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Cooperative and Noncooperative Protection Against Transferable and Filterable Externalities

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Abstract. Given self-protection from an undesirable environmental externality, we examine, under several conditions, the efficiency properties of cooperative and noncooperative behavior. We demonstrate that if self-protection can transfer the externality to another agent, then noncooperative behavior will lead to overprotection. If self-protection filters or dilutes the externality, then noncooperation leads to underprotection. In addition, overprotection will worsen if an agent with more relative power is allowed a first-mover advantage or if the damage function is elastic and transferability is uncertain. Finally, a reduction in uncertainty about transferability will accentuate overprotection if the damage function is inelastic. Our results suggest that coordination of protection activities among agents will enhance the overall gains from environmental policy in the European Single Internal Market of 1992. Coordination minimizes the costs of environmental protection, thereby reducing the public credibility of its foes.

Key words. Self-protection, externality, transferability.

"We must remember, therefore, that the sciences which deal with man deal with a being who is modified by his environment, *but who has the power of modifying that environment by his own conscious effort.*" [emphasis in original] (Ely *et al.*, 1922, pp. 9–10)

I. Introduction

Private self-protection can impact the value of public environmental protection programs (Berger *et al.*, 1987; Shogren and Crocker, 1991). Individuals often act to reduce the chance and the severity of prospective undesirable events. However, the physical or the utilitarian consequences of these self-protection actions need not be limited to the actor (Bird, 1987). Economic agents can self-protect by shifting consequences to other agents. For example, the midwestern industrial states in the U.S.A. have reduced their regional air pollution problems by building tall stacks at emitter sites. Prevailing weather patterns then carry increased proportions of regional emissions to the northeastern states and to eastern Canada. The midwestern states have reduced their damages by adopting abatement technologies that increase air pollution damages elsewhere. Other examples abound. Large present usages

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of pesticides accelerate the development of immune insect strains with which future human generations must contend. The pollution from other sources which affects agriculture encourages agricultural land, fertilizer, and pesticide substitutions that produce pollution which affects others (Adams and Crocker, 1989). Some governments forbid the storage of toxins within their jurisdictions, thereby causing the toxins to be stored (or dumped) elsewhere.

Indeed, from the materials balance perspective of Kneese *et al.* (1970), most environmental policy does not resolve environmental problems. It does not reduce the mass of materials used or cause them to accumulate in the economy. While continuing to allow the mass of waste to flow into the environment, it simply transfers this mass through time and across space. Future generations and other jurisdictions then suffer the consequent damages.

Self-protection can also reduce or filter the chance and the severity of undesirable events that others might suffer. A dam that one jurisdiction builds to reduce flooding from an overcut upstream forest also reduces flooding in other downstream jurisdictions. Similarly, a central waste disposal facility built to reduce the broad dispersal of waste in a particular jurisdiction might filter the trash that its residents spread to other jurisdictions. Generally, an agent need not bear all of the consequences of a negative externality. An agent may transform the waste he receives into an economic asset. The person who uses or sells recycled trash moves material flows from the environment to the economy, thus broadening the domain of efficient price signalling. Alternatively, one agent may filter the externality for his neighbors only by transferring or rearranging its temporal and spatial focus to distant agents.

In this paper, we explore the economics of cooperative and noncooperative self-protection in the presence of transferable and filterable externalities. Explorations like this are plausibly important for environmental policy decisions in the forthcoming European Single Internal Market. We use a simple game-theoretic approach to demonstrate the following four propositions.

(1) If self-protection transfers the externality, then noncooperative Nash behavior leads to economically inefficient overprotection. However, if self-protection filters the externality, then Nash behavior leads to underprotection.

(2) If self-protection transfers the externality and if a more powerful self-protecting agent has a first mover advantage, then non-cooperative Stackelberg behavior will cause this agent to protect more than he would without a first-mover advantage.

(3) If an agent is uncertain about the transferability of an externality and if his damage function is elastic with respect to self-protection, then his incentive to overprotect under Nash behavior will be accentuated. Similarly, with a filterable externality, the incentive to underprotect with Nash behavior will be accentuated.

(4) The provision of more information about transferability will accentuate the incentive to overprotect if the damage function is inelastic and Nash behavior reigns.

We use controlled laboratory experiments to test the first two propositions. The experiments fail to support the second proposition. Though we provide no empirical tests of the last two propositions, we offer them because they fall easily from our basic theoretical framework. The paper proceeds as follows. In Section 2, we construct a model of self-protection and transferable and filterable externalities and develop our four propositions from it. A third section presents the results of experiments to test the first two propositions. The paper concludes with a summary and a brief discussion of the implications that our findings have for environmental policy.

II. Self-Protection and Externalities

1. THE FRAMEWORK

Consider any pair of economic agents, i and j, who confront potential economic losses from exposure to a negative externality. Let X_i represent a measure of the physical self-protection inputs that agent i adopts, and have X_j be the same measure for agent j. We write agent i's expected damage function as:

$$D_i(X_i, X_j) = [1 - \pi_i(X_i, X_j)]\, L_i(X_i, X_j) \tag{1}$$

where $[1 - \pi_i(\cdot)]$ is the *ex ante* probability that agent i will suffer the money equivalent of the *ex post* loss, $L_i(\cdot)$. The expected damage function captures the two key components of a prospective undesirable event: the probability, $1 - \pi_i(\cdot)$, that the event will occur and the severity, $L_i(\cdot)$, if the event does occur (Ehrlich and Becker, (1972).[1] Though this distinction between probability and severity is not fundamental to Proposition 1, it allows us to test subsequent propositions using different functional forms for the probability (e.g., the logit) or the severity (e.g., the hyperbolic) of an undesirable event. The distinction between probability and severity is not idle. Shogren (1990) has empirically demonstrated that individuals value reductions in the probability of an undesirable event significantly higher than they value reductions in severity.

Agent i's self-protection is assumed to reduce his expected damages such that

$$\frac{\partial D_i}{\partial X_i} < 0, \quad \text{given } \frac{\partial \pi_i}{\partial X_i} > 0, \quad \text{and } \frac{\partial L_i}{\partial X_i} < 0.$$

The impact of agent j's protection on agent i's expected damage function can take two distinct forms. First, under a given liability regime, if j's protection transfers some portion of the negative externality to agent i, then

$$\frac{\partial D_i}{\partial X_j} > 0, \quad \text{given} \ \frac{\partial \pi_i}{\partial X_j} < 0, \quad \text{and} \ \frac{\partial L_i}{\partial X_j} > 0. \qquad (i \neq j) \tag{2}$$

When agent i transfers some of the externality to agent j, the signs of the equivalent terms in (2) are identical.

Alternatively, if agent j's self-protection activities filter the negative externality for agent i, then

$$\frac{\partial D_i}{\partial X_j} < 0, \quad \text{given} \ \frac{\partial \pi_i}{\partial X_j} > 0, \quad \text{and} \ \frac{\partial L_i}{\partial X_j} < 0. \qquad (i \neq j) \tag{3}$$

Agent i gains from agent j's protection since j has reduced the potency of the externality. When agent i filters for agent j, the signs of the equivalent terms in (3) are identical.

Given that self-protection exists, write agent i's expected costs of exposure to the negative externality as $C_i(X_i, X_j)$. His expected costs include his cost of protection $P_i(X_i)$ and his expected damage function $D_i(X_i, X_j)$. Assume $\partial P_i/\partial X_i > 0$. The expected costs for agents i and j are

$$C_i(X_i, X_j) = P_i(X_i) + D_i(X_i, X_j), \tag{4a}$$

$$C_j(X_j, X_i) = P_j(X_j) + D_j(X_j, X_i). \tag{4b}$$

Assume that $C_i(\cdot)$ is a strictly convex function of X_i, given X_j. Make the same assumption for $C_j(\cdot)$ and X_j, given X_i.

2. COOPERATIVE AND NONCOOPERATIVE BEHAVIOR

A pair of agents can cooperate, where they jointly adopt self-protection measures, or they can act noncooperatively, where they take each other's self-protection measures as given. For example, Germany and Holland can act jointly to reduce pollution of the Rhine River or they can presume that neither is able to influence the waste disposal practices of the other. In the Nash case, the problems of agents i and j are

$$\min_{X_i} C_i(X_i, X_j) = P_i(X_i) + D_i(X_i, X_j), \tag{5a}$$

$$\min_{X_j} C_j(X_j, X_i) = P_j(X_j) + D_j(X_j, X_i). \tag{5b}$$

Given our convexity assumption on the $C(\cdot)$'s, the noncooperative interior solution is obtained when

$$\frac{\partial C_i}{\partial X_i} = \frac{\partial P_i}{\partial X_i} + \frac{\partial D_i}{\partial X_i} = 0, \tag{6a}$$

$$\frac{\partial C_j}{\partial X_j} = \frac{\partial P_j}{\partial X_j} + \frac{\partial D_j}{\partial X_j} = 0. \tag{6b}$$

Let the solutions in (6a) and (6b) be $\hat{X}_i$ and $\hat{X}_j$. The noncooperative solution can therefore be defined as $(\hat{X}_i, \hat{X}_j)$ such that $C_i(\hat{X}_i, \hat{X}_j) \leqslant C_i(X_i, \hat{X}_j)$ and such that $C_j(\hat{X}_j, \hat{X}_i) \leqslant C_j(X_j, \hat{X}_i)$.

The cooperative solution requires that joint costs be minimized, thus

$$\min_{X_i, X_j} \bar{C} \equiv C_i(\cdot) + C_j(\cdot) = P_i(X_i) + P_j(X_j) + D_i(X_i, X_j) + D_j(X_j, X_i). \tag{7}$$

The conditions for an interior solution to (7) are

$$\frac{\partial \bar{C}}{\partial X_i} = \frac{\partial P_i}{\partial X_i} + \frac{\partial D_i}{\partial X_i} + \frac{\partial D_j}{\partial X_i} = 0, \tag{8a}$$

$$\frac{\partial \bar{C}}{\partial X_j} = \frac{\partial P_j}{\partial X_j} + \frac{\partial D_j}{\partial X_j} + \frac{\partial D_i}{\partial X_j} = 0. \tag{8b}$$

Let the solutions in (8a) and (8b) be $\bar{X}_i$ and $\bar{X}_j$. The cooperative solution can therefore be defined as $(\bar{X}_i, \bar{X}_j)$ such that $C_i(\bar{X}_i, \bar{X}_j) \leqslant C_i(X_i, \bar{X}_j)$, and such that $C_j(\bar{X}_j, \bar{X}_i) \leqslant C_j(X_j, \bar{X}_i)$. We can now state our first proposition.

PROPOSITION 1. *For the case of transfer, $\bar{X}_i < \hat{X}_i$, and $\bar{X}_j < \hat{X}_j$. This means that noncooperation results in overprotection. For the filtering case, $\bar{X}_i > \hat{X}_i$, and $\bar{X}_j > \hat{X}_j$. This means that noncooperation results in underprotection.*

Proof: Following Marchand and Russell (1973), evaluate the cooperative optimality conditions (8a) and (8b) at the noncooperative solution $(\hat{X}_i, \hat{X}_j)$. This results in

$$\frac{\partial \bar{C}(\hat{X}_i, \hat{X}_j)}{\partial \hat{X}_i} = \frac{\partial P_i(\hat{X}_i)}{\partial \hat{X}_i} + \frac{\partial D_i(\hat{X}_i, \hat{X}_j)}{\partial \hat{X}_i} + \frac{\partial D_j(\hat{X}_j, \hat{X}_i)}{\partial \hat{X}_i} \neq 0. \tag{9a}$$

$$\frac{\partial \bar{C}(\hat{X}_j, \hat{X}_i)}{\partial \hat{X}_j} = \frac{\partial P_j(\hat{X}_j)}{\partial \hat{X}_j} + \frac{\partial D_j(\hat{X}_j, \hat{X}_i)}{\partial \hat{X}_j} + \frac{\partial D_i(\hat{X}_i, \hat{X}_j)}{\partial \hat{X}_j} \neq 0. \tag{9b}$$

If $\bar{C}(\cdot)$ is strictly convex, and if self-protection transfers the externality from one party to the other such that (2) holds, then (9a) and (9b) are positive, implying $\bar{X}_i < \hat{X}_i$ and $\bar{X}_j < \hat{X}_j$. However if self-protection filters the externality such that (3) holds, then $\bar{X}_i > \hat{X}_i$ and $\bar{X}_j > \hat{X}_j$. Q.E.D.

An observation that noncooperative, unilateral behavior can lead to inefficient resource allocation is hardly unique. Cournot (1838) showed that concerted actions can increase economic efficiency. What is important about Proposition 1 is the observation that self-protection from a transferable or a filterable externality can create yet another externality. Sterner (1990) argues that most environmental policy simply transfers rather than resolves externalities. In the absence of publicly imposed limits to individuals' noncooperative self-protection activities, heedlessness of Proposition 1 could make environmental improvements and preservation seem prohibitively expensive.

When externalities can be transferred, Proposition 1 contrasts with conventional economic arguments regarding externality abatement (self-protection) activities. Conventional theory, which disregards transferability, concludes that efficient resolution of an externality requires abatement. If externality reductions are to some degree indivisible in consumption and nonexclusive, free riding behavior appears and underprotection results, just like the filterable case (see Baumol and Oates, 1988). Transferable negative externalities suggest however that noncooperating self-protectors abate too much. Externality control strategies that achieve abatement by encouraging self-protection that induces transfers need to be reconsidered. When transfers are technically feasible, the strategies only intensify the inefficiencies inherent in noncooperative behavior.

Empirical research to estimate the magnitude of the inefficiencies engendered by noncooperative environmental protection policies should be of high priority. This research will be eased by prior restrictions that reduced the set of stories consistent with the data. We now develop three such restrictions on the manner in which these inefficiencies change with differences in damage function elasticities, information about transferability, and access to self-protection inputs. Specification of how these inefficiencies change is crucial to any systematic evaluation of the tradeoff between the cost-savings of cooperation and the costs of the sovereignty losses that cooperation entails.

3. FIRST MOVER ADVANTAGE AND EXTERNALITY TRANSFERS

Conventional economic analysis focuses solely upon the actual or the expected size of the monetary or the utility gains from the market participation game. The game exists and it is costlessly available to anyone who wishes to play it. Access is free; no ante is required to play the game. Each individual is already active in it. However, because of differences in information or in endowments, agents often differ in their access to opportunities to participate. The classic David—Goliath matchup is an example. Goliath's better access may provide him a first-mover advantage because he can commit his level of self-protection (Dixit, 1987).

In order to illustrate the effects of strategic commitment upon self-protection, we focus exclusively upon transferable externalities. Following Tullock (1980), presume that agent i's probability of suffering or not suffering damages can be represented by a logit function such that

$$D_i(X_i, X_j) = \left[1 - \frac{\alpha X_i^r}{\alpha X_i^r + X_j^r} \right] L_i, \tag{10}$$

where r is a parameter. The logit function is widely used in the economic theory of contests, e.g., Hirshleifer (1988).[2]

Let α be a measure of agent i's access to self-protection opportunities relative to agent j's access. If $\alpha > 1$, then agent i has better access than does agent j. For example, control agencies make errors in their assessments of pollution damages and control costs. If the control agency cannot recognize efforts to mislead it, pollution perpetrators can then gain by using input combinations that increase the likelihood of those errors that exaggerate control costs; pollution sufferers will use input mixes that increase the likelihood of those errors that exaggerate pollution damages (Crocker, 1984). Both sufferers and perpetrators are practicing self-protection. If $\alpha > 1$, and if the sufferer were agent i, then errors that exaggerate pollution damages would be easier to assure than would those that exaggerate control costs. If the opposite were true, then $\alpha < 1$.

For simplicity, assume that $r = 1$ in (10), and that $L = L_i = L_j$ is exogenous.[3] As with (5a) and (5b), any noncooperative solution then results from agents i and j respectively solving

$$\min_{X_i} C_i(X_i, X_j) = P_i(X_i) + \left[1 - \frac{\alpha X_i}{\alpha X_i + X_j}\right] L, \tag{11a}$$

$$\min_{X_j} C_j(X_j, X_i) = P_j(X_j) + \left[1 - \frac{X_j}{\alpha X_i + X_j}\right] L. \tag{11b}$$

Again, let the Nash solution be $\hat{X} = (\hat{X}_i, \hat{X}_j)$.

Given that $P_i(X_i)$ and $P_j(X_j)$ are symmetric constants and no greater than L, the reaction functions $R_i(X_j)$ and $R_j(X_i)$ resulting from (11a) and (11b) are

$$R_i(X_j) = \frac{1}{\alpha} \left[(L\alpha X_j/(\partial P_i/\partial X_i))^{1/2} - X_j\right], \tag{12a}$$

$$R_j(X_i) = \left[(L\alpha X_i/(\partial P_j/\partial X_j))^{1/2} - \alpha X_i\right]. \tag{12b}$$

If both agents self-protect simultaneously against the transferable externality such that neither has a first-mover advantage, then the Nash equilibrium is

$$\hat{X} = (\hat{X}_i, \hat{X}_j) = \left[\frac{\alpha L}{(\partial P_j/\partial X_j)(1+\alpha)^2}, \frac{\alpha L}{(\partial P_i/\partial X_i)(1+\alpha)^2}\right]. \tag{13}$$

According to (13), if $\alpha > 1$ such that agent i has better access to self-protection opportunities, then he has more than an even chance of not having to endure the externality, i.e., of transferring it to agent j.

Now allow agent i to be a first-mover such that he is able to commit his self-protection. For example, because he expects that the public will soon demand pollution control, an agriculturist who is a pollution sufferer might now adopt production strategies that exaggerate the appearance of damages before the perpetrator can do anything to make his control costs appear greater. The relevant Stackelberg solution to expressions (11a) and (11b) is then

$$X^* = (X_i^*, X_j^*) \begin{cases} \left[\dfrac{\alpha L}{4(\partial P_j/\partial X_j)}, \dfrac{\alpha L(2-\alpha)}{4(\partial P_i/\partial X_i)}\right] & \text{iff } \alpha \leqslant 2, \\ \left[\dfrac{L}{(\partial P_j/\partial X_j)\alpha}, 0\right] & \text{iff } \alpha > 2. \end{cases} \tag{14}$$

Proposition 2 results from a comparison of the Nash solution $\hat{X} = (\hat{X}_i, \hat{X}_j)$ in (13) to the Stackelberg solution $X^* = (X_i^*, X_j^*)$ in (14).

PROPOSITION 2. *If one noncooperating agent has a first-mover advantage as well as better access to self-protection resources, then this agent will self-protect more than in the Nash case, and total protection will exceed the Nash case.*

Proof: Without loss of generality, consider a specific parameterization of (13) and (14). In particular, let $\alpha = 2$, $L = 36$, and $\partial P_i/\partial X_i = \partial P_j/\partial X_j = 1$. The Nash solution is then $(\hat{X}_i, \hat{X}_j) = (8, 8)$, where agent i has a 2/3 chance of transferring the externality. For the same chance, the Stackelberg solution is $(X_i^*, X_j^*) = (18, 0)$. This implies that in a noncooperative setting the more powerful agent commits more resources to self-protection in the Stackelberg case than in the Nash case. Q.E.D.

Proposition 2 suggests that if the more powerful agent moves first, then noncooperative behavior among asymmetric players will lead to greater inefficiency relative to the Nash and to the cooperative outcomes. Given the uneven economic strengths of European Economic Community members, this source of greater inefficiency adds strength to the argument that coordinated environmental policies can make important contributions to the benefits of the Single Internal Market of 1992.

4. UNCERTAIN TRANSFERABILITY

Our first two propositions presume that all agents are uncertain about damages but that they know the extent to which the externality can be transferred or filtered. We now consider the implications for self-protection decisions of uncertainty about the extent to which a negative externality can be transferred.[4] For example, the U.S. midwestern states may be uncertain about the extent to which tall stacks will shift air pollution damages to the northeastern states and to Canada. Let $\beta \geqslant 0$ be the unknown degree of transferability, and let $F(\beta;\ \theta)$ be the cumulative distribution of β defined over the support $[a, b]$, where θ is an information parameter and where a and b are respectively the zero and the complete transfers. $F(\cdot)$ is twice continuously differentiable in θ for every value of β. For simplicity, we let $F(\cdot)$ be identical for all agents. Assume that as $\beta \to 1$, the full externality is transferable. A $\beta > 1$ implies that the recipient overestimates the degree to which the externality can be transferred to him.

The noncooperative protection problem can now be written as:

$$\operatorname*{Min}_{X_i} \tilde{C}_i(X_i, \beta X_j) = P_i(X_i) + \int_a^b D_i(X_i, \beta X_j)\, \mathrm{d}F(\beta; \theta), \tag{15a}$$

$$\operatorname*{Min}_{X_j} \tilde{C}_j(X_j, \beta X_i) = P_j(X_j) + \int_a^b D_j(X_j, \beta X_i)\, \mathrm{d}F(\beta; \theta). \tag{15b}$$

Given uncertain transferability, let the Nash solution to (15a) and (15b) be $\tilde{X} = (\tilde{X}_i, \tilde{X}_j)$. We can now state our third proposition.

PROPOSITION 3. *Given noncooperation in self-protection, uncertain transferability increases self-protection effort relative to the certainty case if the damage function is elastic with respect to self-protection effort, i.e.,* $\tilde{X} > \hat{X} > \bar{X}$.

Proof: Consider the first-order necessary conditions for (15a) and (15b):

$$\frac{\partial \tilde{C}_i}{\partial X_i} = \frac{\partial P_i}{\partial X_i} + \int_a^b \frac{\partial D_i}{\partial X_i}\, \mathrm{d}F(\cdot) = 0, \tag{16a}$$

$$\frac{\partial \tilde{C}_j}{\partial X_j} = \frac{\partial P_j}{\partial X_j} + \int_a^b \frac{\partial D_j}{\partial X_j}\, \mathrm{d}F(\cdot) = 0, \tag{16b}$$

and compare these to the Nash solutions under certainty. For the certainty case, let $\beta = E(\beta)$, where E is the expectations operator. Damages in the certainty case thus become $D_i[X_i, E(\beta)X_j]$ and $D_j[X_j, E(\beta)X_i]$. Finally, write

$$\frac{\partial E(D_i)}{\partial X_i} = \int_a^b \frac{\partial D_i}{\partial X_i}\, \mathrm{d}F(\cdot), \tag{17}$$

for agent i's marginal expected damages.

When the damages for the certainty case are substituted into (16a) and (16b), we obtain

$$\frac{\partial \tilde{C}_i}{\partial X_i} = \frac{\partial P_i}{\partial X_i} + \frac{\partial D_i(X_i, E(\beta)X_j)}{\partial X_i} = 0, \tag{18a}$$

$$\frac{\partial \tilde{C}_j}{\partial X_j} = \frac{\partial P_j}{\partial X_j} + \frac{\partial D_j(X_j, E(\beta)X_i)}{\partial X_j} = 0. \tag{18b}$$

However, Jensen's Inequality implies that

$$\frac{\partial E(D_i)}{\partial X_i} \gtrless \frac{\partial D_i(X_i, E(\beta)X_j)}{\partial X_i}, \tag{19}$$

according to whether $\partial E(D_i)/\partial X_i$ is strictly convex or concave with respect to X_j. An identical argument holds for agent j. It then follows that

$$\tilde{X}_i \lesseqgtr \hat{X}_i \text{ according to } \frac{\partial^3 E(D_i)}{\partial X_i \partial X_j^2} \gtreqless 0. \tag{20}$$

Symmetrical results apply to agent j.

Generalizations about the conditions which determine the sign that expression (20) takes on are difficult. In order to provide more specificity, consider the following hyperbolic form for agent i's damage function.

$$D_i(X_i, X_j) = (X_j/X_i)^{\phi}, \tag{21}$$

where i's probability of damages is constant. The ϕ parameter has a simple and precise interpretation: ϕ is the elasticity of agent i's damages with respect to the contribution of agent j's self-protection to these damages relative to the (negative) contribution to his own damages of agent i's self-protection: that is

$$\phi = \frac{\mathrm{d}D_i}{\mathrm{d}(X_j/X_i)} \cdot \frac{(X_j/X_i)}{D_i}. \tag{22}$$

Given the form in (21), expression (20) is then

$$\frac{\partial^3 D_i}{\partial X_i \partial X_j^2} = \frac{\phi^2 D_i}{X_i X_j^2}(1 - \phi), \tag{23}$$

and

$$\frac{\partial^3 D_i}{\partial X_i \partial X_j^2} \lesseqgtr 0 \text{ according to } \phi \gtreqless 1. \tag{24}$$

Thus if the damage function is elastic such that $\phi > 1$, then agent i's marginal damages are concave in the X_j. Given strict convexity in the $\tilde{C}(\cdot)$, a convex marginal damage function therefore implies that $\tilde{X} > \hat{X}$. Q.E.D.

COROLLARY 3.1. *If the damage function is hyperbolic and sufficiently inelastic, noncooperative self-protection efforts under uncertain transferability will approach the cooperative self-protection efforts under certainty, i.e.,* $\hat{X} > \tilde{X} \rightarrow \bar{X}$.

Proof: Follow the proof of Proposition 3 but assume that the damage function is inelastic, $\phi < 1$. Given strict convexity in the $\tilde{C}(\cdot)$, a convex marginal damage function implies that $\hat{X} > \tilde{X}$. If the function is sufficiently elastic, then $\tilde{X}$ will approach $\bar{X}$ from above. Q.E.D.

COROLLARY 3.2. *A sufficiently inelastic hyperbolic damage function* can *cause the noncooperative behavior under uncertain transferability to result in underinvestment in self-protection.*

Proof: Evaluate agent *i*'s cooperative optimality condition (8a) under certain transferability at his Nash solution under uncertain transferability:

$$\frac{\partial \bar{C}(\tilde{X}_i, \tilde{X}_j)}{\partial \tilde{X}_i} = \frac{\partial P_i(\tilde{X}_i)}{\partial \tilde{X}_i} + \frac{\partial D_i(\tilde{X}_i, E(\beta)\tilde{X}_j)}{\partial \tilde{X}_i} + \frac{\partial D_j(\tilde{X}_j, E(\beta)\tilde{X}_i)}{\partial \tilde{X}_i}. \tag{25}$$

A similar condition will apply to agent *j*. Given strict convexity of the marginal damage function, it then follows that if $\phi < 1$ such that

$$\frac{\partial E(D_i)}{\partial \tilde{X}_i} - \frac{\partial D_i(\tilde{X}_i, E(\beta)\tilde{X}_j)}{\partial \tilde{X}_i} < 0,$$

then

$$\Phi = \frac{\partial P_i(\tilde{X}_i)}{\partial \tilde{X}_i} + \frac{\partial D_i(\tilde{X}_i, E(\beta)\tilde{X}_j)}{\partial \tilde{X}_i} < 0, \tag{26}$$

and the sum of the first two terms on the right-hand-side of expression (25) is negative. Given strict convexity of $\bar{C}(\cdot)$, if Φ is greater than the last term, $\partial D_j(\cdot)/\partial \tilde{X}_i$, on the right-hand-side of (25), then $\partial \bar{C}/\partial \tilde{X}_i < 0$, and $\tilde{X}_i < \bar{X}_i$.

Q.E.D.

Proposition 3 and its corollaries demonstrate that the impact of uncertain transferability upon the inefficiencies of noncooperative self-protection depends on the convexity of the marginal damage function, $\partial D_i/\partial X_i$, with respect to X_j. If the damage function is hyperbolic, this convexity can be directly related to the damage function elasticity. An elastic damage function implies that the marginal impact of self-protection upon own-damages is highly responsive to the self-protection acts adopted by other agents. An elastic damage function with noncooperation and uncertain transferability accentuates overprotection; an inelastic damage function attenuates it. Thus environmental policies that transfer externalities by shifting space and time foci in an imperfectly understood fashion will prompt strenuous protection efforts on the part of recipients who have an elastic damage function. Limited empirical evidence supports an elastic damage function for environmental aesthetics and for environmental health hazards when pollution levels are low and an inelastic damage function when pollution levels are high.[5] Therefore, for the aesthetic and the health impacts of pollution, noncooperative environmental improvements could be self-defeating when pollution levels are already low. Aggregate expenditures on protection may then outweigh the environmental benefits generated. Alternatively, some pollutants such as ambient carbon monoxide exhibit inelastic damages at low levels and elastic damages at high levels. It follows that accurate assessments of the benefits of moving from noncooperative to cooperative environmental protection policies require precise knowledge of the form of the noncooperative damage function.

5. ADDITIONAL INFORMATION

Assume that players costlessly acquire additional information on β, the degree of transferability. For example, improvements in abatement technologies, altered liability rules, or hazard warnings might reduce uncertainty about β.[6] Recall that θ is an information parameter for which an increase results in a mean-preserving reduction in the spread of the distribution $F(\beta;\, \theta)$, that is

$$\int_a^\beta \frac{\partial F(\cdot)}{\partial \theta}\, \mathrm{d}K < 0. \tag{27}$$

This leads to a fourth proposition.

PROPOSITION 4. *With an inelastic (elastic) damage function, an increase in information about the transferability of a negative externality accentuates (attenuates) the overinvestment in self-protection that results from noncooperative Nash behavior.*

Proof: This counterintuitive proposition can be demonstrated by assuming that the implicit function theorem holds, applying Cramer's rule, and twice integrating by parts. One then obtains

$$\frac{\partial \tilde{X}_i}{\partial \theta} = \frac{-1}{Z}\left[\int_a^b \left\{\int_a^\beta \frac{\partial F(K;\, \theta)}{\partial \theta}\, \mathrm{d}K\right\} \frac{\partial^3 D_i}{\partial X_i \partial X_j^2}\, \mathrm{d}\beta\right], \tag{28}$$

where, by assumption that the second-order conditions are fulfilled such that

$$Z = \frac{\partial^2 P_i}{\partial X_i^2} + \frac{\partial^2 E(D_i)}{\partial X_i^2} > 0.$$

From Proposition 3,

$$\frac{\partial^3 D_i}{\partial X_i \partial X_j^2} \lesseqgtr 0 \text{ according to } \phi \gtreqless 1.$$

Therefore, for an inelastic damage function

$$\phi < 1 \text{ implies } \frac{\partial \tilde{X}}{\partial \theta} > 0. \tag{29}$$

The opposite holds with an elastic damage function. Q.E.D.

Sandler and Lapan (1988) obtain a result similar to Proposition 4. They show that a piecemeal policy of information provision only accentuates the inefficiencies of noncooperative protection activities. Note in our model, however, that additional information can reduce the inefficiency associated with the transferable externality. If one is on an elastic portion of the damage function, then the provision of information about transferability will cause noncooperative protection expenditures to approach from above the level of cooperative expenditures. Again, our results suggest that precise knowledge of the elasticity of the damage function is imperative for economically efficient environmental policies. In a noncooperative setting, if public provision of information about transferable environmental hazards is to reduce inefficiencies, the damage function must be elastic. Damage function elasticities are likely to be hazard specific and activity specific, as well as concentration or level specific. Consequently, the generalizations of Viscusi and Magat (1987) and Smith *et al.* (1990) about the efficacy of hazard information programs as alternatives to direct regulation must be qualified. Though these authors readily grant that public information provision may cause individuals to self-protect, they do not address the idea that this information may induce them to self-protect in economically inefficient ways.

III. Experimental Results: Propositions 1 and 2

We have constructed experiments to test the first two propositions. Brief descriptions follow. Detailed explanations of the experiment to test Proposition 1 are available in Shogren (1990) and in Crocker and Shogren (1991b); Shogren and Baik (1990) set forth the details of the Proposition 2 experiment.

In order to test Proposition 1, we constructed sixteen experimental markets for the purchase of protection from four probability levels of suffering a wealth loss. Each market involved six participants. In each market, every participant, either cooperatively or noncooperatively, made a sequence of twelve bids to reduce a particular probability of a wealth loss to zero. Gains, losses and purchases were not transferable across bidding rounds and side payments were forbidden.

The cooperative processes were constructed as modified Smith (1980, 1982) auctions. If the sum in these auctions of the individual participants' bids in each bidding round equaled or exceeded the predetermined cost of reducing the probability of a wealth loss to zero, then an adjusted bid was posted. If each participant then agreed to contribute this bid to the sum, the protection asset was provided to all. Otherwise, no protection was provided. Before making their initial individual bids, all participants knew the conditions under which protection would be provided.

The noncooperative processes were structured as Vickrey (1961) sealed-bid, second price auctions. Only the highest bidder received protection. He had to pay the second highest bid. Both his randomly assigned number and the amount of the second highest bid were posted as public information at the end of each bidding round. The sealed bids in each round were submitted simultaneously. In accordance with the definitions in Expression (1), four of the sixteen protection markets involved assets that reduced the probability (1, 10, 20, or 40 percent) of a wealth loss to zero. These assets could only be purchased noncooperatively. Another four markets were for the cooperative acquisition of these same assets. The noncooperative acquisition of severity-reducing assets made up a third set of four markets, while the final four markets allowed participants to cooperate in acquiring severity-reducing assets.

In each market, Wilcoxon rank-sum tests showed that arithmetic mean bids taken over twelve bidding rounds to reduce risk levels of forty, twenty, ten, and one percent to zero were not drawn from the same parental distribution (ninety-five percent confidence). More significantly, these same tests showed that the arithmetic mean bids in the noncooperative markets for each risk level were not drawn from the same parental distribution as the corresponding bids in the cooperative markets. For probability-reducing assets, noncooperative bids exceeded cooperative bids in each and every round for each and every risk level but one. For severity-reducing assets, noncooperative bids exceeded cooperative bids in each and every bidding round for each and every risk level but one. These results are consistent with Proposition 1. Figures 1 and 2 display the experimental results. Bidding rounds are on the horizontal axes and bids in dollars reside on the vertical axes.

The experiments reported by Shogren and Baik (1990) do not support Proposition 2. These experiments confronted participants with an explicit payoff matrix with elements in numbers of dollars. Twenty-two participants were divided equally into favorites (Goliaths) and underdogs (Davids) and communication between groups was forbidden. Each participant competed to preserve an initial endowment against an opponent from the other group. Every participant knew that the chance he would be able to preserve this endowment depended upon the dollar number he selected from the payoff matrix as well as the number selected by his opponent. A one-to-one relation existed between numbers and their costs. Participants thus had to choose between endowment preservation and cost. Goliaths first selected a number in each trial: they had a first-mover advantage. The Stackelberg equilibrium had the favorite select the number 18, the underdog zero (see Figure 3).

Goliaths did not overcommit relative to the Nash case even though they had the first-mover advantage. They behaved as Nash agents where each player selected the number 8. Moreover, the Davids never exited the game. Instead, they consistently bought more protection than did the Goliaths. Strategic commitment did not accentuate the Goliaths' overprotection. The experimental evidence offered no support for Proposition 2. Figure 3 illustrates the evidence from 20 actual trials and 2 practice trials. Over the last

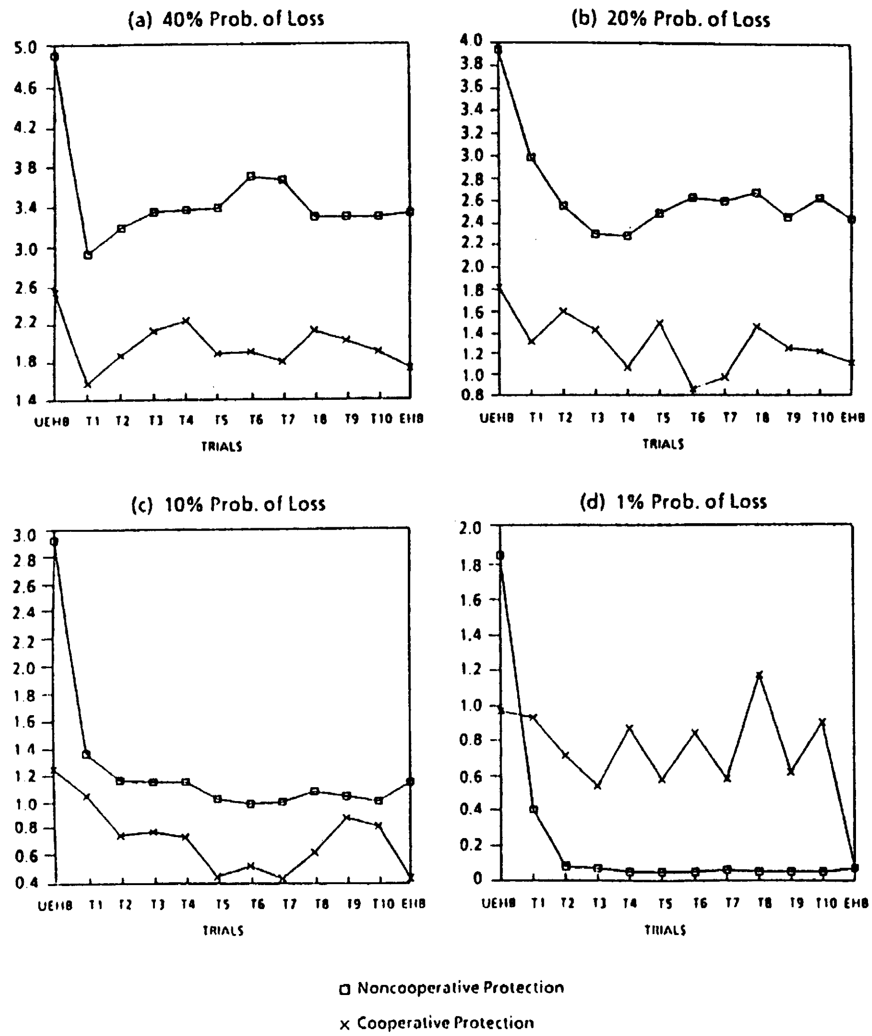

Fig. 1. Cooperative and noncooperative severity protection (mean bids).

10 trials, Goliath's mean bid was not significantly different (95% confidence) from the Nash level.

IV. Summary and Conclusions

Contrary to the literature, self-protection need not be thoroughly nonrivalrous and excludable. My protective actions can transfer some of the bad to

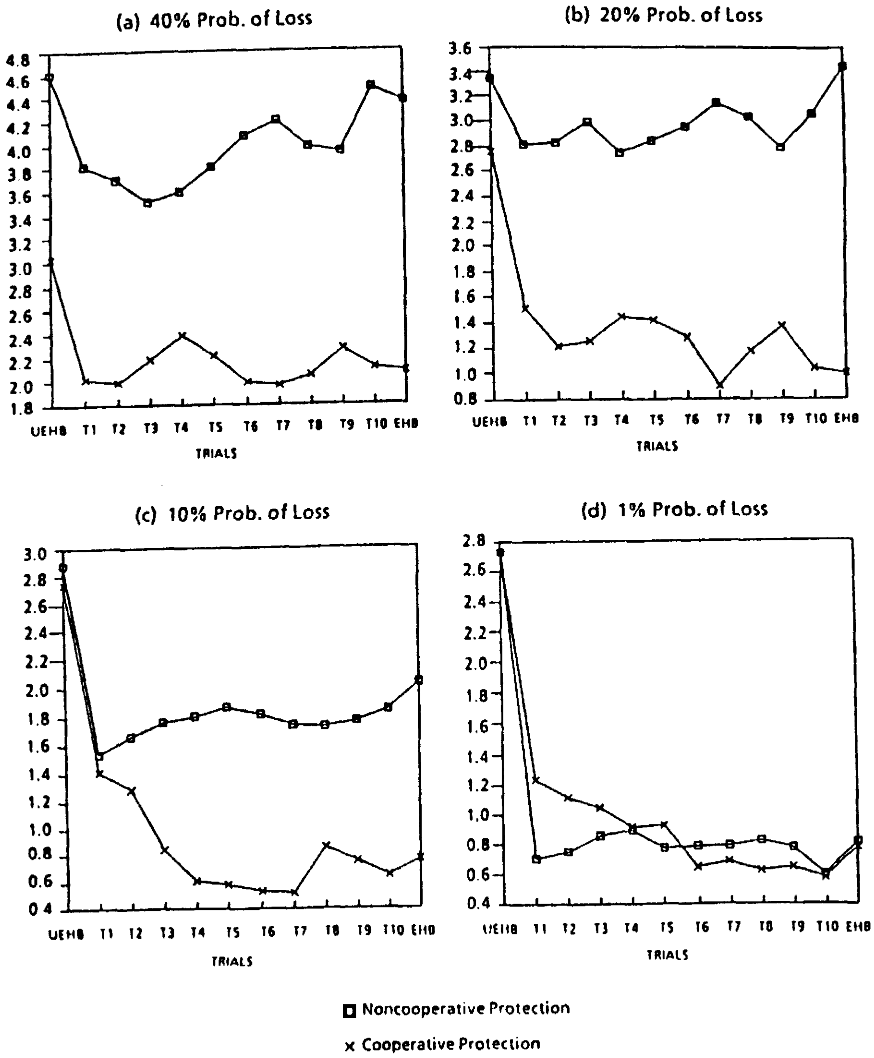

Fig. 2. Cooperative and noncooperative probability protection (mean bids).

you, or I can filter the bad, diluting it before it reaches you. We have demonstrated that the manner in which agents who are affected by a bad produce self-protection has efficiency implications. In particular, noncooperation will lead to economically excessive commitments of self-protection resources if the bad is transferable with certainty and undercommitments of self-protection resources if the bad is filterable with certainty. Experimental evidence is offered to support this theoretical result but it does not support

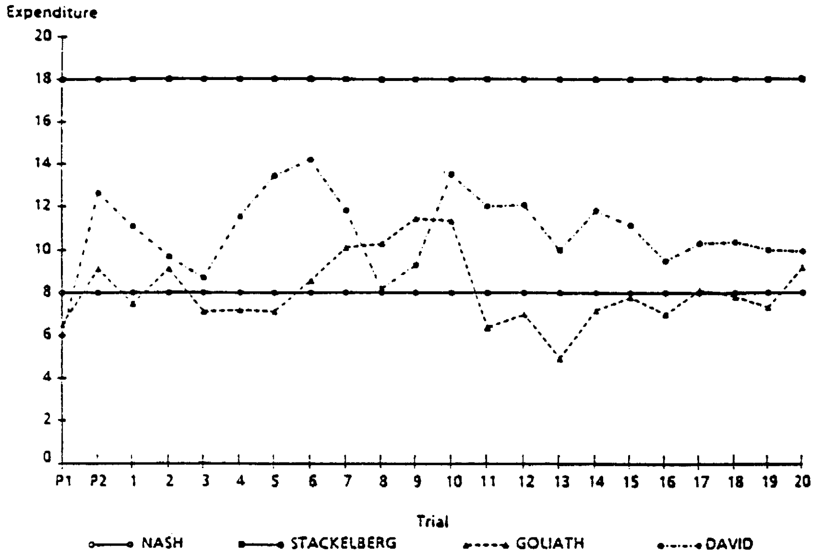

Fig. 3. Protection from transferable externality: Stackelberg noncooperative behavior (mean expenditure).

another result which stated that a first-mover advantage will intensify the overprotection inherent in noncooperation. Although no empirical evidence is offered in support or denial, two further propositions and associated corollaries are easily developed from our basic formulation. In particular, we are able to show that if damages are elastic with respect to self-protection, uncertainty about transferability will accentuate the overprotection that noncooperation causes. Finally, if noncooperation dominates, transferability is uncertain, and damages are inelastic, an improvement in information about transferability will further accentuate the incentive to over-protect. Nearly every complication (strategic behavior, damage function elasticities, uncertainty, reduced uncertainty) that we introduced to our elementary noncooperative Nash case accentuated the opportunity cost of noncooperative self-protection. The foregone opportunity was cooperative self-protection. All of our results suggest that in the presence of transferable or filterable bads, societies can save considerable resources by developing risk sharing institutions, perhaps with side payments, that foster cooperation in their environmental protection efforts. Failure to do so results in the expenditure of valuable protection resources at no gain in environmental quality. Moreover, coordination minimizes the costs of environmental protection and thereby reduces the public credibility of its numerous foes.

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Notes

[1] The adoption of an *ex ante* perspective is imperative. Self-protection is inherently forward-looking and must therefore involve uncertainty.

[2] Hirshleifer (1988) points out that the logit function implies a contest played under near-ideal conditions: a level playing field, full information, and consistent efficiency of effort. When conditions are ideal, a player devoid of skill must loss his initial endowment every time that he plays. We call upon the logit function to construct a specific example amenable to laboratory testing of the general theory of contests. If the general theory holds, then the specific example must hold.

[3] Shogren and Baik (1991) have used (10) to demonstrate that a pure strategy Nash equilibrium exists if and only if $r \leqslant 2$.

[4] We leave to subsequent work the question of whether or not the cooperative equilibrium exists in these circumstances and the threat points in a repeated games context necessary for it to persist. Lave (1982), for example, believes that institutional roadblocks and the uncertainties surrounding climate modelling make near impossible cooperative equilibrium with respect to CO_2 — induced climate change. He suggests that individual jurisdictions should self-protect unilaterally.

[5] See for example, Crocker and Shogren (1991a) on atmospheric visibility and Smith and Desvousges (1987) on health hazards from toxic wastes. Shogren and Crocker (1991) show that in the presence of self-protection this pattern of increasing marginal valuations with decreasing pollution is *not* in violation of expected utility theory.

[6] In the United States, hazard warnings and self-protection advice are currently being considered as potentially attractive alternatives to traditional command-and-control regulations regarding consumer product safety (see Colantoni, *et al.* 1976 and Johnson, 1989). The premise is that individual autonomy involves informed consent. Given that the aversion to hazards varies widely in the population, hazard warnings require that the government or a third party disseminate information in forms most useful to the population. The individual then selects a level of self-protection consistent with his aversion to the hazard. Nothing forbids transfer as a means of self-protection.

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