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COOPERATIVE TECHNOLOGY SOLUTIONS TO EXTERNALITY PROBLEMS: THE CASE OF IRRIGATION WATER

by
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Working Paper No. 92-01

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Abstract

Cooperative technology improvements may ameliorate externalities, and potentially produce Pareto superior outcomes compared to noncooperative abatement strategies, but may not be adopted without appropriate institutional mechanisms. To achieve such Pareto superior outcomes, there is the need for new institutional mechanisms giving incentives for adoption of cooperative technologies. Here, the design of such institutions is proposed based on aspects of games proposed for public goods, common property resources and externality problems. Because of problems of existence of the core, a more modest solution concept -- an "acceptable cooperative solution" -- is suggested. Such a solution is unanimously preferred to the status quo and to a noncooperative "threat point."

The proposed institutional design is based on a repeated Prisoner's Dilemma game. Both noncooperative and cooperative outcomes are defined in terms of political weights on game players. Cost shares in the cooperative case are used to cover the cost of joint facilities, and Pigouvian taxes are used to give appropriate information signals. Cost shares are equal to political weights to give incentives for correct demand revelation. At the equilibrium of such a game, a set of political weights is produced corresponding to an acceptable cooperative solution.

Concepts are applied to an irrigation externality problem in the Central Valley of California to demonstrate existence of an acceptable solution.

Introduction

For externality problems, the Pigouvian tax has traditionally been proposed as a solution which, at least in theory, maximizes net social benefits, although the concept may have implementation problems (Baumol and Oates, 1989). Such a policy achieves abatement of the externality through noncooperative (private response) actions on the part of those engaged in producing externalities, presumably using existing private technologies. This paper argues that a cooperative technology solution requiring joint action is another type of solution which may produce a preferred social outcome. However, achieving such a cooperative solution may be difficult because of the need to make a cooperative agreement. This paper concerns the design of an institutional mechanism such that a cooperative technology solution would be adopted in preference to a noncooperative solution for an externality problem when it is Pareto superior.

An important type of externality problem concerns technology adoption for irrigation. Cooperative technology for irrigation is used as an example in this paper to demonstrate that cooperative solutions may be preferred to noncooperative solutions.

Irrigation water used for agricultural production under certain conditions may result in wetlands, acquifers, lakes, and rivers receiving elevated levels of pollutants such as selenium and other trace elements present in soil (SJVDP, 1990). Such pollutants can affect recreation benefits of those engaged in hunting, fishing, and bird-watching (Loomis, et al., 1991). For example, selenium is known to reduce reproduction rates of fish (Saiki, et al., 1991) and waterfowl (Skorupa and Ohlendorf, 1991). For high enough selenium levels, health effects may also occur to those who consume local water and produce. However, food consumption is not considered to be a problem for local consumers since food is usually purchased from multiple sources (Klassing, 1991). An additional associated externality is high water table which may have negative effects on production for downslope producers (Rhoades and Dinar, 1991).

Adoption of improved irrigation technologies by individual producers could improve drainage water quality alleviate water scarcity problems and also (Dinar and Zilberman, 1991). Examples of such technologies are sprinklers and drip irrigation which localize the delivery of water, as opposed to gravitational technologies such as border and furrow irrigation. Because of their increased capital and labor costs, such improved technologies may not be adopted without incentives.

Regional water management and treatment systems requiring cooperation among irrigation water users can either complement or substitute for improvements in privately applied technologies. Such systems include drainage collection, water treatment, and recycling of treated water. There may be economies of scale in the cost of achieving an improvement in water quality with a regional water system as compared to the cost of improvements in privately applied technologies. In spite of these potential benefits, a regional cooperative solution may not be achieved because of the costs associated with information and coordination, and the necessity of making agreements about the level of quality to be achieved and cost sharing to finance regional management and treatment.

Defining the appropriate tradeoff between water quality and agricultural production is a social choice problem requiring the balancing of consumer and producer interests. If externalities are severe enough, consumers may organize politically to cause regional and/or state authorities to set improved water quality standards. The countervening political power of producers limits the extent to which purely environmental objectives can be met. Even so, the policies selected by authorities should be based on appropriate economic considerations.

The problem of appropriate water management is viewed here from a mechanism design and game perspective. A case study for the San Joaquin Valley in California is used to demonstrate that a cooperative solution may be Pareto superior to noncooperative solutions to ameliorate an externality problem resulting from irrigation practices. Similar externality problems can be found in other geographic areas.

In contrast to market situations with large numbers of participants, the situation in the San Joaquin Valley involves a relatively small number of game players. Agricultural producers are organized into water districts, with a representative water board and a water district manager. The district manager has the power to set water rates and determine water use practices for the district with the acquiescence of the board. A regulatory body exists as well, namely the California Water Quality Control Board. To achieve a cooperative solution instead of a noncooperative solution, an expanded role for the district manager is suggested here: the manager will need to collect information, negotiate agreements, develop and implement procedural rules, and execute cooperative water activities.

The discussion in this paper parallels the paradigm of welfare economics for the case of perfect competition; namely for the case of an externality which may be alleviated by cooperation, the paper will define a solution concept, consider a mechanism or sequential game process which may achieve such a solution, and then show existence of a preferred cooperative solution for the particular case of irrigation in the San Joaquin Valley. An algorithm presented here to define alternative noncooperative and cooperative outcomes can be applied by a manager as part of the sequential game process.

Traditional Economic and Game Theory Solutions for Externalities and Public Goods

Traditional solutions for externality problems proposed in economic literature include use of Pigouvian taxes and Coasian bargaining.

Use of a Pigouvian tax will set the level of the externality at a Pareto optimal level for a noncooperative (private) response to externality abatement. As discussed below, the level of a Pigouvian tax here depends on the relative values and costs for consumers and producers. Therefore, preference and cost information is needed to set the tax. Traditionally (Davis and Whinston, 1962), a centralized authority (such as the regional water district manager) has been assigned the task of collecting such information and setting the tax at the level to produce Pareto optimality.

It is well-known that Coasian bargaining solutions, preceded by a necessary definition of property rights, will also achieve Pareto optimality as long as transaction costs are not too large. To reach agreements, such solutions require direct communication about values and costs for externalities. Bargaining may fail to achieve an outcome requiring joint action unless problems of achieving cooperation are specifically addressed; i.e. the problems of achieving cooperation may represent a very large transaction cost.

An example of bargaining related to the situation in this paper is the "unitization" of oil fields. Without unitization, a high rate of pumping by one firm can produce significant externality effects on the extraction of oil for other firms. Unitization is a method by which extraction is centrally managed, and all the firms must agree to share profits according to a sharing formula related to lease holdings (Wiggins and Libecap, 1985). From historical and experimental comparisons, the success of such schemes has been shown to depend on the nature of information: asymmetric information tends to lead to the breakdown of bargaining, whereas bargaining has been more successful in cases where information about lease locations is publically available (Wiggins and Libecap, 1985; Wiggins, Hackett, and Battalio, 1991).

As an alternative to markets, game theory provides a method of resource allocation in which players determine strategies consistent with their own objectives, given information and rules regarding payoffs. Cooperative and noncooperative games differ with respect to the nature of interactions among participants and related information. In a cooperative setting, to make binding agreements regarding joint action requires direct communication among participants (Bacharach).

Game theory has previously been applied to externalities and public goods separately. Here, the irrigation situation with the adoption of a cooperative technology is a combination of aspects of externalities and public goods: the definition of the level of the externality (the water quality to be achieved) must be determined in addition to how costs of joint treatment to reach this level are to be shared.

In cooperative games, cost allocation (Young; Loehman and Whinston) has been viewed as a critical aspect of cooperation. Alternative methods of cost allocation are different types of core allocations such that each participant and subcoalition of participants is better off than acting separately. Whether a core solution exists depends on the nature of cost relationships.

Literature concerning game theory applied to public goods has addressed how to determine the quantity and finance of a public good, and restrictive assumptions have been required. In order that public good quantity and cost allocation be separable decision problems, utility must be linear in the value of private goods (Bergstrom and Cornes). To show existence of the Lindahl equilibrium -- a type of solution for which tax shares are used to finance a public good (Feldman) -- marginal cost was assumed to be constant (rather than exhibiting economies of scale as in the situation here).

Recent research in public goods concerns avoiding the free rider problem by using a demand revealing mechanism, or "truth tax", to induce truthful behavior as the best strategy. As with other types of public goods, determining demand or benefits for a regional system may induce incentive problems such as free-riding. Such schemes generally do not satisfy Pareto optimality because of producing a budget surplus (Hurwicz, 1975, reported in Feldman). The advantages of using such schemes in light of their complexity has been debated (Roth, 1985).

Little attention has been given to alleviating externality problems in a cooperative game setting. Game theory applied to two firms shows that the maximum of joint profits for firms involved in externalities may be achieved through a taxation scheme as long as there is not a bilateral externality (Bacharach; Davis and Whinston). Another view stated by Samuelson (1985) is that with information asymmetry "the parties affected by an externality will, in general, be unable to negotiate efficient agreements...". Also, the core of an externality game may not exist when there are more than two players (Shapley and Shubik, 1969). A focus in more recent externality literature, as in the public goods literature, has been on the need for a demand-revealing process to elicit truthful information about values (Groves).

In summary, results concerning the possibility of solving externality problems by traditional economic and game methods is largely negative unless information problems can be solved and gains from cooperation are evident to those participating.

Definition of a Mechanism Leading to a Cooperative Solution

The mechanism to be defined here uses a manager as an integral part of the game to ease information problems and to facilitate determination of the existence of socially preferred outcomes. The process involves searching among pairs of noncooperative and cooperative outcomes until a socially preferred cooperative outcome is found (if this is possible).

Here, pairs of cooperative and noncooperative outcomes represent alternative technology solutions to the externality problem; these pairs are defined in terms of political weights as described below. A noncooperative outcome, imposed through taxes on water and land use, is a reference point or "threat point" (Thompson, 1981; Friedman,1986) if the cooperative outcome is not agreed to. The equilibrium of this process produces a set of political weights corresponding to a cooperative outcome (if it is socially preferred). These weights are also the cost shares for financing joint facilities for incentive compatibility reasons. Below, aspects of this mechanism are described in more detail.

The proposed process is based on a repeated Prisoner's Dilemma game. The Prisoner's Dilemma has been applied to many institutional settings (Schotter, 1981). The choice between cooperation and no cooperation in the Prisoner's Dilemma depends on the relative payoffs for the cooperative and noncooperative cases. Therefore, one problem here is to define the appropriate payoff structure to lead to the eventual selection of a cooperative outcome. An algorithm for this purpose is described below.

Application of game theory to real world problems has been limited because of the problem of representing preferences in common monetary units. Here, producer payoffs are naturally defined as profits. Following recent environmental literature, the concept of equivalent variation (EV) is used to represent consumer preferences for environmental quality in monetary terms. This type of information can be obtained through surveys (see Loomis, 1990 for the values used here) although there is some controversy about the validity of willingness to pay data.

Political Weights and Choice Among Solutions

Any noncooperative solution can be interpreted in terms of the relative political power of persons or interest groups in determining the social outcome. For example, the status quo point (SQ) in Figure 1 corresponds both to a point on the production possibility frontier (in quantity space) using current private water use technologies and to a point are the payoff possibility frontier which maximizes agricultural profit ($\Sigma\pi$) with a zero weight on consumer environmental benefits (EV). An improved water quality corresponds to a greater weight on consumer environmental benefits. The point along the noncooperative frontier most preferred by consumers is denoted by CP. A noncooperative political solution NC is between SQ and CP. Such a solution is associated with a set of political weights indicated by the slope of the possibility frontier at the chosen point.

Any solution on the noncooperative production frontier could be achieved as a noncooperative Nash equilibrium in which private technologies are chosen by profit maximizing decisions by individual producers in response to Pigouvian taxes. There is a noncooperative Nash equilibrium solution and corresponding Pigouvian taxes for each set of political weights.

Cooperative technologies such as a regional treatment plant may allow improved drainage water quality to be obtained without a decrease in agricultural output; in such cases a cooperative solution would lie outside the noncooperative production possibility frontier and, as discussed by Samuelson, (1950), an expanded production frontier should be socially preferred because all interest groups (producers and consumers) would have the potential of being made better off.

However, in the cooperative case, technology improvements which are technically more efficient may not be Pareto preferred. Points on the

Figure 1. Noncooperative Production Frontier related to Pareto Optimality and Political Weights.

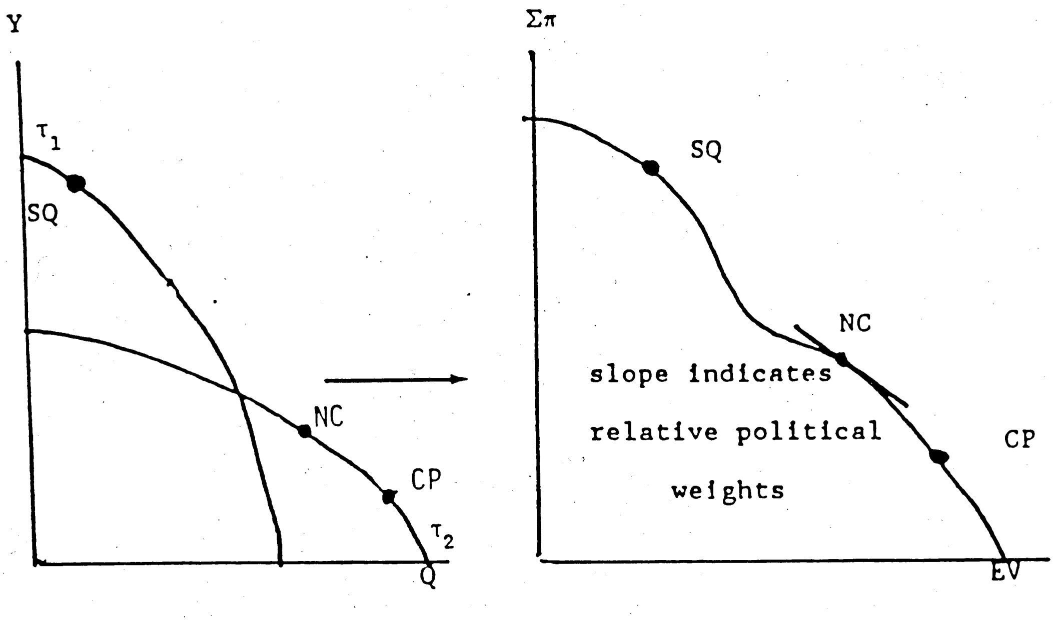
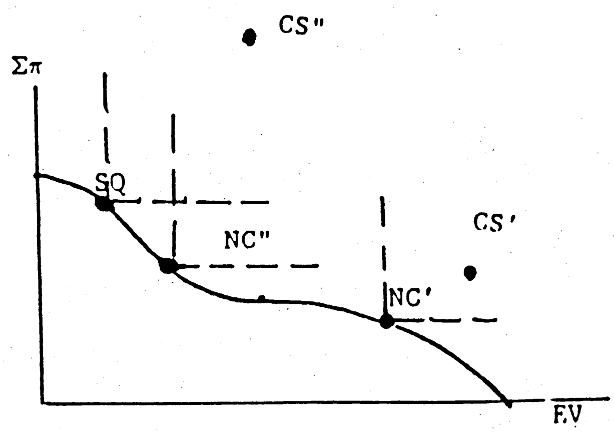


Figure 2. Acceptable and Unacceptable Cooperative Solutions



payoff possibility frontier corresponding to cooperative technologies cannot be specified without defining the costs shares to be paid by each party. Therefore, the correspondence between the two frontiers depends on the method of cost allocation.

A technically efficient cooperative solution may not be a Pareto improvement once cost shares are considered. (See Appendix A.) Joint costs incurred to improve water quality to make consumers of recreation better off would generally make producers worse off compared to the status quo unless an efficiency improvement with the cooperative technology offsets additional costs.

If cost shares for producers in a cooperative solution are less than taxes in a noncooperative case and agricultural output is not diminished in the cooperative solution, then the cooperative solution would be preferred to the noncooperative solution by producers. However, without some sharing of joint cost by consumers, it may not be possible to find a cooperative solution which is preferred by producers to the status quo.

Consumers will generally be better off in a noncooperative solution with improved water quality than at the status quo. However, consumers may prefer a noncooperative to a cooperative solution (since no cost sharing is required in the noncooperative case) if their share of joint costs is too large. The problem of finding a Pareto superior cooperative solution is to determine whether there are outcomes which are improvements for both consumers and producers given cost sharing rules.

Definition of an Acceptable Solution

Because of potential problems with subcoalition formation and existence of the core, this paper proposes use of a weaker solution concept. The proposed solution concept satisfies a necessary condition for the formation of "the grand coalition," namely that each player be better off than acting individually. However, core conditions for benefits for each subcoalition are ignored. The rationale for ignoring formation of subcoalition is that high information costs may be associated with subcoalition formation.

Information problems for the grand coalition can be reduced by the presence of a regional manager who can collect information as one part of management duties.

The solution concept proposed here is called an "acceptable cooperative solution". A "threat point" for a cooperative solution is a noncooperative solution representing the same political power for game participants as the cooperative solution (explained below). An acceptable cooperative solution should satisfy the following properties:

(i) each player is better off than at the status quo;

(ii) each player is better off than at the noncooperative solution;

(iii) joint costs are covered by cost shares paid by players.

That is, the acceptable cooperative solution would be voluntarily adopted, compared to both the noncooperative solution and the status quo, because all participants in the grand coalition are made better off.

Figure 2 illustrates two possible cases in the comparison of a cooperative solution and a noncooperative solution. In the first case, the cooperative solution (CS') is preferred to the noncooperative solution (NC') but is not Pareto superior to the status quo, because it is too expensive for producers, after joint costs are shared according to a specified rule, to produce a gain for each player relative to the status quo. The second case (CS") is an "acceptable cooperative solution" in which all parties are better off compared to the status quo and to the noncooperative solution (NC").

Here, existence of an acceptable solution is not generally guaranteed because of nonconvexities associated with externalities (Starrett) and economies of scale (Calsamiglia). There may be no acceptable solution or there may be multiple solutions. Therefore below, we demonstrate the existence of an acceptable cooperative solution for an empirical example representative of the situation in the San Joaquin Valley.

Principles of Mechanism Design Applied to the Externality Problem

Here, as in other cases of "nonclassical environments", game theory and mechanism design principles are the basis for designing institutional arrangements. The desired outcome for the proposed sequential game is that an equilibrium be an acceptable cooperative solution, as defined above, if such a solution exists.

Generally, the goal of resource allocation is to achieve social efficiency (Bohm, 1973). Mechanism design (Hurwicz, 1972) refers to the design of organizational structure, allocation rules, and information systems to achieve a desired social outcome. In mechanism design, social efficiency is defined more broadly -- not only in terms of Pareto optimality and technical efficiency -- but also in terms of minimizing the social costs associated with information collection and enforcement of agreements.

Principles for design of resource allocation systems were first defined by Hurwicz (1972) for "nonclassical environments" by generalizing from the characteristics of a market mechanism operating under perfect competition. Preferred characteristics of mechanisms identified by Hurwicz are: incentive compatibility, individual rationality, information decentralization, unbiasedness, and nonwastefulness. "Nonwastefulness" refers to being on the production frontier. "Unbiasedness" refers to having the possibility of achieving any Pareto optimum by a lump sum redistribution of income. (To apply "unbiasedness" to our externality case, consumers could be given lump sum income supplements to ease budget constraints to enable them to pay a greater share of joint costs.)

In general, once conditions of perfect competition do not hold, it is not possible simultaneously to minimize the social costs of waste, information, and enforcement (Feiwel). That is, complete information decentralization is not possible in nonclassical environments such the cases of externalities and public goods.

The design of the sequential game process proposed here draws on several previously proposed games including repeated Prisoner's Dilemma games (Rosenthal, 1981; Axelrod, 1984), Lindahl equilibrium (Feldman, 1980; Binger and Hoffman, 1987), games of fair division (Friedman and Rosenthal, 1986), alternating offer games (Rubenstein, 1982; Osborne and Rubinstein, 1990), and contracting models (Hackett, 1991).

In addition to cost shares, Pigouvian taxes are used to make individual producer resource decisions correspond to the desired social outcome for both the cooperative and noncooperative cases. In the cooperative case, taxes are used to help finance joint costs. With economies of scale, joint costs will not be fully covered by tax revenues, so cost sharing is still required.

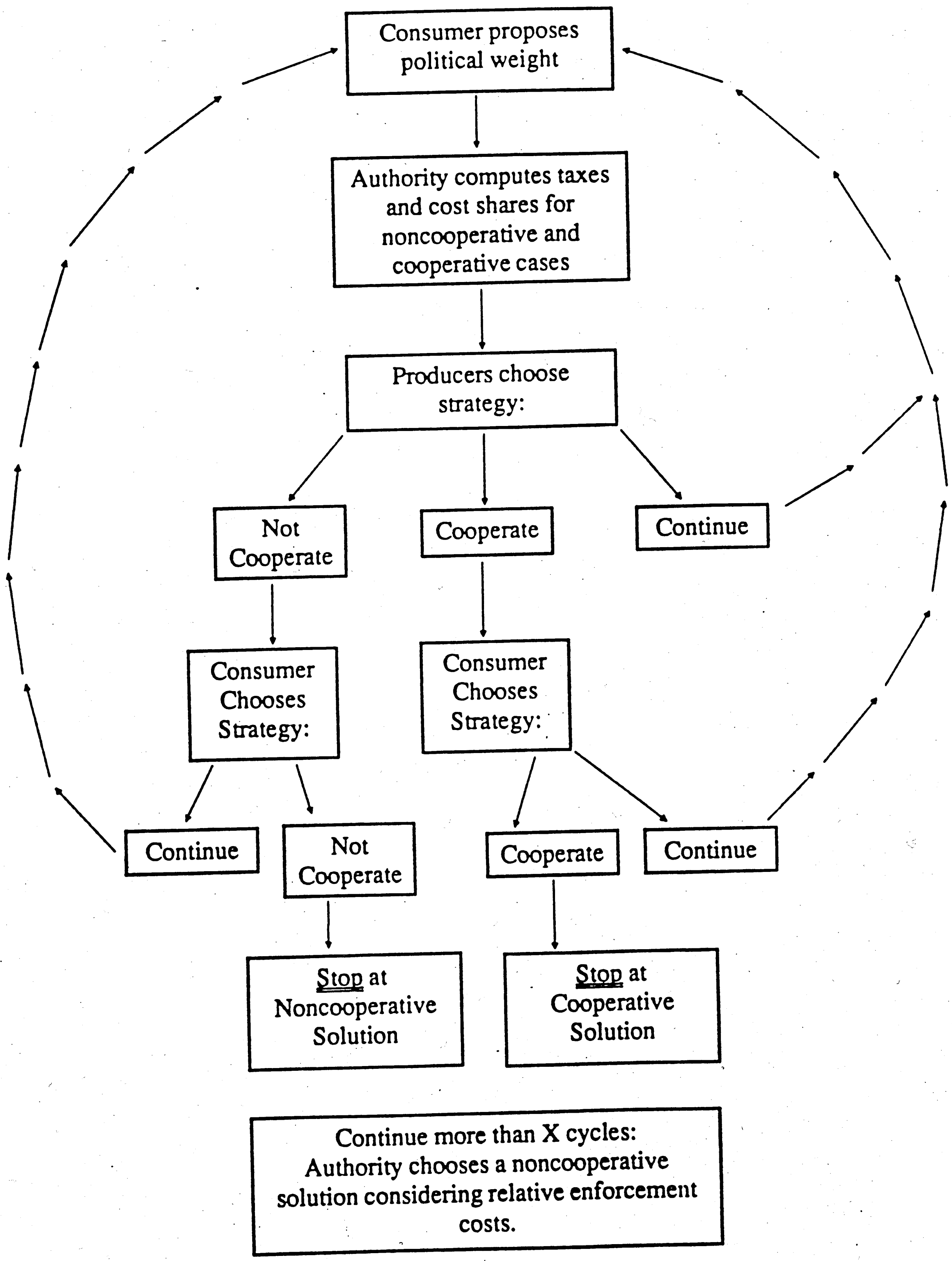
Figure 3 illustrates the sequential nature of the proposed game. To begin the game, one player announces a political weight to be placed on that player's payoff function. If the consumer is the first player, the consumer first announces the political weight to be placed on the consumer's payoff function (using a representative consumer). Producers may be weighted equally (this could be modified to vary by characteristics such as land ownership) so that the selection of a weight for the consumer would then determine the weight for producers. At this point, actual costs and taxes may not yet be known to the participants.

Given a set of weights, corresponding Pigouvian taxes and cost shares are then computed by the manager. Producers then choose between the given noncooperative and cooperative outcomes. If neither outcome is attractive to producers in comparison to the status quo, then game can continue by revising political weights.

Depending on the producers' choices between cooperation, noncooperation, and continuation, and given cost share information, the consumer again chooses whether or not to cooperate or to continue by revising political weights. If all parties agree to cooperate for a given

Figure 3

Cooperative Weight Determination Game



set of weights, then the game stops at the cooperative solution. If such a process stops at a cooperative solution, the resulting equilibrium is an acceptable cooperative solution as defined above. If all agree not to cooperate rather than to continue, then the process stops at a noncooperative solution.

As in the contracting case (Hackett, 1991), the disintegration of the bargaining process may occur even when there are weights which would produce mutual benefits if there is uncertainty about the existence of mutually beneficial outcomes.

If no equilibrium is found after a number of continuation cycles, a noncooperative solution could be imposed by the regional manager, chosen in accordance with management and enforcement costs. Knowing that such an event may happen -- but not which noncooperative outcome would be chosen -- would give additional incentive for players to locate an acceptable cooperative solution.

The voluntary choice between pairs of cooperative and noncooperative solutions is related to a repeated Prisoner's Dilemma game. This problem is usually used to demonstrate that a noncooperative solution may be chosen over a cooperative solution even when the cooperative solution is Pareto optimal. In spite of gains from cooperation, the selection of noncooperation over cooperation may occur if there is no communication among players and there are no incentives to cooperate or penalties for noncooperation beyond the relative payoff values (Oppenheimer, 1990).

Here, the activities of the regional manager may ameliorate the Prisoner's Dilemma and bargaining problems. The manager acts as a mediator during the process of finding political weights corresponding to an acceptable solution. The regional manager also computes Pigouvian taxes and cost shares for each proposed set of political weights for cooperative and noncooperative solution pairs. The activities of the regional manager will therefore reduce transactions costs of bargaining and provide information about the benefits of cooperation.

Once a cooperative agreement is obtained, the manager is also responsible for implementing the cooperative solution in terms of operating joint facilities, collecting taxes and cost shares, and monitoring activities for compliance with the agreement. Therefore, the regional manager has a much more important role in the proposed game than the "central authority" in traditional Pigouvian externality solutions.

Joint Cost Allocation and Political Weights

An important part of the cooperative game rules is to define how joint costs will be apportioned among consumers and producers. Here, it is proposed that joint costs be allocated according to shares (similar to a Lindahl game). Setting shares equal to political weights gives an incentive compatiable rule. If the consumer's share of the joint costs is equal to the consumer's political weight, a greater weight in determining the tradeoff between water quality and agricultural profit along the production frontier will also imply a larger share of joint cost. If a smaller cost share is desired by consumers, then less weight will also be placed on consumer interests in defining the joint outcome.

Other more complicated cost allocation schemes have been proposed in game theory literature; such procedures have desirable properties such as fairness (Young). In comparison, the shares procedure is relatively simple and it can also correspond to core solutions (Loehman, 1985).

Here, tax revenues are used in the cooperative case to reduce the joint costs to be covered by cost shares. Tax revenues by law must be used within the water district since a water district is non-profit. Tax revenues should not be given back to producers directly, because then there would be no incentive to adopt improved technologies. Tax revenues should also not be used to compensate consumers directly because then consumers would have incentives to overstate their political weights (Baumol and Oates, 1989). Also, if tax revenues are used to compensate the regional manager, his/her incentive for finding a cooperative solution would be reduced.

Algorithm for Noncooperative and Cooperative Outcome Pairs

Here, we present an algorithm to determine noncooperative and cooperative outcome pairs for each set of political weights. The irrigation situation is a simplified representation of that in the San Joaquin Valley of California. Two producers (upslope and downslope) and one consumer represent others in the geographic area.

Below, payoff functions and production constraints are described as related to pollution load (inversely related to water quality) and production. Separate optimization problems are defined for noncooperation and cooperation outcomes for each set of political weights. The two optimization problems can be solved for varying political weights, making corresponding tax and cost share computations, to determine whether an acceptable solution exists for any set of weights.

Producers' Payoffs

Below, irrigation technology is represented by a continuous index variable τ such that higher levels denote improved technologies which are also more costly. (The "Christiansen Uniformity Coefficient" for irrigation is such an index; Dinar and Zilberman, 1991.)

Profit for each type of producer (upslope -- π^u; downslope -- π^d) is revenue from production minus: annual fixed costs per acre for water technologies used, denoted by $F(\tau^i)$ for technologies τ^i for each type of producer (i=u,d); variable water-related production costs ($v(\tau^i)$ per unit of water); and taxes for water and land use (t_ω^i, t_ℓ^i, i=u,d). In the status quo case (denoted by π_o^i), there are no taxes. Water and land constraints are represented by $\overline{W}^i$ and $\overline{A}^i$.

The upslope producer's yield (Y^u) per unit land area is related to the irrigation technology (τ^u) and water use (w^u) per unit land area:

$$Y^u = Y^u(w^u;\ \tau^u). \qquad (1)$$

The upslope producer maximizes profits by choosing acres planted in each crop (A^u), total water use for each crop (W^u), and irrigation technologies. Water use per acre (w^u) is determined by W^u and A^u. The profit maximization problem is:

$$\max_{\tau^u, W^u, A^u} \ [p_f Y^u - v(\tau^u)w^u - F(\tau^u) - t_\ell^u]\, A^u - t_\omega^u\, W^u \qquad (2)$$

$$\text{s.t.} \quad A^u \leq \overline{A}^u$$

$$w^u A^u = W^u \leq \overline{W}^u$$

$$Y^u = f(w^u; \tau^u).$$

(To represent several crop activities and technologies, Y, w, A, and τ can be vectors.)

The downslope producers' yield is also related to water use per acre (w^d), the irrigation technology used, but is also affected by the externality due to the water use of the upslope producer. Drainage caused by total water use of upslope producers will reduce yield of downslope producers if there is excess water and salinity in the root zone. A factor (k) adjusts for the amount of water received downslope, where $0 \leq k \leq 1$:

$$Y^d = Y^d(w^d, kW^u; \tau^d). \qquad (3)$$

The proportion k depends on the topography, soil type, and upslope technologies.

The downslope producer chooses total water use, acres planted, and irrigation technology to maximize profit. The optimization problem for this producer is similar to the above:

$$\max_{\tau^d, W^d, A^d} [p_f Y^d - v(\tau^d)w^d - F(\tau^d) - t_\ell^d] A^d - t_\omega^d W^d \qquad (4)$$

$$\text{s.t.} \quad A^d \leq \bar{A}^d$$

$$w^d A^d = W^d \leq \bar{W}^d$$

$$Y^d = f(w^d, kW^u; \tau^d).$$

Pollution Impacts

Total pollution reflects the effects of both upslope and downslope producers' land, water, and technology decisions. Pollution (S^u) produced by the upslope producer can be described by

$$S^u = \delta^u(\tau^u) W^u; \qquad (5)$$

that is, pollution is proportional to the total amount of water used depending on the water technology and the topography and soils. The downslope producer's own effect on pollution is similarly represented, except that the resulting pollution includes both effects from his/her own water use and the drainage from the upslope producer:

$$S^d = \delta^d(\tau^d) (W^d + kW^u). \qquad (6)$$

The total pollution load (S) is the sum of S^u and S^d:

$$S = S^u + S^d. \qquad (7)$$

A tax could be assessed per unit of pollution load, but because of information problems associated with nonpoint source pollution, land and water are more easily taxed than pollution load if physical relationships such as (1), (3), (5), and (6) are known.

Consumers' Payoffs

Preferences of consumers are usually represented by a utility function which, because utility is not in dollar units, is not directly comparable to producer profits. The equivalent variation provides a dollar measure of welfare which gives the same ranking of outcomes as utility (McKenzie).

The expenditure function is defined from the indirect utility function:

$$\bar{U} = \bar{U}(M, S, p_f, p_h, p_r, p_z) \qquad (8)$$

where M denotes initial wealth or income, S denotes pollution, and p_i, i = f,h,r,z denote respectively prices of food, health, recreation, and other goods (Loehman, 1991). Reduction of drainage water or improvement of its quality would improve consumer welfare. The amount of money (EV) which is equivalent to a change in pollution load satisfies the following relation when the pollution level is reduced from S^o to S' with $S^o > S'$:

$$\bar{U}(M + EV, S^o, p_f, p_h, p_r, p_z) = \bar{U}(M, S', p_f, p_h, p_r, p_z). \quad (9)$$

The equivalent variation is an implicit function of initial drainage water quality, change in water quality, income, and prices. Note that $\partial EV/\partial S < 0$, i.e. as the pollution load decreases, the equivalent variation increases. To define net consumer benefit in income terms when water quality improves with a cost share to be paid by consumers, EV will be reduced by the amount of the cost share.

We will assume that the market for products grown in the region is open so that food prices are not affected by changes in technology.

The Noncooperative Solution and Corresponding Pigouvian Taxes

The optimization problem solved for the noncooperative solution (following welfare economic formulations of Pareto optimality such as Negishi, 1960) is to maximize the weighted sum of payoffs subject to production and pollution constraints. The weighted sum of payoffs for consumers and producers is maximized over the set of private water technologies, acres planted, and water use for each producer. Constraints for the joint maximum problem include water and land constraints, and yield and pollution production functions. The resulting optimal pollution level and profits are a function of the political weights α.

$$JW(\alpha;NC) = \max_{\substack{A^u, A^d, \\ \tau^u, \tau^d, W^u, W^d}} \alpha_c EV(S;\ S^o) + \alpha_u[p_f Y^u - F(\tau^u) - v(\tau^u)w^u]A^u$$

$$+\alpha_d[p_f Y^d - F(\tau^d) - v(\tau^u)w^d]\ A^d$$

$$\text{s.t.}\quad A^u \leq \bar{A}^u \tag{10}$$

$$A^d \leq \bar{A}^d$$

$$w^u A^u = W^u \leq \bar{W}^u$$

$$w^d A^d = W^d \leq \bar{W}^d$$

$$S^u = \delta^u(\tau^u)\ W^u$$

$$S^d = \delta^d(\tau^d)\ (W^d + kW^u)$$

$$S = S^u + S^d$$

$$Y^u = Y^u(w^u;\tau^u)$$

$$Y^d = Y^d(w^d,\ kW^u;\tau^d).$$

The multipliers μ^i associated with the water constraints $\overline{W}^i$ denote marginal cost; μ^i will be zero if water constraints are met. Denote the above expressions for profits before taxes for upslope and downslope producers by $\hat{\pi}^u(\alpha)$, $\hat{\pi}^d(\alpha)$.

Pigouvian taxes to achieve a given noncooperative equilibrium are found from the first order conditions for the noncooperative joint maximum problem; they also depend on political weights. The Pigouvian taxes (t^i_ω, t^i_ℓ) on water and land use are the right hand sides of the expressions below, derived from first order conditions evaluated at the optimum technologies and water and land use:

$$\frac{\partial \hat{\pi}^u}{\partial W^u} = \frac{\mu^u}{\alpha_u} - \frac{\alpha_c}{\alpha_u} \frac{\partial EV}{\partial S} (\delta^u + \delta^d k) - \frac{\alpha_d}{\alpha_u} \frac{\partial \hat{\pi}^d}{\partial W^u}; \tag{11}$$

$$\frac{\partial \hat{\pi}^d}{\partial W^d} = \frac{\mu^d}{\alpha_d} - \frac{\alpha_c}{\alpha_d} \frac{\partial EV}{\partial S} \delta^d. \tag{12}$$

$$\frac{\partial \hat{\pi}^u}{\partial A^u} = \frac{\lambda_u}{\alpha_u} - \frac{\mu^u}{d^u} w^u \frac{\alpha_c}{\alpha_u} \frac{\partial EV}{\partial S} (\delta^u + \delta^d k) w^u - \frac{\alpha_d}{\alpha_u} \frac{\partial \hat{\pi}^d}{\partial A^u} \tag{13}$$

$$\frac{\partial \hat{\pi}^d}{\partial A^d} = \frac{\lambda_d}{\alpha_d} - \frac{\mu^d}{\alpha^d} w^d \frac{\alpha_c}{\alpha_d} \frac{\partial EV}{\partial S} \delta^d\, w^d. \tag{14}$$

λ_u and λ_d represent land rental values. Because of the external cost on the downstream producer, even if land rent values and water allocations are equal for upslope and downslope producers and the weights α_u, α_d are equal, the upslope producer should pay a higher tax per unit than the downslope producer because of the additional externality effect on the downslope producer.

Net profits for the noncooperative solution for a given set of weights α are obtained by subtracting taxes from profits $\hat{\pi}^i$ in the joint maximum:

$$\pi^u(\alpha;\ NC) = \hat{\pi}^u(\alpha) - t^u_\omega(\alpha;\ NC)\ W^u - t^u_\ell(\alpha;\ NC)\ A^u \tag{15}$$

$$\pi^d(\alpha;\ NC) = \hat{\pi}^d(\alpha) - t^d_\omega(\alpha;\ NC)\ W^d - t^d_\ell(\alpha;\ NC)\ A^d \tag{16}$$

Each producer will then make individual decisions corresponding to the noncooperative joint solution when solving (2) and (4). Water and land use are reduced by the taxes compared to that for the status quo since the status quo solution satisfies $\frac{\partial \hat{\pi}^i}{\partial W^i} = 0$ and $\frac{\partial \hat{\pi}^i}{\partial A^i} = 0$.

The Cooperative Solution

In the cooperative case, regional cooperative technologies are available in addition to the private technologies used in the noncooperative case. Regional water technology improvements in the cooperative case could include regional drainage systems, regional water treatment plants, technical advice for operation of more sophisticated private technologies, regional systems for storage and reuse of treated water, etc. The algorithm below for the cooperative case defines an optimization problem over technologies independent of the cost sharing method. Cost allocation can then be determined ex post.

The objective function is the weighted sum of payoffs minus joint cost (JC):

$$JW(\alpha; CS) = \max_{\substack{W^u, W^d, A^u, A^d, \\ W^{CS}, \tau^u, \tau^d, \tau^R}} \alpha_c EV(S; S^o) + \alpha_u [p_f Y^u - F(\tau^u) - v'(\tau^u, \tau^R) w^u] A^u \tag{17}$$

$$+ \alpha_d [p_f Y^d - F(\tau^d) - v'(\tau^d, \tau^R) w^d] A^d - JC(S, W^{CS}; \tau^R).$$

$$\text{s.t.} \quad A^u w^u = W^u \leq \bar{W}^u$$

$$A^d w^d = W^d \leq \bar{W}^d$$

$$A^u \leq \bar{A}^u$$

$$A^d \leq \bar{A}^d$$

$$W^u + W^d \geq W^{CS}$$

$$S^u = \delta^u(\tau^u) W^u$$

$$S^d = \delta^d(\tau^d) (W^d + kW^u)$$

$$S = S^u + S^d$$

$$Y^u = Y^u(w^u; \tau^u)$$

$$Y^d = Y^d(w^d, kW^u; \tau^d).$$

The solution to (17) will satisfy a necessary condition for acceptability. (See Appendix A for a discussion of alternative optimization problems and their relationships.)

Regional cooperative technologies are denoted by τ^R. The joint regional cost of treating and reusing water is a function of polution load and water treated denoted by $JC(S, W^{CS}; \tau^R)$. Variable charges associated with water use (v'), may be less than in the corresponding noncooperative solution because the recycling of drainage water can reduce the marginal cost of water supply, and management cost per unit of water can also be reduced through cooperation.

As in to the noncooperative solution, applying Pigouvian taxes to land and water use will make private decisions about individual land and water use consistent with the joint welfare maximum. As above, tax levels are computed from first order conditions as related to political weights. In addition to externality effects, the tax now also includes marginal (variable) cost for the joint facility.

With economies of scale in treatment, joint costs are not covered by such taxes, so that cost sharing is still necessary to cover costs. Here, cost shares (C^i) of the remaining cost are computed after solving the optimization problem and subtracting taxes from joint costs, where TR denotes total tax revenue collected from the Pigouvian taxes:

$$C^i = \alpha_i [JC\text{-}TR], \; i = c,u,d. \tag{18}$$

Irrigation Externality Application

Applying the algorithm above, we present a simplified example from the San Joaquin Valley to demonstrate that it is possible to find a set of political weights corresponding to an acceptable cooperative solution. Knowledge that an acceptable solution exists, shown in an example below, may be relevant for the success of a negotiating process such as that proposed above.

Upslope and downslope producers grow one crop (cotton) with yield related to water use including the downslope externality effect of drainage water. Two irrigation technologies are included here at the individual producer level: technology 1 -- furrow irrigation, and technology 2 -- sprinklers which reduce irrigation water use and drainage generated for the same amount of water applied because of better distribution of water. Use of sprinklers requires less water per unit ouput but involves higher capital and labor costs because it is a more complex technology. Private technology choices exhibit indivisibilities or "lumpiness" because they must be done on large acre units (here, 100 acre increments).

The type of regional cooperation is a treatment plant to remove selenium (Se). There are economies of scale in the volume of drainage water treated. The regional treatment plant reduces selenium concentration by passing drainage water over iron filings. Better quality is produced by multiple passes over iron filings. The final output has a fixed quality per unit volume. Regional cooperation also reduces the variable cost of use of private sprinklers because the regional manager provides technical assistance to reduce labor costs.

Water from the treatment plant is disposed of in a water-receiving body which is the source of recreation and fishing for consumers in the area. Increased selenium concentration means decreased quality in this water body. The functional relationships defining yield, pollution, effects of selenium on fish and wildlife, and the consumers' equivalent variation are given in the Appendix B.

Producers respond to taxes on water and land by making changes in area of irrigated land, per acre applied irrigation water, and the share of the two technologies used on the irrigated land. In the case of regional cooperation, drainage water is sent through the treatment plant before disposal in a water-receiving body; the whole volume of drainage may not be treated.

Table 1 compares resource use for noncooperative and cooperative solutions as related to political weights, computed according to the algorithm above. For the cooperative solutions, the treated quantity is about the same for all weights but total drainage quantity is reduced as the consumer weight increases because of increased use of the sprinkler

Table 1. **Resource Use for Noncooperative and Cooperative Solutions, as Related to Political Weights.**

Consumer Weight	% Share, Tech 2 upsl.	% Share, Tech 2 downsl.	Water Use (ac/ft/acre) upsl.	Water Use (ac/ft/acre) downsl.	Drainage Quantity (ac/ft.)	Se Conc. (ppb)
			Noncooperative Solution			
.60	79	87	1.80	1.83	1173	22.14
.50	77	86	1.76	1.82	1300	23.54
.42	74	81	1.76	1.74	1410	25.64
.40	74	81	1.76	1.74	1410	25.64
.33	63	77	1.56	1.69	1517	26.44
0	58	67	1.58	2.00	1824	31.95
			Cooperative Solution			
.60	91	90	1.83	1.91	787	14.43
.50	91	88	1.82	1.88	987	15.43
.42	87	86	1.81	1.88	999	15.64
.40	87	86	1.81	1.88	999	15.64
.33	82	77	1.70	1.85	1020	22.55

technology. Therefore, as the consumer weight is increased, a lower pollution level in the water receiving body is obtained. (The volume of water treated at the regional plant is actually slightly less for higher consumer weights because improved water utilization reduces the need for treatment.)

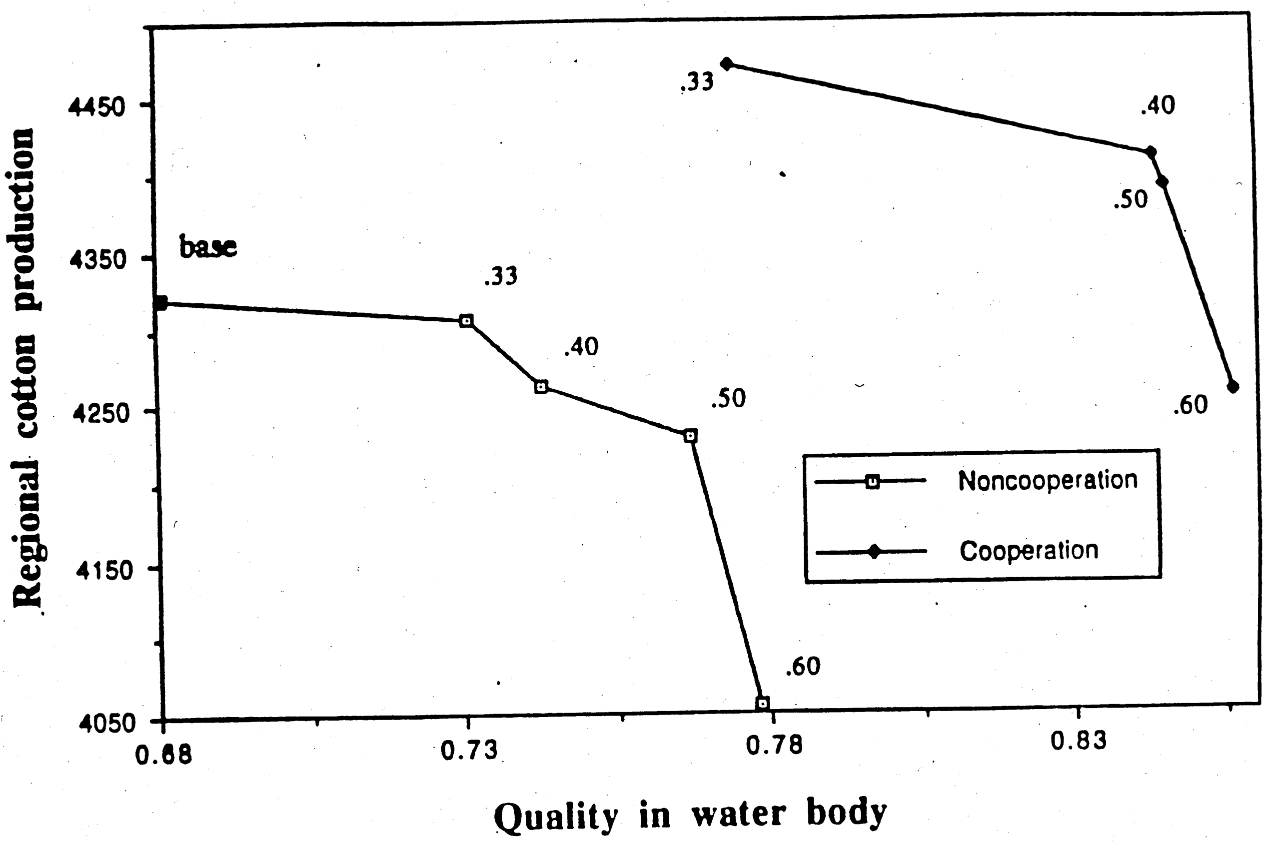
In the noncooperative solutions, drainage is also reduced as the consumer weight increases, but drainage is about a third higher than in the corresponding cooperative case. Therefore, consumers must compare higher pollution with higher costs in choosing between noncooperative and cooperative solutions. Figure 4 compares the noncooperative production frontier to cooperative cases with corresponding weights.

In both cooperative and noncooperative cases, the share of Technology 2 with improved water utilization increases for both types of producers with increased consumer weight. The share of Technology 2 is higher in the cooperative case because its variable costs are reduced by cooperation. Although better water quality is achieved by cooperation through the combination of reduced drainage and treatment, average water use per acre in the cooperative case is actually higher than in the noncooperative case. Output is higher in the cooperative solutions compared to the corresponding noncooperative solution because of improved yield with the second technology and reduction in the externality for the downslope producer.

Table 2 shows payoff values for the status quo and noncooperative and cooperative solutions for varying consumer political weights computed according to the algorithm above. An acceptable cooperative solution, where all parties are better off than at the status quo and at the noncooperative solution, is found for the consumer weight of .40. (This solution actually gives the same point on the production frontier as a weight of .42 but represents a different cost allocation.)

Fig. 4

Substitution between agricultural production and environmental quality in a regional setup with and without cooperation for various weights



$$Q = 1 - \frac{Se}{100}$$

For the acceptable solution, because of increased efficiency in water use and lower tax rates, the net income of upslope producers is increased in the cooperative solution by 17.5% compared to the noncooperative solution and by 1.2% compared to the status quo. For downslope producers net income is increased by 18.7% compared to the noncooperative solution and by 5% compared to the status quo. (See Table 3.)

Table 4 shows the tax prices and cost share for the acceptable solution. At this solution, each consumer has to pay about $3.60 per year for an improvement of about 16 ppb in selenium concentration, compared to a willingness to pay of about $5.90 for this change. Taxes paid by producers in the cooperative solution are about $14.70 per acre for upslope producers (compared to $54.20 in the noncooperative case) and $4.00 per acre for downslope producers (compared to $51 in the noncooperative case). The Pigouvian tax rates per acre foot of water are $3.80 for upslope producers (compared to $12.90 in the corresponding noncooperative solution) and $1.40 for downslope producers (compared to $11 per acre ft. in the noncooperative solution). (In comparison the price of water is $60 per acre foot and the price of land is $150 per acre.)

Table 2. **Net Payoffs ($1000). Status Quo, Noncooperative, and Cooperative Outcomes as Related to Political Weights.**

Consumer Weight	Consumer EV	Producer Profits upslope	Producer Profits downslope
		Status Quo	
0	248	825	516
		Noncooperative Solution (NC)	
.60	284	657	422
.50	279	712	436
.42	271	714	441
.40	271	710	440
.33	268	708	443
		Cooperative Solution	
.60	265	799	495
.50	264	804	533
.42	269	837	542
.40	272	836	541
.33	253	835	542

Net Benefit of Cooperative Solution

Consumer weight	Consumer (compared to NC)	Producers upslope (compared to Status Quo)	Producers downslope (compared to Status Quo)
.60	-19	-26	-21
.50	-15	-21	+17
.42	- 2	+12	+26
*.40	+ 1	+11	+25
.33	-15	+10	+26

* Acceptable cooperative solution

Table 3. **Payoffs ($). Status Quo, Noncooperative, and Cooperative Outcomes for Acceptable Cooperative Solution ($).**

	Producers upslope	Producers downslope	Consumer
		Status Quo	
Gross Payoffs	825,465	515,987	248,528
		Noncooperative	
Gross Payoffs	823,998	521,003	271,414
Taxes Collected	113,118	81,075	
Net Payoffs	710,880	439,928	271,414
		Cooperative	
Gross Payoffs	889,789	573,110	307,914
Taxes Collected	27,105	6,910	
Cost Shares	27,092	27,092	36,122
Net Payoffs	835,592	541,327	271,792

Table 4. **Taxes and Cost Shares: Cooperative and Noncooperative Outcomes for Acceptable Cooperative Solution.**

	Taxes: Land*	Taxes: Water**	Joint Cost Shares
	Noncooperative		
Producers			
upslope	$54.20	$12.90	
downslope	$51	$11	
	Cooperative		
Producers			
upslope	$14.70	$3.80	$16 per acre
downslope	$4	$1.40	$21 per acre
Consumer			$3.60 per person
Base Price	$150* per acre	$60** per acre ft.	

Conclusions

This paper demonstrates that externality problems may have a cooperative technology solution which is Pareto superior to a traditional abatement solution. The basic concepts presented in this paper are:

(i) Traditional economic solutions for externality problems (i.e. the Pigouvian tax) achieve noncooperative technology solutions, whereas technologies associated with cooperative solutions may be Pareto superior.

(ii) An acceptable cooperative solution is possible even if core solutions do not exist or require too much information.

(iii) Appropriate institutional mechanisms needed to achieve an acceptable cooperative solution, including cost sharing rules, can be designed based on mechanism design principles.

For such situations, this paper has proposed a sequential game process based on the Prisoners' Dilemma to locate an acceptable cooperative solution. An algorithm to find such a solution (or more than one such solution) was also demonstrated here. Application of the algorithm may be helpful to obtain a successful end to the bargaining process of creating an agreement to use a cooperative technology.

An institution for implementation of such a process already exists in the irrigation externality case studied here -- namely the water district and the water district manager -- but greater responsibilities than traditionally are proposed for the manager including mediation, information provision, computation of costs and taxes, management of cooperative technologies, and enforcement. Therefore, further consideration may need to be given to developing incentives for managers for good performance of these functions.

Even with potential gains for relevant parties and interest groups, actual acceptance of a cooperative solution in any given situation is a remaining question. Considering the Prisoner's Dilemma, indicated gains from cooperation do not always lead to cooperative outcomes. Behavioral research should also be undertaken to determine whether a cooperative game process such as that proposed here could actually result in finding an acceptable cooperative solution. The use of experimental games (Binger and Hoffman, 1987; Ostrom and Gardner, 1990; Hackett, 1991) could be an important tool to test actual acceptability and to specify institutional design more completely.

The concepts presented and demonstrated in this paper apply to other externality problems which have potential cooperative technology solutions as an alternative to private abatement activities. Generally in such cases, economists can help to design solutions by applying mechanism design and other economic principles.

To apply the methods proposed here to other real world situations, appropriate demographic, physical, and preference models would need to be determined. Here, the required relationships were determined by the San Joaquin Valley Drainage Program (SJVDP). For other real settings, development of information and computer models is also essential.

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Appendix A:

Technical Efficiency, Pareto Optimality, and Acceptability with Cooperation

Welfare economic results for perfect competition (the noncooperative case) concern the relationship between technical efficiency and Pareto optimality (Negishi; Takayama). This section discusses this relationship and its nature in the cooperative case and the role of political weights.

Technical Efficiency

Technical efficiency is represented by the production frontier. Figure 1 illustrates the production frontier for agricultural production (Y) and water quality (Q). Consider the case when there are several private water technologies $\tau^P = \{\tau_j\}$ where j denotes a private technology such as traditional furrow irrigation, sprinklers, and drip irrigation. Each technology is represented by a locus in terms of possible combinations of agricultural production and water quality produced for a given quantity of water and land available. The production frontier for a set of technologies is the envelope of loci for the set of technologies; production is said to be efficient if it occurs on this frontier. Introducing regional cooperative technology (τ^R) in combination with the set of private technologies adds another locus which may be outside the noncooperative frontier.

Note that the envelope formed in this way may define a nonconvex set even if each underlying locus is associated with a convex production set. In the noncooperative case, externalities may cause further nonconvexity, and in the cooperative case, nonconvexity may also occur because of increasing returns (Calsamiglia). Therefore, nonconvexity may cause problems in achieving Pareto optimal solutions through market incentives such as taxes (Starrett).

Pareto optimality is traditionally represented by a utility possibility frontier. To obtain the utility possibility frontier, each point on the production frontier is associated with preference functions, or payoff functions, for each relevant person or interest group. Any point along the noncooperative efficiency frontier can be represented, for some set of weights, as a solution of maximizing a weighted sum of preference functions (Negishi) over the given set of technologies.

As is well-known for the noncooperative case, a Pareto optimum solution is efficient. This correspondence may break down for the cooperative case because of the need to share joint costs.

Below, efficiency is defined for the irrigation problem as a frontier in terms of water quality Q and agricultural production Y constrained by production relationships and resource constraints:

$$\max_{\{\tau_i\},Q,Y} \quad \lambda Q + (1-\lambda)Y$$

$$Y^u = Y^u(w^u;\tau^u)$$

$$Y^d = Y^d(w^d,\ kW^u;\ \tau^d).$$

$$Y = Y^u A^u + Y^d A^d$$

$$A^u + A^d \le \bar{A}^u + \bar{A}^d$$

$$W^u + W^d \le \bar{W}^u + \bar{W}^d$$

$$S^u = \delta^u(\tau^u)\ W^u$$

$$S^d = \delta^d(\tau^d)\ (W^d + kW^u)$$

$$S = S^u + S^d$$

$$Q = 1 - \frac{S}{100}$$

where $w^i A^i = W$. For cooperative case additional constraints are:

$$W^{CS} \leq W^u + W^d$$

$$S^{CS} = f(S, W^{CS}; \tau^R)$$

$$Q = 1 - \frac{S^{CS}}{100}.$$

Pareto Optimality

A Pareto optimum solution maximizes a weighted sum of payoffs subject to production constraints, with maximization over the same set of technologies and W^i, A^i. Here, in the noncooperative case Pareto optimality is defined by (10). A noncooperative Pareto optimum is efficient because a λ value can be found correspond to a solution to (10) for any given $\{\alpha\}$.

In the cooperative case, Pareto optimality is defined similar to (10) in terms of the objective function and constraints, but optimization is over cooperative as well as private technologies. Also, an additional feasibility constraint is required: joint costs of cooperation should not exceed the total value of payoffs, i.e.

$$EV(S^{CS}; S^o) + [p_f Y^u - F(\tau^u) - v'(\tau^u, \tau^R) w^u] A^u + [p_f Y^d - F(\tau^d) - v'(\tau^d, \tau^R) w^d] A^d - JC(S^{CS}, W^{CS}; \tau^R) \geq 0. \quad \text{(A1)}$$

Because this condition must be added to the production constraints present in the noncooperative problem (10), and there is no such requirement for the technical efficiency problem, the correspondence between production efficiency and Pareto optimality breaks down in the cooperative case. A cooperative solution will be feasible but not optimal for the technical efficiency problem. Also, a noncooperative solution will be feasible but not optimal for the cooperative problem since the noncooperative solution has zero joint costs.

Acceptability

Acceptability can be imposed in the form of additional constraints on the cooperative Pareto optimality problem. Because of these additional constraints, an acceptable solution may not be a Pareto optimum for the cooperative problem.

The constraints for acceptability are defined as follows.

Let $\pi^i(\alpha;\ CS)$ and $\pi^i(\alpha;\ NC)$ denote profit after Pigouvian taxes for upslope and downslope producers and C^c, C^u, C^d denote cost shares for consumers, upslope producers, and downslope producers which sum to the joint cost. For acceptability, profits for the cooperative case after cost sharing should be greater than profit in the noncooperative case:

$$\pi^i(\alpha;\ CS) - C^i \geq \pi^i(\alpha;\ NC). \tag{A2}$$

For consumers in the cooperative solution, there should be a gain after paying cost shares compared to the noncooperative solution:

$$EV(S^{CS};\ S^o) - C^c \geq EV(S^{NC};\ S^o). \tag{A3}$$

This condition says that water quality S^{CS} for the cooperative solution must be sufficiently improved compared to S^{NC} to offset the cost share paid by consumers in the cooperative case.

Rather than imposing (A2) and (A3) in the Pareto optimum problem, a weaker necessary condition for acceptability can be defined without specifying cost sharing rule. This necessary acceptability condition is obtained by adding the inequalities (A2) and (A3) (since cost shares must sum to joint costs):

$$\pi^u(\alpha;\ CS) + \pi^d(\alpha;\ CS) + EV(S^{CS};\ S^o) - JC(S^{CS},\ W^{CS};\ \tau^R) \geq \tag{A4}$$
$$\pi^u(\alpha;\ NC) + \pi^d(\alpha;\ NC) + EV(S^{NC};\ S^o).$$

For acceptability, all players should also benefit compared to the status quo. Consumers will be better off than at the status quo if

$$EV(S^{CS};S^{o}) - C^{c} \geq EV(S^{o};S^{o}) = 0. \quad \text{(A5)}$$

For producers, the following additional requirement, that there be positive benefits of cooperation compared to the status quo, should also hold:

$$\pi^{i}(\alpha;\ CS) - C^{i} > \pi^{i}_{o},\ i = u,d. \quad \text{(A6)}$$

Adding the inequalities (A5) and (A6), another necessary condition for acceptability is

$$\pi^{u}(\alpha;CS) + \pi^{d}(\alpha;CS) + EV(S^{CS};\ S^{o}) - JC(S^{CS},\ W^{CS};\ \tau^{R}) \geq \pi^{u}_{o} + \pi^{d}_{o}. \quad \text{(A7)}$$

However, because the externality between producers is alleviated in the noncooperative problem, joint profits in the noncooperative case will be greater than the sum of profits for the status quo. Also, $EV(S^{NC};\ S^{o})$ is greater than zero. Therefore, any solution satisfying the acceptability constraint (A4) will automatically satisfy (A7), so that (A7) does not need to be imposed if (A4) is a constraint. Also, note that (A1) is automatically satisfied by (A4) if producers have positive profits in the noncooperative case. Therefore, the constraint (A4) added to production constraints in the Pareto optimality problem (10) can be used to identify potential acceptable solutions without defining a specific cost-sharing rule.

However, rather than adding the constraint (A4) to the constraints in (10), the objective function in formulation (17) tends to give larger net benefits and so is better at identifying potential accepable solutions. The necessary condition (A4) can be satisfied by a solution to (17). Since the noncooperative problem is feasible but not optimal for the cooperative problem (denoting the alternative solutions by subscripts NC and CS),

$$\alpha_c \ EV_{CS} + \alpha_u \ \pi^u_{CS} + \alpha_d \ \pi^d_{CS} - JC \geq \alpha_c \ EV_{NC} + \alpha_u \ \pi^u_{NC} + \alpha_d \ \pi^d_{NC}. \tag{A8}$$

That is,

$$\alpha_c(EV_{CS}-EV_{NC}) + \alpha_u(\pi^u_{CS}-\pi^u_{NC}) + \alpha_d(\pi^d_{CS}-\pi^d_{NC}) \geq JC. \tag{A9}$$

If the individual gains from cooperation are positive, since $0 \leq \alpha_i \leq 1$, then (A4) is satisfied:

$$(EV_c-EV_{NC}) + (\pi^u_{CS}-\pi^u_{NC}) + (\pi^d_{CS} - \pi^d_{NC}) \geq JC.$$

Since (A4) is only necessary, but not sufficient for acceptability, the full set of acceptability conditions (A2), (A3), (A5), (A6) must be tested ex post after defining a specific cost sharing rule. The proposed allows alternative cost sharing rules to be tested without having to resolve the cooperative optimization problem.

Appendix B:

Specification of Relationships for the Regional Model

Upslope (u) and downslope (d) producers grow the same single crop (cotton) with a limited amount of land and water. A crop-water production function for cotton was estimated using data from the west side of the San Joaquin Valley. Water supply is of a given quality (here, in terms of selenium) and two water use technologies are available [furrow (f) and sprinklers (s)]. A yield index for production on a per unit area basis for upslope and downslope producers is given by:

$$(RY^i)_f = .143 + .516w^i_f - .075(w^i_f)^2 \quad , i = u, d.$$

$$(RY^i)_s = .174 + .544w^i_s - .084(w^i_s)^2 \quad , i = u, d.$$

where $(RY^i)_j$ is the relative yield per acre for producer i with technology $j(j=f,s)$. w^i_k is the per acre amount of applied water by irrigation technology. Maximum per acre potential yield for producer i is MY^i; for simplicity, it is assumed to be independent of the water use technology. Yield per acre (Y^i) is then $(RY^i)_j$ times MY^i.

A portion of the irrigation water results in drainage which has quality (selenium) and quantity dimensions. For simplicity we assume a constant level of selenium in the drainage water for both producers. However, the upslope producer has a larger fraction of irrigation water which results in drainage. A fraction of the upslope producer's drainage moves laterally to produce the externality effect on the downslope producer. The summation of the two producers' drainage water creates regional drainage. This can be either disposed of directly into a water body or treated in a regional treatment facility to lower the level of selenium concentration before disposal in the water body. The original quality of water in the water-receiving body is initially better than both the untreated and treated drainage. (Treated drainage water could also be returned to the water supply system but this is not included in our analysis here.)

The final concentration in the water-receiving body after drainage water is introduced is:

$$S^1 = [VL \cdot S' + Q^R \cdot S^R]/[VL + Q^R]$$

where S' is the initial concentration in the water receiving body; VL is the volume of the water body; S^R is the quality of the drainage water disposed of the region; and Q^R is the volume of drainage water disposed from the region. S^1 denotes either the concentration of untreated drainage or that of final drainage after treatment in case of cooperation.

The estimated annual cost function for a regional treatment facility (Algal-Bacterial Selenium Removal System) is based only on quantity D' treated (Gerhardt and Oswald, 1990, pp. 215-220):

$$C = -11{,}552{,}000 + 3{,}593{,}700 \cdot \log D'$$

where C is annual total cost, and D' is the regional volume of drainage water to be treated ($D' \leq Q^R$). Quality of treated drainage is fixed at 15 ppb, achieved by passing a given quantity over iron fillings a number of times until this quality is achieved.

Consumers' benefit from improved water quality in the receiving water body are the sum of benefits from recreation and from health effects. The lower the concentration, the greater the consumer benefit.

$$EV = N \cdot \phi \cdot (100 - S^1)$$

where EV is total consumer benefits, N is the consumer population, ϕ is estimated benefit per unit change in water quality. For more details, see Loehman and Dinar (1990).

Variable	Description	Value(s)
MY^u	Maximum potential yield, upslope	1,100 lb/acre
MY^d	Maximum potential yield, downslope	1,000 lb/acre
β^u	Upslope drainage coefficient	.15
β^d	Downslope drainage coefficent	.10
δ_f	Furrow drainage coefficient	1.30
δ_s	Sprinkler drainage coefficient	1.15
k	Proportion of upslope drainage received on downslope fields	.90
P^w	Water supply cost	60$/AF
S'	Initial quality in water body	10 ppb
S^R	Quality of treated drainage	15ppb
	Initial quality of untreated drainage	35ppb
ϕ	Estimated benefit per consumer	
ψ	per ppb improvement	.365$/ppb
P	Cotton price	.75$/lb
v^u_f	Non-water variable cost of production, upslope furrows	$416/A
v^d_f	Non-water variable cost of production, downslope furrows	$427/A
v^u_s	Non-water variable cost of production, upslope sprinklers	$401/A
v^d_s	Non-water variable cost of production, downslope sprinklers	$415/A
F_f	Fixed cost for furrows	$20/A
F_s	Fixed cost for sprinklers, cooperative case	$98/A
F_s	Fixed cost for sprinkers, noncooperative case	$138/A
P^D	Cost of drainage pumping	15$/AF
$\bar{A}^u$	Land area upslope	2,500 acres
$\bar{A}^d$	Land area downslope	2,500 acres
$\bar{W}^u$	Water quota upslope	3,000AF/YR
$\bar{W}^d$	Water quota downslope	3,000AF/YR
N	Consumer population	10,000 people
VL	Volume of water receiving body	500 AF