An Examination of the Stability of Cooperation in a Voluntary Collective Action: The Case of Nonpoint-Source Pollution in an Agricultural Watershed

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Selected Paper to be presented at the American Agricultural Economics Association Annual Meeting, August 5-8, 2001, Chicago, IL

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Introduction

The term "collective action" is used to describe social situations where individuals put forth a coordinated effort to achieve a common goal. Examples of collective actions in our everyday lives are easy to spot: a neighborhood watch group is formed to reduce crime, Public Television viewers make financial donations to support children's programming, a Habitat for Humanity house is built by community volunteers. A common thread in each of these examples is that the actions of each participant are *interdependent*. The benefits realized by each individual depend on the actions of the group (Sandler). These interdependencies are the key to the success or failure of a collective action.

This paper addresses the collective action problem of nonpoint-source pollution in a small agricultural watershed, and explores ways of preventing collective failure among the group of producers who farm within the watershed's boundaries. Using a game-theoretic representation of the collective action problem, the interaction between producers and their joint impact on pollutant levels within the watershed is formulated as a computational multi-agent system. The multi-agent system is then used to simulate the evolution of collective behavior among the producers and to evaluate the effectiveness of selected incentive mechanisms in preventing the collapse of joint cooperation.

Description of the Collective Action Problem

The Blue Creek watershed is located in the eastern portion of Pike County, situated between the Illinois and Mississippi Rivers in west-central Illinois. The watershed has a drainage area of 11.15 square miles (7,136 acres) with approximately 50 percent of the land used for cropland. The predominant crops grown are corn and soybeans, with some wheat also grown. Located at the lower end of the watershed is Lake Pittsfield, a 222-acre impoundment with a storage volume of 2,679 acre-feet. The lake was constructed in 1961 and serves as the domestic water supply for the 4,400 residents of the City of Pittsfield, located 3 miles southwest of the lake.

In July 1991, atrazine was detected in Lake Pittsfield at a concentration of 13 parts per billion (ppb), more than four times the maximum contaminant level (MCL) established by the Federal Safe Drinking Water Act. The MCL was also exceeded the following year in September and November of 1992 (4.4 and 5.0 ppb, respectively). In response to these elevated concentrations, the local farmers voluntarily agreed to discontinue the use of atrazine within the watershed. As an incentive for switching to nonatrazine chemicals, farmers within the watershed were paid $7 per acre for cooperating. For many of these farmers, atrazine was replaced by cyanazine (trade name: Bladex), another broad spectrum herbicide with properties similar to those of atrazine (both atrazine and cyanazine belong to the triazine class of herbicides). With the availability of the incentive program, the switch from atrazine to cyanazine involved only a small increase in weed control costs for farmers.

Given the availability of a low cost replacement, the decision to discontinue the use of atrazine was perceived by local farmers to be in the best interests of the community. However, on August 2, 1995, the DuPont Agrichemical Company announced that in response to a special review of the triazine herbicides being initiated by the Environmental Protection Agency, cyanazine would no longer be produced after December 31, 1999. With cyanazine no longer available, herbicide alternatives to atrazine become significantly more expensive, often more difficult to apply, and in some instances less effective. This is particularly true for farmers who must use no-till in order to remain compliant with soil conservation plans. The farmers in the watershed now faced a dilemma: continue their voluntary moratorium on atrazine at much greater cost, or resume using atrazine and increase the likelihood of contributing to the contamination of Lake Pittsfield.

Model

The collective action problem is represented as a repeated game with imperfect public information. The stage game is modeled as a simultaneous move assurance game played by N producers, indexed $i = 1, 2,\dots, N$, with the game repeated over t discrete periods. At the beginning of each period, the producers simultaneously decide whether to *cooperate* by using corn herbicides that contains no atrazine, or *defect* and apply herbicides with atrazine as an active ingredient. In each period, there is a small chance that the producer will deviate from his intended action. These deviations, or "mistakes," represent random variations in optimal behavior caused by unforeseen circumstances (Kaniovski and Young), and are consistent with the underlying assumption that producers act with bounded rationality. The occurrence of mistakes is assumed to be perfectly uncorrelated across producers. The inclusion of a mistake process in evolutionary models involving repeated interactions is well documented in the literature (Young; Kandori, Malaith and Rob).

Let a_i denote whether producer i intends to cooperate ($a_i = 0$) or defect ($a_i = 1$), and let a_i' denote producer i's realized action. The number of cooperating producers is $\hat{n}^C = N - \sum_{i=1}^{N} a_i'$. It is assumed that at the beginning of the game all producers are initially cooperating. This assumption relies on the notion that the cooperative equilibrium at the beginning of play is a *focal point* (Schelling) supported by the voluntary agreement among the producers to discontinue using of atrazine. Once the producers' decisions have been made and the actions implemented, Nature randomly generates the public outcome y, the concentration of atrazine in the lake. The stochastic process that determines the public outcome depends on the combined actions of the producers and the inherent variability of environmental conditions, which is typical of many nonpoint source pollution problems (Segerson). Each producer's contribution to the public outcome is independent of the actions of the other producers, and depends on the realized action as well as the size and physical characteristics of the producer's farm. Let the vector $a' = (a_1', \ldots, a_N')$ represent the *action profile* of the producers. Each unique action profile induces a probability distribution over the public outcome y. Let $F(y;\Theta)$ represent the distribution of y, with the value of the parameter Θ being a function of the realized actions of the individual producers:

(1) $$\mathbf{Q} = \sum_{i=1}^{N} a_i' \cdot \boldsymbol{q}_i$$

where $\boldsymbol{q}_i$ is the effect of producer *i*'s actions on the distribution of *y*.

Producers are assumed unable to observe the actions of others, and must rely on the public outcome as an indicator of the group's collective behavior. At the beginning of each period, producers revise their beliefs about the behavior of the group as new information about past play becomes available. In the repeated game, a *naïve Bayesian learning* process is used to model the revision of beliefs, which assumes that producers act as if they face a stationary, but unknown, distribution of opponents' strategies. The actual learning algorithm used in the model is based on an adaptation of fictitious play with unobservable stochastic actions (Boutilier). The learning process focuses on identifying the correct sampling distribution of *y*, and then extrapolating to arrive at a subjective assessment of the level of cooperation. Producers' beliefs are structured as a *finite mixture distribution*, which characterizes each producer's subjective assessment of the true sampling distribution of *y* as a vector of mixing proportions associated with a finite mixture of component distributions. Each component distribution represents the expected sampling distribution of *y* associated with the realization of a specific state of cooperation by others. Producers use a stochastic adaptation of the fictitious-play learning model to revise the vector of mixing proportions over the course of play, where each producer is assumed to hold an initial prior belief about the true state. We assume that the prior density of the mixing proportions takes the form of a Dirichlet (generalized beta) distribution. A quasi-Bayesian procedure developed by Smith and Makov is used in the model to sequentially update each producer's beliefs. Producers' use their updated beliefs about the mixing proportions to revise their estimates of $\hat{n}_{-i}^{C}$, the number of other producers believed to be cooperating.

The decision environment of producers is based on the Brock and Durlauf model of individual choice in the presence of social interactions, where producer *i*'s utility depends directly on his own action a_i and indirectly on the actions of the other N-1 producers. Let $\boldsymbol{p}_i^C$ and $\boldsymbol{p}_i^D$ represent player *i*'s expected returns in the current period from cooperating and defecting, respectively. Since cooperation is costly for producers, $\boldsymbol{p}_i^C - \boldsymbol{p}_i^D < 0$ for all *i*. Social utility is represented by a simple linear relationship, as discussed in Schelling and later adopted by Ellison and Fudenberg and Brock and Durlauf. We define social utility as

$$(2) \qquad S(a_i, \mathbf{D}(a_{-i})) = \begin{cases} -\boldsymbol{s}_i(1-2\overline{m}_i^C) \text{ when } a_i = \text{"cooperate"} \\ -\boldsymbol{s}_i(1-2\overline{m}_i^D) \text{ when } a_i = \text{"defect"} \end{cases}$$

where $\overline{m}_i^C$ is the proportion of others believed to be cooperating, $\overline{m}_i^D$ is the proportion of others believed to be defecting, and $\boldsymbol{s}_i$ is a dimensionless parameter indicating producer *i*'s preference for conformity. This last parameter is a measure of the importance producers' place on coordinating their actions with the actions of others, with larger values of $\boldsymbol{s}_i$ indicating a greater desire to coordinate.

Producers are assumed to behave myopically in the sense that they seek to maximize utility in the current period without considering the impact of their actions on the course of play in future periods. Each producer's best response choice rule is to cooperate when the social utility gained through coordination exceeds the cost to cooperate; i.e.,

$$(3) \qquad \text{choose } c \text{ if : } \quad (\boldsymbol{p}_i^C - \boldsymbol{p}_i^D) - 2\boldsymbol{s}_i(1-2\overline{m}_i^C) \geq 0$$

This decision-making process describes a threshold model (Granovetter), where the "threshold" for each producer is the point where the cost of an action exceeds the perceived benefits. After expressing $\overline{m}_i^C$ in terms of $\hat{n}_{-i}^C$ and rearranging (3), this choice rule can also be expressed in terms of n_i^*, producer *i*'s threshold for cooperating, which identifies the critical number of other cooperators required for cooperation to be *i*'s best response:

$$\text{(4)} \qquad \text{choose } c \text{ if : } \quad \hat{n}_{-i}^C \geq n_i^* = \frac{N-1}{2}\left(1-\frac{(\pi_i^C-\pi_i^D)}{2\sigma_i}\right).$$

This threshold will vary among producers, due to differences in the individual costs of adopting alternative weed control technologies.

Since producers respond only to their expectations about the aggregate play of others and not the play of each individual producer, the stage game played by producer *i* can be represented as an *N*-person assurance game. The diagram in Figure 1 illustrates the threshold concept defined in equations (3) and (4). The solid upward-sloping line shows the increasing level of utility associated with the decision to cooperate as the perceived level of cooperation among the others increases, while the solid downward-sloping line is the expected utility when defection is chosen. Cooperation is a best response when at least n^* others are believed to be cooperating. The game has two pure-strategy Nash equilibria: joint cooperation at (N-1, $\pi^C + \sigma_i$), and joint defection at (0, $\pi^D + \sigma_i$). If the expected return from cooperation decreases to $\pi^{C'}$, cooperation becomes more costly and the expected utility function for cooperation shifts outward, as indicated by the dashed line. This shift increases the cooperation threshold to n^{**}.

Modeling Collective Behavior as a Computational Multi-Agent System

To study the dynamics of cooperative behavior among the producers in the watershed, a computational multi-agent system (MAS) was developed that simulates the evolution of the repeated assurance game over many time periods. A MAS is a computational game environment where artificial agents are designed to interact as boundedly-rational utility maximizers without complete information about the other agents in the system (Parkes and Ungar). MAS are particularly well suited to the study of cooperation among agents, where learning and adaptation are important characteristics of an agent's behavior (Boutilier; Vidal and Durfee).

The MAS is constructed in Powersim© (Powersim Corp.), a system dynamics modeling environment capable of simulating complex systems. The structure of the MAS consists of seven individual producer modules and a lake module that aggregates the actions of the producers to determine the realization of the public outcome (the level of atrazine in the lake). Two interrelated processes are used to characterize each producer: the learning process and the decision process. The learning process uses the latest observation of the public outcome to update a producer's subjective beliefs about the actions of the other six producers. The decision process uses these revised beliefs to determine a best-response action that maximizes expected utility in the current period, taking into account the agronomic characteristics of the producer's farm, the crop production technologies available, and knowledge of the potential impact of their choices on the public outcome.

The seven “farms” used to represent each producer are contiguous clusters of small drainage basins delineated by an extensive Geographic Information System database of the Lake Pittsfield watershed (Hornbaker et al.). The GIS provides site-specific information about the physical and agronomic characteristics of the cropland within each drainage basin. Six soil types and three erodibility classifications are used to characterize the variability of cropland within each farm and to assign productivity criteria and management constraints. The inherent differences that exist between producers in terms of the cost of cooperation and the potential impact on the public outcome are determined solely by the variability of cropland across farms. Table 1 shows the distribution of cropland by erodibility class across the seven farms.

When a producer decides to cooperate or defect, the choice of production technology is determined by the solution of a constrained profit-maximization problem. A production technology is defined by three components: a cropping pattern or rotation, a tillage system, and a weed control strategy. Producers must choose between three crops (corn, soybeans, and winter wheat), four cropping patterns (continuous corn, corn-soybean, corn-corn-soybean, and corn-soybean-wheat), and three tillage systems (clean till, mulch till, and no-till). Weed control strategies are defined by the specific corn herbicide used and consist of a primary and secondary treatment. The primary treatment occurs either before or at planting, while the secondary treatment, if necessary, takes place after the crop has emerged. When a producer chooses to defect, his choice of technology is constrained only by the amount of erosion that is allowed to occur on fields designated as highly erodible (HEL) and exceedingly erodible (XHEL). When cooperation is chosen, the producer is also limited to using weed control strategies that do not rely on atrazine-based products. In the event that a mistake occurs when cooperation is the intended action, atrazine is applied only as a primary treatment on HEL and XHEL fields where no-till is used. These lands are the most vulnerable to unexpected weed pressure due to the reliance on no-till to control erosion.

A linear programming (LP) model (Önal et al.) was used to identify the optimal production technologies associated with cooperation and defection for each individual producer. The objective function of the model is the maximization of total farm expected net returns, calculated as the difference between expected crop revenues and production costs. An additional $7 per acre subsidy payment for switching to non-atrazine herbicides was also included in the model to imitate the effect of a water quality incentive program available to farmers in the watershed. Detailed crop budgets for Illinois (Newton, Hornbaker and White) were used to estimate the production costs associated with the different crop rotations and tillage systems. Weed control costs were based on 1996 retail herbicide prices, and include all additional application costs. The LP results are used to determine the producers' expected returns from cooperation and defection ($\boldsymbol{p}^C$ and $\boldsymbol{p}^D$). These results are shown in Table 2. The numbers shown in parentheses are the expected losses per acre when producers cooperate, and reflect each producer's cost of cooperation.

Each farm's potential impact on the concentration of atrazine in the lake depends on three factors: (1) the choice of crop and production technology, (2) the distribution of soils across land types, and (3) the number of acres of each land type in corn production. Given the inherent randomness of the hydrologic factors that affect herbicide loadings to surface water, the actual levels of atrazine observed in the lake vary considerably from year to year. For this reason, the atrazine pollution potentials resulting from the range of management and technology choices available to each farm are specified in probabilistic terms. Estimates of the atrazine pollution potential for each farm were generated using a watershed response model that simulates the impact of soils, chemical properties, rainfall variability, application methods and timing, and cropping practices on the delivery and accumulation of atrazine in Lake Pittsfield.[1] This model provides the data necessary to estimate the parameters θ_i , which are parameters of an exponential distribution that describes each producer's impact on the July 1 concentration of atrazine in the lake.[2] The estimated parameters for each farm are shown in Table 3.

The loss of cyanazine as a substitute for atrazine is represented as a "shock" in the MAS. From a modeling perspective, this shock is represented as a sudden exogenous change that influences the decision-making process of producers. Following the shock, producers experience a significant increase in the cost of continued cooperation due to the additional expense of using the remaining atrazine alternatives. These additional costs put upward pressure on the producer's cooperation threshold, reducing the potential for cooperation in the periods following the shock. Using the MAS, a series of simulation experiments were conducted to examine the evolution of collective behavior among the producers and to evaluate the effectiveness of selected incentive mechanisms in preventing the collapse of joint cooperation after the removal of cyanazine. An experiment consists of 100 independent simulation runs of the MAS. Each run involves

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[1] A detailed description of the watershed response model, while beyond the scope of this paper, is available from the authors upon request.

[2] July 1 was selected as the time of year when elevated atrazine concentrations were most likely to be found in the lake (Spalding et al.)

20 discrete time-steps, with each time-step representing a single interaction of the stage game. The first eight interactions of each run simulate group behavior with cyanazine available.[3] Cyanazine is then removed in the ninth period, and the collective behavior of the group is allowed to evolve over the remaining eleven periods of play. The likelihood of the emergence of joint cooperation among the group is measured as the proportion of runs where play has converged to the cooperative equilibrium by the twentieth period. Given the uncertainty about producers' intrinsic desire to coordinate their actions with others, the experiments were performed over a range of possible values for the conformity preference parameter, where producers are assumed to hold identical preferences. A preliminary analysis was performed to establish a lower bound for the conformity preference parameter. By necessity, this value must be consistent with producers' observed behavior, and large enough to yield convergence to the cooperative equilibrium within the first eight periods of play. This preliminary analysis identified a lower bound for the conformity preference parameter equal to three.

Results

The first series of simulation experiments examined the effect of increasing the level of subsidy payments on the probability of joint cooperation, with the increased payments programmed to coincide with the shock. The results of these experiments are summarized in Figure 2. When preferences are equal to the lower bound of three, a subsidy payment of at least \$16 per corn acre is required for joint cooperation to continue after the shock. At the current \$7 per acre payment level of the incentive program, joint

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[3] This is approximately the length of time between the initial agreement among the producers in 1992 and the DuPont's removal of cyanazine from the market in 1999.

cooperation is expected to continue with 90 percent probability only for values of the conformity preference parameter at or above 6.5.

While joint cooperation can be sustained by simply increasing the subsidy payments to producers, the appeal of this approach from a policy maker's perspective will ultimately depend on the implementation cost involved. At the lower bound of the conformity preference parameter, the annual cost of implementing this program would increase by $9 per corn acre, more than twice the original payment levels. As an alternative to a pure subsidy, we introduce a multiple instrument incentive scheme that combines a subsidy payment with a penalty that depends on the amount by which the 3 ppb MCL is exceeded. This is similar in spirit to a payment/penalty system described by Segerson. In Segerson's model, a tax/subsidy payment proportional to the amount by which ambient water quality is above/below a specified cutoff level is used in conjunction with an additional fixed penalty that is assessed whenever ambient water quality exceeds the cutoff level. Given the uncertainty of ambient pollution levels resulting from nonpoint source emissions, this payment scheme motivates polluters to opt for higher levels of abatement than would otherwise be chosen when incentives are based solely on emissions.

In the MAS, penalties are based on the simple step function shown in Figure 3. While the specification of this function is purely arbitrary, the relationship is based on the underlying premise that the social costs of atrazine use are an increasing function of the ambient atrazine concentration. The actual amount of the penalty in dollars per acre is the relative penalty multiplied by an adjustable policy parameter in the MAS. Producers form expectations about their expected liability under the penalty based on a subjective assessment of the probability that atrazine concentrations will exceed the MCL. This subjective assessment depends on the producers' own estimated impact on the sampling distribution of atrazine in the lake as well as their current estimate of the combined impact of the other producers. As long as producers recognize that their actions impact the distribution of the public outcome, the threat of a penalty will reduce a producer’s effective cost of cooperation, lowering the threshold for cooperation and improving the potential for cooperation as a best response.

Figure 4 shows that when preferences are equal to the lower bound, there is a distinct shift in the potential for cooperative outcomes once subsidy levels reach $13. To the left of the $13 level, producers do not share a common incentive structure, and joint cooperation becomes possible (though with less than 90 percent probability) only when penalties are greater than $4 per acre. At the $13 level and above, each producer’s incentive structure is compatible with an assurance game, and joint cooperation observed at the 90 percent probability level is attainable.

Our results also indicate that producers do not respond uniformly to the penalty. With a $7 subsidy payment, there are three unique incentive structures exhibited among the seven producers, as shown in Figure 5. Farms A and B defect unconditionally when penalties are below $9, and then switch to a Prisoner's Dilemma incentive structure at penalty levels above $9. Eventually both will cooperate unconditionally when penalties are sufficiently high, although for Farm A this point occurs at a much higher penalty. At $8, Farm C switches from unconditional defection to a transitional state, where defection is the best response when the majority are either cooperating or defecting. Cooperation is chosen when the actions of the group are split. For lack of a better term, we refer to this state as a waver game. Above $8, Farm C switches to a Prisoner's Dilemma before cooperating unconditionally at penalties greater than $12. Farm D switches from unconditional defection to an assurance game when penalties are greater than $6, and cooperates unconditionally above $8. This divergence in behavior among producers is due to differences in both farm size and the impact that atrazine use has on the sampling distribution of the public outcome. Of the farms shown in Figure 5, Farm A has the fewest acres and the smallest impact on the atrazine concentration in the lake. When penalties are low and cooperation among the others is high, the additional penalty that a small farm would expect to pay while defecting may not be large enough to make cooperation a best response. In effect, the penalty targets producers having the greatest impact on water quality.

Figure 6 summarizes how the payment and penalty interact to influence the underlying incentive structure of the collective action problem facing the seven producers. Each row indicates the mixture of incentive structures within the given penalty range. For example, when a $9 penalty is used with a $7 subsidy payment, five producers will have an incentive structure consistent with the Prisoner's Dilemma, while two producers will cooperate unconditionally. The long run equilibrium in this case is mixed, with two cooperators and five defectors. When the subsidy payment is $13, all producers are playing an assurance game, with joint cooperation and joint defection as the dual long-run equilibria. These results raise the following question: Can atrazine concentrations over time be controlled below the MCL with mixed equilibria outcomes, or is joint cooperation required?

To answer this question, consider the two graphs displayed in Figure 7. The open triangles indicate the frequency of MCL violations at different penalty levels, while the open circles show the average payment per acre received by producers (net any penalties incurred) in the periods following the shock. When a $35 penalty is used with a $7 payment, the probability of violating the MCL in any given year is less than 0.05, and producers receive an average payment of about $3 per cropland acre. Referring back to Figure 5, this penalty-payment combination results in a game structure where the two producers with the smallest impact on the lake (Farms A and F) play a Prisoner's Dilemma, while the remaining five producers cooperate unconditionally. An equivalent MCL violation frequency can be achieved when a $13 subsidy payment is offered in combination with a $4 penalty. This results in all seven producers playing an assurance game and receiving an average effective payment of $5.67 per cropland acre.

Summary

This paper addresses the collective action problem of nonpoint-source pollution control in a small agricultural watershed. At issue is the stability of cooperative behavior among a group of farmers, who have voluntarily agreed to discontinue their use of the herbicide atrazine due to high concentrations of the herbicide being detected in a local water supply. Continued cooperation among the group is threatened by the cancellation of cyanazine, an inexpensive and widely used alternative to atrazine. With cyanazine no longer available, the farmers face a significant increase in weed control costs if they continue to use products that do not contain atrazine. Is cooperation among the farmers still possible despite the increased cost of cooperation? This paper explores the economic and behavioral factors that influence the collective outcome of this social dilemma.

Our results suggest that without additional incentives, farmers are likely to abandon their voluntary agreement and resume their use of atrazine within the watershed. We then demonstrated how a combination of policy instruments could be used to alter the underlying game configuration of the collective action problem, resulting in cooperative outcomes. An ambient-based penalty, when used in conjunction with a subsidy payment, is shown to produce divergent incentive structures that shift the classification of the collective action problem away from a coordination problem with two equilibria to a mixed configuration with multiple game structures and many possible equilibria. This result has important consequences in terms of the evolution of producer behavior and the set of possible collective outcomes. The analysis concludes with an example, which demonstrates that joint cooperation is not a prerequisite to the realization of socially desirable outcomes. By thoughtfully selecting the combination of subsidy payment and ambient penalty, a policy maker can manipulate the underlying incentive structure of the collective action, whereby producers with the smallest impact on water quality choose to defect while all others cooperate.

Our examination of cooperative, rather than non-cooperative, behavior among polluting firms represents a significant contribution to the study of nonpoint-source pollution problems. Another contribution is our representation of collective behavior as a repeated game with learning, where interdependent firms adjust their actions over time in response to their evolving expectations about the play of others. This framework could easily be applied to a broad range of social settings involving interdependencies among individual agents. We also explore the role of multiple policy instruments as a means of encouraging the emergence and stability of cooperation. An finally, our use of a multi-agent system as a platform for simulating the evolution of collective behavior represents a further example of the use of computational methods to enhance the analysis of complex economic systems.

Table 1. Distribution of cropland acreage by erodibility class among the seven farms.

	Non-highly erodible (NHEL)	**Highly erodible (HEL)**	**Exceedingly erodible (XHEL)**	**Total Cropland**
Farm	Acres			
A	269.2	71.9	0.0	341.1
B	341.8	235.3	43.0	620.1
C	422.6	30.5	92.2	545.3
D	436.1	99.4	164.9	700.4
E	505.4	68.0	163.6	737.0
F	124.3	54.4	38.9	217.6
G	216.8	82.4	100.9	400.1
Total	2,316.2	641.9	603.5	3,561.6

Table 2. Farm-level expected net returns and income losses resulting from cooperation and defection.

	Cyanazine available		**Cyanazine unavailable**	
	DEFECT	**COOPERATE**	**DEFECT**	**COOPERATE**
Farm	Expected net returns per acre ($)			
A	164.42	163.51 (0.91)	164.42	156.38 (8.04)
B	151.89	150.14 (1.75)	151.84	143.46 (8.38)
C	139.21	138.40 (0.81)	139.10	131.44 (7.66)
D	145.87	144.33 (1.54)	145.82	137.79 (8.03)
E	139.30	138.06 (1.24)	139.22	131.40 (7.82)
F	152.24	150.36 (1.88)	152.22	143.95 (8.27)
G	140.53	138.84 (1.69)	140.48	132.57 (7.91)

Table 3. Estimated parameter values describing the impact of each producer on the distribution of July 1 concentration of atrazine in the lake.

	Cyanazine available		Cyanazine unavailable	
Farm	**DEFECT** q_i^D	**COOPERATE**[a] q_i^M	**DEFECT** q_i^D	**COOPERATE**[a] q_i^M
A	0.596	0.176	0.596	0.176
B	0.740	0.735	1.316	0.735
C	0.407	0.281	1.145	0.281
D	1.182	0.583	1.920	0.583
E	1.023	0.514	1.887	0.514
F	0.402	0.208	0.594	0.208
G	0.776	0.397	1.142	0.397
	$\mathbf{Q}^D = 5.126$	$\mathbf{Q}^M = 2.958$	$\mathbf{Q}^D = 8.6$	$\mathbf{Q}^M = 2.958$

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[a] The nonzero parameter values associated with cooperation reflect the impact of atrazine used when a mistake occurs.

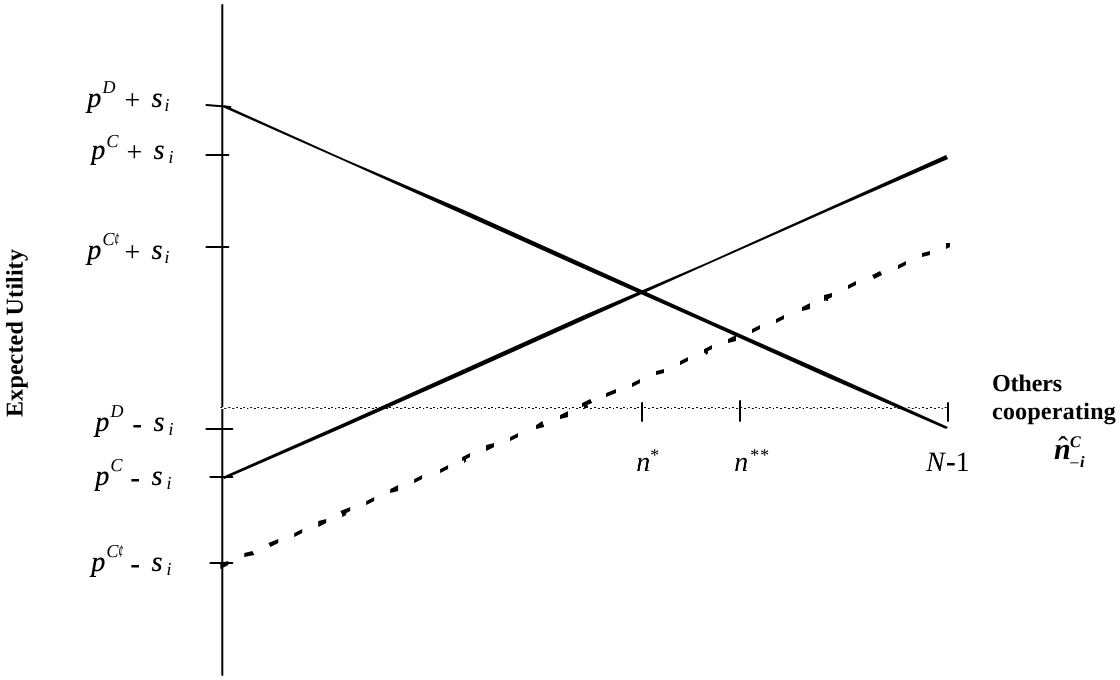

Figure 1. The expected utility of producer *i* when choosing to cooperate (defect) as an increasing (decreasing) linear function of the number of others believed to be cooperating. The dashed line shows the effect of a decrease in the expected return from cooperation, resulting in a higher cooperation threshold at n^{**} (Figure adapted from Dybvig and Spatt).

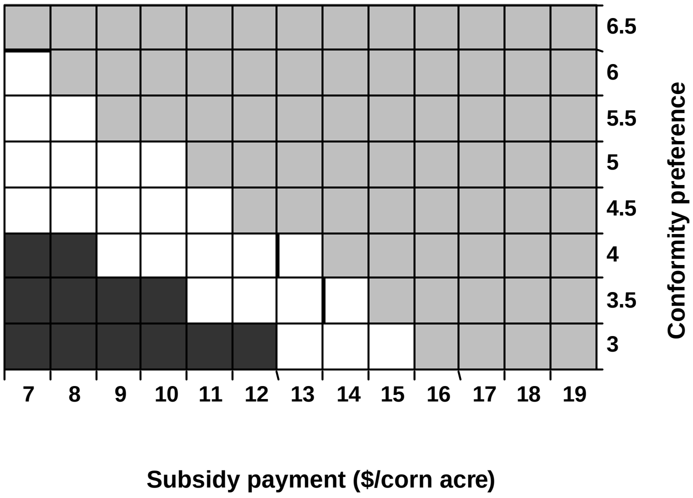

Figure 2. Joint cooperation as a function of conformity preference and the level of subsidy payment. The light gray region identifies combinations where joint cooperation is observed with 90 percent probability, while joint defection dominates in the dark gray portion of the chart. The white region indicates where joint cooperation is possible but with less than 90 percent probability.

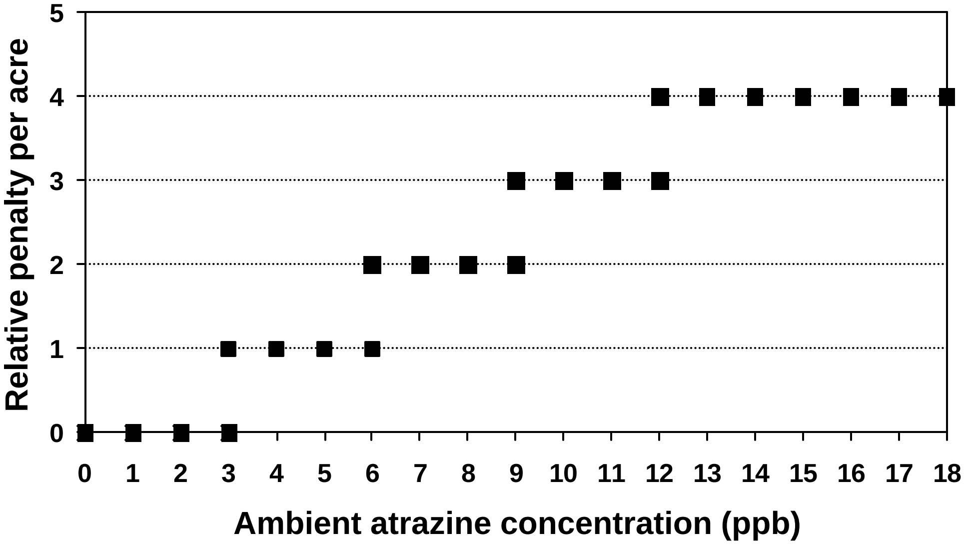

Figure 3. The relationship between the ambient atrazine concentration and the relative penalty.

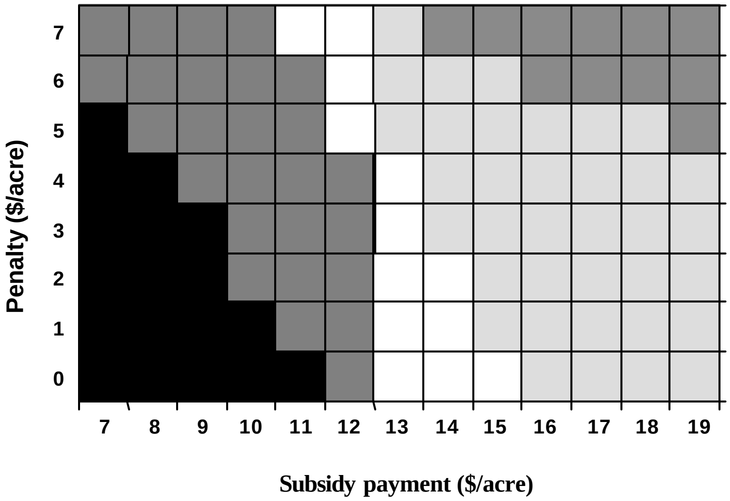

Figure 4. Collective outcomes as a function of the subsidy payment and penalty when the value of the conformity preference parameter is set equal to three. The hatched region indicates where producers always cooperate, while the light gray region shows where joint cooperation occurs with greater than 90 percent probability. The white region shows where joint cooperation is possible but with less than 90 percent probability. The dark gray and black regions show where joint cooperation is not possible, with the black area indicating where joint defection is the only possible outcome.

Farm A *Others believed to be cooperating*

Penalty	**0**	**1**	**2**	**3**	**4**	**5**	**6**
0-8	D	D	D	D	D	D	D
9	C	C	C	C	D	D	D
10-13	C	C	C	C	C	D	D
14-61	C	C	C	C	C	C	D
62+	C	C	C	C	C	C	C

Farm B *Others believed to be cooperating*

Penalty	**0**	**1**	**2**	**3**	**4**	**5**	**6**
0-8	D	D	D	D	D	D	D
9	C	C	C	C	C	D	D
10-15	C	C	C	C	C	C	D
16+	C	C	C	C	C	C	C

Farm C *Others believed to be cooperating*

Penalty	**0**	**1**	**2**	**3**	**4**	**5**	**6**
0-7	D	D	D	D	D	D	D
8	D	D	C	C	C	D	D
9-12	C	C	C	C	C	C	D
13+	C	C	C	C	C	C	C

Farm D *Others believed to be cooperating*

Penalty	**0**	**1**	**2**	**3**	**4**	**5**	**6**
0-6	D	D	D	D	D	D	D
7	D	D	D	D	D	C	C
8	D	D	C	C	C	C	C
9+	C	C	C	C	C	C	C

Figure 5. The best response actions of producers when ambient-based penalties are used in combination with subsidy payments of $7 per corn acre, where cooperation = C and defection = D.

$7 subsidy payment

	Game structure				
Penalty	**D**	**W**	**PD**	**A**	**C**
0-5	7				
6	6			1	
7	5			2	
8	3	2		2	
9-12			5		2
13-15			4		3
16-61			2		5
62-72			1		6
73+					7

$13 subsidy payment

	Game structure				
Penalty	**D**	**W**	**PD**	**A**	**C**
0-6				7	
7				5	2
8+					7

Figure 6. Evolution of the collective action problem at $7 and $13 subsidy payments when the producers' game structure is influenced by the level of the penalty. Each cell indicates the number of producers having a given game structure, where the game structures are classified as: defect unconditionally (D), waver (W), Prisoner's Dilemma (PD), assurance (A) and cooperate unconditionally (C).

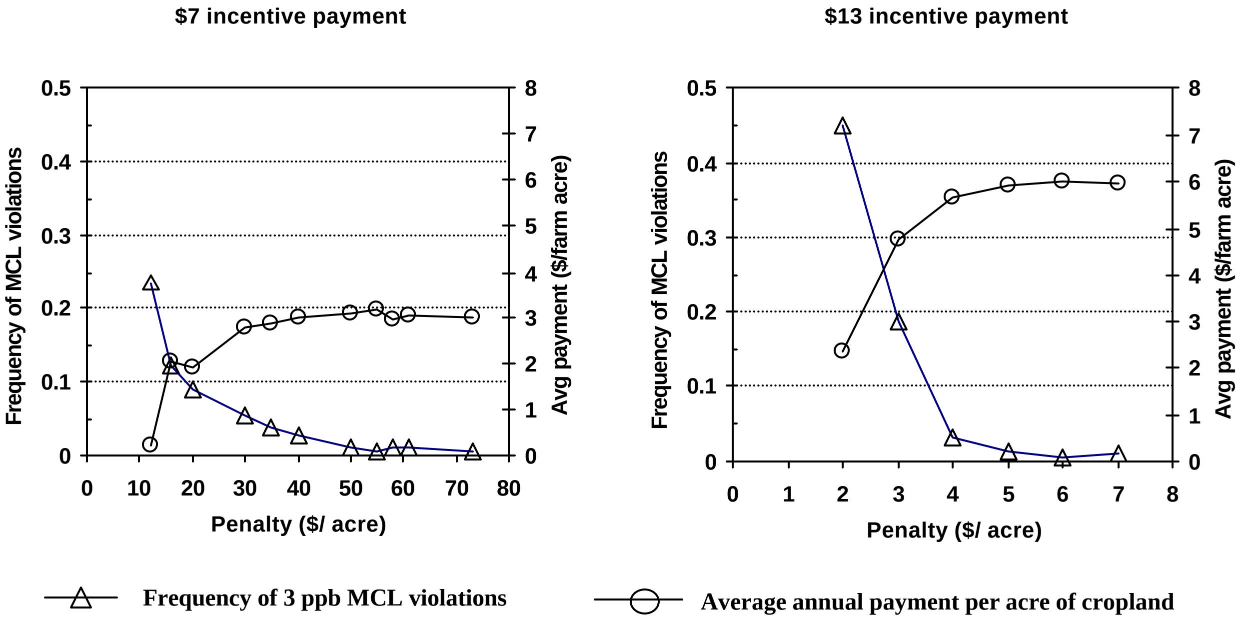

Figure 7. Simulation results showing the effect of subsidy payment and penalty combinations on the frequency of MCL violations, and the expected net payments per cropland acre.

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