
8	1/15	13/30	2.00	69.8	$136
7	1/16	14/32	2.00	59.9	$122
6	1/17	15/34	2.00	49.9	$108
5	1/18	16/36	2.00	39.9	$ 92
4	1/19	17/38	2.00	30.0	$ 76
3	1/20	18/40	2.00	20.0	$ 58
2	1/21	19/42	2.00	10.0	$ 40
1	1/22	20/44	2.00	0.0	$ 20

TABLE VI

Backward Recursion and Symmetric Subgame Perfect Equilibrium $n = 5$

t	K_t	L_t	x_{it}	c_t	**Cumulative Earnings**
20	0.0325	0.0769	0.00	219.5	$136
19	0.0446	0.0738	0.00	219.4	$136
18	0.0512	0.0725	0.01	219.4	$136
17	0.0541	0.0719	0.01	219.3	$136
16	0.0555	0.0714	0.02	219.2	$136
15	0.0561	0.0714	0.03	219.0	$136
14	0.0564	0.0713	0.05	218.8	$136
13	0.0565	0.0713	0.08	218.4	$136
12	0.0566	0.0713	0.12	217.8	$136
11	0.0566	0.0713	0.19	216.8	$136
10	0.0566	0.0713	0.30	215.4	$136
9	0.0566	0.0713	0.46	213.0	$136
8	0.0566	0.0713	0.71	209.5	$136
7	0.0566	0.0713	1.11	203.9	$136
6	0.0566	0.0713	1.73	195.3	$136
5	0.0566	0.0713	2.68	181.9	$135
4	0.0566	0.0713	4.17	161.0	$132
3	0.0566	0.0713	6.48	128.6	$127
2	0.0566	0.0713	10.07	78.2	$113
1	0.0566	0.0713	15.65	0.0	$ 80

TABLE VII

Overview of All Experiments

Case	**Aggregate Net Benefits**	**Efficiency**	**Periods to Exhaustion**
Optimum	$219.00	100%	10 (n = 10) or 20 (n = 5)
Baseline (n = 10)			
Base 1	$ 88.50	40%	3
Base 2	$ 38.80	18%	2
Base-Experienced	$ 69.00	32%	4
Entry Restriction (n = 5)			
Entry 1	$ 83.00	38%	6
Entry 2	$ 93.10	42%	5
Entry-Experienced	$116.30	53%	8
Stock Quota			
Stock Quota 1	$125.30	57%	7
Stock Quota 2	$128.60	59%	4
Stock Quota-Experienced	$ 98.30	45%	3

that round. Subjects were also told if the base token cost ever reached a level where there was no possibility of earning positive returns to buying tokens, the experiment would end.[20]

V. LABORATORY RESULTS AND DISCUSSION

The experimental results are drawn from nine experiments conducted over the three design conditions: (1) the baseline condition where $n = 10$ and $T = 10$; (2) the entry restriction condition where $n = 5$ and $T = 20$; and (3) the stock quota condition where $n = 10$, $T = 10$, and the stock quota is 25. In each condition, we examine results from two experiments using subjects inexperienced in the decision environment and from one experiment using experienced subjects randomly recruited from the subject pool of the inexperienced runs.

An overview of our experimental results is presented in Table VII. For each experiment, aggregate payoffs, experimental efficiency, and duration of the experiment are displayed. The set of baseline and entry restriction experiments reflect an environment in which resource use is the only way to establish ownership. As expected, paths with later exhaustion periods are typically associated with higher efficiencies. With $n = 10$, the average exhaustion round was 3; with $n = 5$ the average increased to 6.33. In the stock quota experiments, the average increased to 4.67. While increasing the life of the resource is not an economic goal per se, it does help explain the increase in average efficiency across experimental settings.

SUMMARY RESULT 1: *In each of the three baseline experiments, efficiencies were well below the efficiency level generated by the optimum and even below that generated by the subgame perfect equilibrium.*

Table VIII reports detailed results for the three experiments with $n = 10$ and $T = 10$, including the actual appropriation levels by decision round and summary statistics. In the first round of these experiments, subjects ordered on average 164 tokens, implying an average second round base cost of $1.65. This compares to an optimal order of two tokens per subject for a total order of 20 tokens in the first round and a second round base cost of $0.21. The subgame perfect equilibrium predicts an order of 14 tokens per subject for a total order of 140. This explosive appropriation of cheap tokens in the first round guarantees very low efficiencies. Efficiencies averaged only 30% of optimum.

---

[20] A complete set of instructions is available from the authors on request.

TABLE VIII

Summary Results: Baseline $n = 10$ Experiment

		Token Order by Subject Number												
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Base Cost**	**Average Cost**	**Total Order**
Experiment: Base 1 Overall Efficiency = 40.4%														
Round	1	10	22	15	6	17	22	15	10	22	15	.01	.77	154
	2	6	0	12	3	4	7	10	3	2	5	1.55	1.81	52
	3	0	0	0	0	0	0	1	2	2	0	2.07	2.09	5
Experiment: Base 2 Overall Efficiency = 17.7%														
Round	1	22	20	3	20	20	22	13	7	22	11	.01	.80	160
	2	0	6	10	10	2	14	13	10	22	3	1.61	2.00	80
Experiment: Base-Experienced-1 Overall Efficiency = 31.5%														
Round	1	10	22	16	23	15	22	17	18	14	22	.01	.90	179
	2	1	3	1	2	2	0	3	2	2	3	1.80	1.89	19
	3	1	1	1	1	1	0	1	1	1	1	1.99	2.04	9
	4	1	0	0	1	1	0	1	1	1	0	2.09	2.11	6

TABLE IX
Summary Results: Entry Restriction $n = 5$ Experiments

	Token Order by Subject Number							
	1	2	3	4	5	Base Cost	Average Cost	Total Order
Experiment: Entry 1 Overall Efficiency = 37.96%								
Round 1	15	22	5	5	22	.01	.35	69
2	10	22	8	15	22	0.70	1.08	77
3	0	3	10	18	3	1.47	1.64	34
4	5	2	4	3	2	1.81	1.89	16
5	0	1	2	6	1	1.97	2.02	10
6	0	1	1	1	1	2.07	2.09	4
Experiment: Entry 2 Overall Efficiency = 42.5%								
Round 1	22	22	15	14	22	.01	.48	95
2	14	7	20	5	8	0.96	1.23	54
3	6	4	10	4	5	1.50	1.64	29
4	2	2	9	3	4	1.79	1.89	20
5	1	2	4	1	2	1.99	2.04	10
Experiment: Entry-Experienced 1 Overall Efficiency = 53.1%								
Round 1	22	20	14	16	22	.01	.47	94
2	11	9	8	8	8	0.95	1.17	44
3	5	5	6	4	6	1.39	1.52	26
4	3	4	5	4	5	1.65	1.75	21
5	2	2	3	2	2	1.86	1.91	11
6	1	1	2	1	2	1.97	2.00	7
7	1	1	1	1	2	2.04	2.07	6
8	1	1	1	0	1	2.10	2.12	4

SUMMARY RESULT 2: *In each of the three experiments that limit entry to five players, efficiencies again were below levels generated in both the optimum and the subgame perfect equilibrium. However, the average efficiency generated by this treatment was distinctly higher than that of the baseline experiments.*

Table IX reports detailed results for the three experiments with $n = 5$ and $T = 20$. In the first round of these experiments, subjects ordered an average of 86 tokens, implying an average second round base cost of \$0.87. This compares to an optimal order of ten tokens in the first round and a second round base cost of \$0.11. The subgame perfect path predicts an order of 16 tokens per subject for a total order of 80. Efficiencies averaged 44% of the optimum.

The set of three experiments using a stock quota rule are summarized in Table X. These experiments were conducted in a manner identical to the baseline experiments where $n = 10$ and $T = 10$, except that each subject was constrained to order no more than 25 tokens over the course of the experiment. This treatment variable was announced in public.

SUMMARY RESULT 3: *In each of the three experiments using the stock quota rule, efficiencies increased markedly relative to baseline, but remained well below the optimum. Efficiencies averaged 54% of the optimum.*

In the first round of these experiments, subjects ordered on average 125 tokens, implying an average second round base cost of \$1.26. Thus, the upper bound on orders slowed down, but did not eliminate, the race to cheap water. These results call into question the optimistic conjectures made in previous research (e.g., Anderson et al. [1983]) about the ability of stock quotas to capture most of a groundwater CPR's scarcity rent.

Note that group behavior most closely resembles the subgame perfect equilibrium in the stock quota experiments. Efficiencies in experiments 1 and 2 (57% and 59%) are in

TABLE X
Summary Results: Stock Quota Rule Experiments

		Token Order by Subject Number												
		1	2	3	4	5	6	7	8	9	10	Base Cost	Average Cost	Total Order
Experiment: Stock Quota 1 Overall Efficiency = 57.2%														
Round	1	15	15	10	14	13	22	8	20	4	10	.01	.66	131
	2	2	0	4	6	6	3	2	5	5	0	1.32	1.48	33
	3	2	4	10	2	3	0	3	0	2	3	1.65	1.79	29
	4	0	0	1	2	2	0	1	0	2	0	1.94	1.98	8
	5	2	0	0	1	1	0	1	0	1	0	2.02	2.04	6
	6	0	0	0	0	0	0	1	0	0	1	2.08	2.09	2
	7	0	0	0	0	0	0	1	0	0	0	2.10	2.10	1
Experiment: Stock Quota 2 Overall Efficiency = 58.7%														
Round	1	18	15	3	10	6	13	10	6	20	5	.01	.54	106
	2	7	10	7	11	9	5	8	1	2	10	1.07	1.42	70
	3	0	0	4	3	4	2	3	2	3	4	1.77	1.89	25
	4	0	0	3	1	1	5	4	4	0	1	2.02	2.11	19
Experiment: Stock Quota-Experienced 1 Overall Efficiency = 44.9%														
Round	1	14	14	17	14	19	14	22	3	12	10	.01	.70	139
	2	6	8	8	6	5	11	3	7	6	3	1.40	1.71	63
	3	1	1	0	1	1	0	0	15	1	0	2.03	2.13	20

line with subgame perfect equilibrium efficiency (59%). In these two experiments, first-round orders averaged 11.8 tokens per subject, lower than the equilibrium prediction of 14; second-round orders averaged 5.2 tokens per subject, slightly higher than the equilibrium prediction of 5. Interestingly, it is the experienced run in the stock quota design that resulted in the poorest performance, generating an efficiency 14% below that predicted by subgame perfection. More generally, this experiment demonstrates a point that holds true across all of our experiments. Individual behavior is quite diverse. As in experiments reported by Ostrom, Gardner, and Walker [1994] and Herr, Gardner, and Walker [1995], average behavior across groups often follows a path similar to that predicted by noncooperative game theory. At the individual level, however, there is too much variation to argue strong support for the theory.

VI. CONCLUSIONS

This paper considers the depletion of a groundwater CPR within a setting of state governance of groundwater resources in the western United States. A benchmark model is constructed with a fixed stock of groundwater and fixed exhaustion time. The optimal solution and subgame perfect equilibrium provide benchmarks for efficiencies observed in laboratory experiments. Although the model and experiments are couched in terms of groundwater CPRs, the research is also informative to dilemmas encountered in other CPRs, such as forests, fisheries, and cooperative irrigation systems.

The laboratory experiments examine the effect on individual strategic behavior of three legal rules for governing groundwater depletion in the West. The experiments show the relative performance of the rules given the study parameters. Average efficiency equals only 30% in the baseline experiments, with a group size of ten players under common-pool depletion. Common-pool depletion mimics the absolute ownership doctrine, in which property rights in land also convey a right to deplete groundwater. Restricting entry to five participants, while still operating under common-pool depletion, increases average efficiency to 44%. The prior appropriation doctrine—the prevalent doctrine in use—uses entry restrictions as its main mechanism to reduce rent dissipation. A stock quota, as a replacement for common-pool depletion, increased efficiency to 54% with group size held at ten. The correlative rights doctrine effectively imposes stock quotas on landowners overlying aquifers. Although entry restrictions and stock quotas distinctly improve performance, a substantial amount of rent remains unappropriated.

REFERENCES

Aiken, J. David. "Nebraska Ground Water Law and Administration." *Nebraska Law Review*, October 1980, 917–1000.

Anderson, Terry L., Oscar R. Burt, and David T. Fractor. "Privatizing Groundwater Basins: A Model and Its Application," in *Water Rights*, edited by Terry L. Anderson. Cambridge: Ballinger Publishing, 1983, 223–48.

Bagley, Edgar S. "Water Rights Law and Public Policies Relating to Ground Water 'Mining' in the Southwestern States." *Journal of Law and Economics*, October 1961, 144–74.

Blomquist, William. *Dividing the Waters: Governing Groundwater in Southern California*. San Francisco: ICS Press, 1992.

Brown, Gardner, Jr. "An Optimal Program for Managing Common Property Resources with Congestion Externalities." *Journal of Political Economy*, January/February 1974, 163–73.

Debreu, Gerard. "The Coefficient of Resource Utilization." *Econometrica*, July 1951, 273–92.

Dixon, Lloyd S. "Models of Ground-Water Extraction with an Examination of Agricultural Water Use in Kern County, California." Unpublished Ph.D. dissertation, Department of Economics, University of California, Berkeley, 1988.

Eswaran, Mukesh, and Tracy Lewis. "Appropriability and the Extraction of a Common Property Resource." *Economica*, November 1984, 393–400.

Gardner, Roy, Elinor Ostrom, and James Walker. "The Nature of Common-Pool Resource Problems." *Rationality and Society*, July 1990, 338–58.

Gisser, Micha. "Groundwater: Focusing on the Real Issue." *Journal of Political Economy*, December 1983, 1001–27.

Gordon, H. Scott. "The Economic Theory of a Common Property Resource: The Fishery." *Journal of Political Economy*, April 1954, 124–42.

Grant, Douglas L. "Reasonable Groundwater Pumping Levels under the Appropriation Doctrine: The Law and Underlying Economic Goals." *Natural Resources Journal*, January 1981, 1–36.

Herr, Andrew, Roy Gardner, and James Walker. "Appropriation Externalities in the Commons: Repetition, Time Dependence, and Group Size." *Games and Economic Behavior*, forthcoming.

Jensen, Eric B. "The Allocation of Percolating Water under the Oklahoma Ground Water Law of 1972." *Tulsa Law Journal*, July 1979, 437–76.

Kim, C. S., Michael R. Moore, John J. Hanchar, and Michael Nieswiadomy. "A Dynamic Model of Adaptation to Resource Depletion: Theory and an Application to Groundwater Mining." *Journal of Environmental Economics and Management*, July 1989, 66–82.

Levhari, David, Ron Michener, and Leonard J. Mirman. "Dynamic Programming Models of Fishing: Competition." *American Economic Review*, September 1981, 649–61.

Levhari, David, and Leonard J. Mirman. "The Great Fish War: An Example Using a Dynamic Cournot-Nash Solution." *Bell Journal of Economics*, Spring 1980, 322–34.

Libecap, Gary D., and Steven N. Wiggins. "Contractual Responses to the Common Pool: Prorationing of Crude Oil Production." *American Economic Review*, March 1984, 87–98.

Negri, Donald H. "The Common Property Aquifer as a Differential Game." *Water Resources Research*, 25(1), 1989, 9–15.

Negri, Donald H. "'Stragedy' of the Commons." *Natural Resource Modeling*, 4(4), 1990, 521–37.

Nunn, Susan C. "The Political Economy of Institutional Change: A Distribution Criterion for Acceptance of Groundwater Rules." *Natural Resources Journal*, October 1985, 867–92.

Ostrom, Elinor, Roy Gardner, and James Walker. *Rules, Games, and Common-Pool Resources*. Ann Arbor: The University of Michigan Press, 1994.

Provencher, Bill, and Oscar Burt. "The Externalities Associated with the Common Property Exploitation of Groundwater." *Journal of Environmental Economics and Management*, 24(2), 1993, 139–58.

Reinganum, Jennifer F., and Nancy L. Stokey. "Oligopoly Extraction of a Common Property Natural Resource: The Importance of the Period of Commitment in Dynamic Games." *International Economic Review*, February 1985, 161–73.

Sax, Joseph L., and Robert H. Abrams. *Legal Control of Water Resources*. St. Paul: West Publishing Company, 1986.

Selten, Reinhard. "A Model of Imperfect Competition Where 4 Are Few and 6 Are Many." *International Journal of Game Theory*, July 1973, 141–201.

Smith, Vernon L. "Water Deeds: A Proposed Solution to the Water Valuation Problem." *Arizona Review*, January 1977, 7–10.

Smith, Zachary A. *Groundwater in the West*. San Diego: Academic Press, 1989.

U.S. Department of Commerce, Bureau of the Census. "Farm and Ranch Irrigation Survey (1988)." AC87-RS-1, 1987 Census of Agriculture, Volume 3, Part 1. Washington, D.C., May 1990.

U.S. Department of the Interior, U.S. Geological Survey. "Estimated Use of Water in the United States in 1990." USGS Circular 1081. U.S. Government Printing Office, 1993.

Walker, James M., and Roy Gardner. "Probabilistic Destruction of Common-Pool Resources: Experimental Evidence." *The Economic Journal*, September 1992, 1149–61.

Walker, James M., Roy Gardner, and Elinor Ostrom. "Rent Dissipation in Limited Access Common Pool Resource Environments: Experimental Evidence." *Journal of Environmental Economics and Management*, 19(3), 1990, 203–11.