Transboundary Fisheries Management under Implementation Uncertainty

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Summary

This paper examines how non-binding co-operative agreements on marine fisheries management can be sustained when management plans in participating countries are implemented with error. The effects of implementation uncertainty on voluntary co-operation are compared to those of recruitment uncertainty. A self-enforcing co-operative solution can only be sustained when uncertainty is not too pronounced. Even when a co-operative agreement can be achieved, frequent phases of reversion to non-co-operative harvest levels are needed to support the agreement. The implications of recruitment uncertainty for implicit co-operation are less detrimental than those of implementation uncertainty.

Keywords: Fisheries management, Transboundary fisheries, Non-cooperative games, Implementation uncertainty

JEL: Q22, C72

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1 Introduction

Problems in marine resource management have over the years received increasing attention among the media and policy makers. Disputes over the management of fish stocks have been heated both at the national and international level. At times conflicts have culminated in military vessels being summoned to the fishing grounds. Conflicts in fisheries management are difficult enough to resolve within a single jurisdiction. The difficulties are compounded when a fish stock is divided among separate jurisdictional regions, each with their own management authority. Despite a mutual advantage in cooperative harvesting of shared stocks, agreements on cooperative harvesting have proved to be difficult to establish. Why is cooperation in the international management of fisheries such a fragile endeavor?

One challenge to transboundary fisheries management is the lack of international jurisdiction with the authority to enforce agreements. Any agreement on cooperative management has to be self-enforcing. A large literature of game theory models illustrates mechanisms designed to resolve conflicts over the international harvesting of fish. Munro (1979), Clark (1980), Kaitala and Pohjola (1988), Levhari and Mirman (1980), and Vislie (1987), among others, study simultaneous harvest of a single fish stock by competing fleets. Hannesson (1997) examines how critical the number of agents sharing a fish stock is for realizing the cooperative solution. Hannesson (1995) and McKelvey (1997) address the management of a sequentially harvested fish stock. Hannesson examines cooperative management as a self-enforcing equilibrium in a non-cooperative game. McKelvey studies the transboundary fishery problem in a principal-agent setting. Kaitala and Munro (1997) and Kaitala and Lindroos (1998) study the related question of the management of straddling fish stocks.

With the exception of McKelvey (1997), the game theoretic literature reviewed above neglects uncertainty. Yet fisheries are plagued by uncertainty regarding biological processes as well as implementation of management objectives.[1] When stock recruitment varies stochastically or management plans are implemented with error, parties negotiating over cooperative management cannot monitor adherence to the agreement by other fleets.

[1] In the context of a fishery managed by a single authority, fisheries management under uncertainty has received considerable attention. Sethi et al. (2002) analyze a bioeconomic model with multiple sources of uncertainty. Reed (1978, 1979) considers stochastic variation in recruitment. Clark and Kirkwood (1986) examine variation in stock measurements.

Enforcement of agreements becomes more difficult. Laukkanen (2003) considers stochastic stock recruitment in a transboundary fishery where two fleets operate sequentially, and describes a self-enforcing agreement that can support cooperative harvesting. Another important source of variation is the ability of management in each country participating in negotiations to achieve management targets in any one year. We study the effects of this source of uncertainty, which we refer to as implementation uncertainty, on the prospects of international cooperation. We compare the implications of implementation uncertainty and recruitment uncertainty for cooperative harvesting. Differing from the sequential fishery model in Laukkanen (2003), we consider a shared fishery where the competing countries harvest simultaneously. Growth and reproduction depend on how much each fleet leaves behind after harvesting.

The results indicate that non-binding cooperation in a shared fishery with implementation uncertainty can only be sustained when uncertainty is not too prevalent. Even when cooperative harvesting can be agreed upon, the parties engage in frequent punishment phases of reversion to the non-cooperative harvesting strategies. The implications of recruitment uncertainty for non-binding cooperation are less detrimental than those of implementation uncertainty. The agreement obtains for larger fluctuations, and less frequent punishment phases are necessary to sustain cooperation.

2 The Bioeconomic Model

We extend Hannesson's (1997) model of a transboundary fishery to consider uncertainty in the form of inaccurate implementation of target escapements. Consider two countries that harvest a shared stock of fish. Each country harvests in its own area where harvest is controlled by a single management authority. The fish migrate only slowly between the areas. Each country harvests the portion of the stock that is present in its fishing area. Stock growth depends on the aggregate size of the stock. Such interdependency arises for example when fish migrate in a seasonal pattern or when eggs and larvae are distributed over the entire habitat of the stock irrespective of where they are spawned. Following Hannesson (1997) we let the stock be measured as a density, i.e. units of fish per unit area. The unit cost of harvest depends on the density of the stock and thus indirectly on the size of the stock, provided that the area that the stock occupies remains constant throughout the fishing season. Without loss of generality we define the area that the stock occupies as the unit area.

The aggregate stock available for harvest in the beginning of a fishing season is X^t. The stock is uniformly distributed over the fishing area shared by two agents. Agent *i* has access to the stock $\gamma_i X^t$, where γ_i is agent *i*'s share of the fishing area.[2] By assumption, the fish do not migrate from one agent's area to another during the fishing season. Each agent then controls harvest and escapement in his area. After the fishing season the stock grows and redistributes itself over the entire area. The growth of the fish stock is determined by how much is left behind in total after harvesting. In the absence of uncertainty, the fish stock changes from one period to the next as follows:

$$(1) \qquad X^{t+1} = R\left(\sum_{i=1}^{2} S_{i,t}\right),$$

where S_i^T is the escapement set by fishery manager *i* and $R\left(\sum_{i=1}^{2} S_{i,t}\right)$ is a differentiable and strictly concave spawning stock – recruitment function.

Implementation uncertainty occurs when there are discrepancies between the intended consequences of management actions and the actual consequences. We model this discrepancy by including random variation in the form of a multiplicative shock on the intended escapement S_i^T of Agent *i*. The actual escapement in subfishery *i* then is $S_{i,t}^R = \theta_{i,t} S_{i,t}^T$. The random shocks $\theta_{i,t}$, $\mathrm{i} = 1,2$, are independent of each other and *t.* Each shock is distributed on a finite interval $[a_i, b_i]$, where $0 < a_i < 1 < b_i < \infty$, with a cumulative distribution function F_i and continuous density f_i. By assumption, the fishery managers know the distributions.

Let *x* denote the size of the stock available to Agent *i* at any moment in time, *c* the unit cost of fishing effort, and *p* the price of catch. Assuming that the harvest follows the Schaefer production function, the marginal cost of harvest for each agent is c/x. In period *t* Agent *i*'s profits from harvesting the stock from $\gamma_i X^t$ down to $S_{i,t}^R = \theta_{i,t} S_{i,t}^T$ are

[2] As noted by Hannesson (1997), the assumption that the fish are uniformly distributed over the fishing area is not necessary for maintaining constant share parameters. It is sufficient to assume that the stock redistributes itself in the same way after each fishing period.

(2) $$\pi_{i,t} = \int_{\theta_{i,t} S_{i,t}^T}^{\gamma_i X^t} \left(p - \frac{c}{x} \right) dx = p\left(\gamma_i X^t - \theta_{i,t} S_{i,t}^T\right) - c\left(ln\,\gamma_i X^t - ln\,\theta_{i,t} S_{i,t}^T\right).$$

The expected present value of harvest is $E_{\theta_{i,t}} \sum_{t=0}^{\infty} \delta^t \pi_{i,t}$, where δ^t denotes the common discount factor δ raised to the tth power. Each agent can either act alone to maximize the expected flow of profits from his share of the fishery, or cooperate with the other fishery manager in order to maximize the joint profit and then bargain for a fair share of that profit.

The action available to Agent i is setting the target escapement $S_{i,t}^T$, which together with the initial stock $\gamma_i X_t$ feeding in Agent i's area and the stochastic multiplier $\theta_{i,t}$ determines Agent i's profits. Agent i's strategy $s_i^t : \Re_+^{2t+1} \to \Re_+$ defines Agent i's target escapement as a function of past and present recruitments and Agent i's past target escapements by $S_{i,t}^T = s_i^t\left(\gamma_i X_0, ..., \gamma_i X_t, S_{i,0}^T, ..., S_{i,t-1}^T\right)$. The choice of domain reflects the fact that Agent i does not observe target escapements set by the competitor but only observes the initial stock $\gamma_i X_t$ available in Area i in the beginning of the fishing season. A contingent strategy for agent i is an infinite sequence $s_i = \{s_i^0, s_i^1, ...\}$. A Nash equilibrium is a strategy profile (s_{1*}, s_{2*}) that satisfies

$$E_{s_1, s_{2*}}\left[\sum_{t=0}^{\infty} \delta^t \pi_1\left(s_{1,t}^T, S_{2,t}^{T*}\right)\right] \le E_{s_{1*}, s_{2*}}\left[\sum_{t=0}^{\infty} \delta^t \pi_1\left(s_{1,t}^{T*}, S_{2,t}^{T*}\right)\right]$$

$$E_{s_{1*}, s_2}\left[\sum_{t=0}^{\infty} \delta^t \pi_2\left(s_{2,t}^T, S_{1,t}^{T*}\right)\right] \le E_{s_1^*, s_2^*}\left[\sum_{t=0}^{\infty} \delta^t \pi_2\left(s_{2,t}^{T*}, S_{1,t}^{T*}\right)\right],$$

for each agent i and all feasible strategies s_i.

We will next consider the implications of non-cooperative harvest in the shared fishery where target escapements are implemented with error. We will then describe a cooperative agreement that can be supported in the presence of implementation uncertainty. We will conclude with a numerical example of the joint management game under implementation uncertainty, and compare the results to an agreement in the case of recruitment uncertainty.

3 Non-cooperative harvesting

We first describe the consequences of non-cooperative harvesting, where each fishery manager sets a target escapement without accounting for its effect on the expected payoff to the other fleet. There are no negotiations or understandings between the agents. Each agent maximizes his expected payoff, taking as given the other fleet's target escapement which he can only infer from his knowledge of the other fleet's objective function. Fleet *i* will participate in harvest in period *t* only if its marginal net revenue $p-\frac{c}{\gamma_i X_t}$ at the outset of harvest is positive. By assumption, $\gamma_i R\left(\sum_j \theta_{j,t} S_{j,t}^{T*}\right) > c/p$ for all $\theta_j \in \left(a_j, b_j\right)$, $j=1,2$, where $S_{j,t}^{T*}$ is Agent *j*'s non-cooperative target escapement. Both agents then participate in non-cooperative harvest in any state of nature.

Agent *i*'s non-cooperative expected discounted payoff in period *t* is

$$(3) \qquad EV_i^* = E\left[\sum_{t=0}^{\infty} \delta^t \left\{p\left(\gamma_i X_t - \theta_{i,t} S_{i,t}^T\right) - c\left(\ln \gamma_i X_t - \ln \theta_{i,t} S_{i,t}^T\right)\right\}\right]$$

subject to

$$(4) \qquad X_t = R\left(\sum_{j=1}^{2} \theta_{j,t-1} S_{j,t-1}^T\right).$$

By assumption, at time *t* the current stock X_t is known but X_{t+n}, $n \geq 1$ is not. That is, $\theta_{i,t}$ is realized after the period *t* target escapement $S_{i,t}^T$ has been set. The first order condition for maximizing (3) subject to (4) is

(5) $$p-\frac{c}{S^T_{i,t}}=E\left[\delta\theta_{i,t}R'\left(\sum_{j=1}^{2}\theta_{j,t}S^T_{j,t}\right)\gamma_i\left\{p-\frac{c}{\gamma_i R\left(\sum_{j=1}^{2}\theta_{j,t}S^T_{j,t}\right)}\right\}\right].$$ [3]

We call the target escapement $S^T_{i,t}$ that solves equation (5) the non-cooperative target escapement S_i^{T*}. The non-cooperative escapements give rise to the expected non-cooperative equilibrium profits $E\pi_i^*$. Note that the predictions from the shared fishery model, where each fishery controls the portion of the stock feeding in its exclusive fishing area, are less pessimistic that those from the sequential fishery models by Hannesson (1995), McKelvey (1997), and Laukkanen (2003). Instead of harvesting down to the zero marginal profit level c/p, the agents now partially account for the expected effect of their harvest on the stock available next year.

We next study how the solution to the individual agent's problem in equation (5) compares to the global optimum where one agent controls the entire fishery. The expected payoff EV_{TOT} is the sum of the two agents' payoffs,

(6) $$EV_{TOT}=E\left[\sum_{t=0}^{\infty}\delta^t\sum_{i=1}^{2}\left\{p\left[\gamma_i X_t-\theta_{i,t}S^T_{i,t}\right]-c\left[ln\,\gamma_i X_t-ln\,\theta_{i,t}S^T_{i,t}\right]\right\}\right].$$

The first order condition for the globally optimal target escapement $S^T_{i,t}$ that maximizes equation (6) subject to the stock equation in (4) is

(7) $$p-\frac{c}{S^T_{i,t}}=E\left[\delta\theta_{i,t}R'\left(\sum_{j=1}^{2}\theta_{j,t}S^T_{j,t}\right)\sum_{j=1}^{N}\gamma_j\left(p-\frac{c}{\gamma_j R\left(\sum_{j=1}^{2}\theta_{j,t}S^T_{j,t}\right)}\right)\right].$$ [4]

We denote the globally optimal target escapement that solves (7) by S_i^O.

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[3] Appendix 1 presents the derivation of equation (5).
[4] Appendix 1 presents the derivation of equation (7).

The individual agent's first order condition in (5) balances the marginal benefit of an additional unit of harvest this year to the expected marginal loss of profits next year that follows reduced recruitment. An individual agent does not account for the effect of reduced recruitment on the expected benefits accruing to the other fleet harvesting the stock. The global first order condition in (7) instead accounts for the effect of additional harvest in one fishery on the expected benefits to both fisheries in the following year. Since $p - c / S_i$ is increasing in S_i, the S_i solving (5) is smaller than the S_i solving (7). An individual agent that makes harvest decisions independently of other fleets targeting the shared stock leaves a suboptimal escapement from the point of view of the fishery as a whole.

We next study whether negotiating on a joint harvesting strategy enables the agents to manage the resource more successfully. We describe an agreement that is designed to support cooperation when management plans are implemented with error and commitment is not possible. What is the likelihood that two agents sharing a fish stock will cooperate in setting their management objectives? How does the likelihood of cooperation depend on the degree of uncertainty in implementing escapement targets?

4 Cooperative harvesting

Suppose that the agents negotiate, and agree on a cooperative management strategy that yields higher expected payoffs to each agent. Hannesson (1997) provides a deterministic model to study cooperative harvesting in a shared fishery. Cooperative management is supported by the threat of reverting to non-cooperative harvesting if deviation is detected. Uncertainty in implementation of target escapements complicates the enforcement of harvesting agreements. Agents are no longer able to observe the management actions of the competitor, and agents themselves cannot be sure of what will be interpreted as defection. Reverting to non-cooperative harvest for ever if low stock levels are observed, the punishment strategy used in most repeated game models of shared resource management, would be unnecessarily harsh in that non-cooperative harvest could be triggered by bad luck rather than cheating. Instead, we follow Green and Porter (1984) and consider an agreement where the agents settle on the threat strategies of reversion to the non-cooperative target escapements for a finite number of periods if violations of the agreement are detected.

Suppose that the agents agree on constrained Pareto efficient cooperative escapement levels that maximize the expected joint benefit from the fishery, subject to the constraint that it is in each agent's interest to adhere to the agreement. Side payments are not considered and each agent must harvest to earn a profit. In order to enforce cooperation the agents settle on the trigger strategy of reverting to the non-cooperative target escapements S_i^{T*} if stock levels below an agreed upon trigger stock level $\overline{X}$ are observed. The punishment phase will last for $T-1$ periods. At the conclusion of the punishment phase, the agents return to the cooperative target escapement levels. The agents commence harvesting in accordance with their cooperative target escapement levels S_i^{TC} in a Nash equilibrium in trigger strategies. They continue to do so until the recruitment X^t falls below the trigger level $\overline{X}$. Once an X^t below $\overline{X}$ has been observed, $T-1$ periods of punishment follow, during which the agents harvest to the non-cooperative target escapements S_i^{T*} regardless of what X^t is. At the conclusion of the $T-1$ punishment periods cooperation is resumed. Once resumed, cooperation prevails until the next time that $X < \overline{X}$.

The agreement is defined as follows. The game has *normal* and *reversionary* stages. Agent *i* regards period *t* as *normal* if

(a) $t = 0$,

(b) $t-1$ was normal and $X^t > \overline{X}$, or $X^{t-T} < \overline{X}$ and $t-T-1$ was normal,

and *reversionary* otherwise.

The agents' strategies are

$$\begin{cases} S_i^{TC} & \text{if } t \text{ is normal} \\ S_i^{T*} & \text{if } t \text{ is reversionary.} \end{cases}$$

The target escapement that Agent *i* sets in a normal period determines his expected current payoff and the probability of triggering a punishment phase. Cooperative target escapements result in stock recruitment $\widetilde{X}^C = R\left(\sum_j \theta_j S_j^T\right)$. The probability that cooperation continues in the following period is $P\left(\widetilde{X}^C \geq \overline{X}\right)$ and the probability of a punishment phase $P\left(\widetilde{X}^C < \overline{X}\right)$.

When setting the period *t* target escapement, the agents know the current stock X_t but future stocks X_{t+n}, $n \geq 1$ are not known. Given the current stock X, the expected payoff from setting a target escapement S_i^T in a normal period is

$$EV_i^C\left(X,S_i^T\right)=E\pi_i\left(X,\theta_i S_i^T\right)+P\left(\widetilde{X}^C\geq\overline{X}\right)\delta EV_i^C\left(\widetilde{X}^C,S_i^T\right)\Big|_{\widetilde{X}^C\geq\overline{X}} + P\left(\widetilde{X}^C<\overline{X}\right)\delta EV_i^*\left(\widetilde{X}^C,S_i^T\right)\Big|_{\widetilde{X}^C<\overline{X}}, \tag{8}$$

where

$$E\pi_i\left(X,\theta_i S_i^T\right)=E\left[p\left(\gamma_i X-\theta_i S_i^T\right)-c\left(ln\,\gamma_i X-ln\,\theta_i S_i^T\right)\right] \tag{8a}$$

is the expected current period payoff given the current stock X, and

$$EV_i^C\left(\widetilde{X}^C,S_i^T\right)\Big|_{\widetilde{X}^C\geq\overline{X}}=E_{\theta_i,\theta_j}\pi_i\left(\widetilde{X}^C,\theta_i S_i^T\right)+P\left(\widetilde{X}^C\geq\overline{X}\right)\delta EV_i^C\left(\widetilde{X}^C,S_i^T\right)\Big|_{\widetilde{X}^C\geq\overline{X}} + P\left(\widetilde{X}^C<\overline{X}\right)\delta EV_i^*\left(\widetilde{X}^C,S_i^T\right)\Big|_{\widetilde{X}^C<\overline{X}}, \tag{8b}$$

$$EV_i^*\left(\widetilde{X}^C,S_i^T\right)\Big|_{\widetilde{X}^C<\overline{X}}=\omega_{1,i}^p+\sum_{\tau=1}^{T-2}\delta^\tau\omega_{2,i}^p+\delta^{T-1}\omega_{3,i}^p+P\left(\widetilde{X}^C\geq\overline{X}\right)\delta^T EV_i^C\left(\widetilde{X}^C,S_i^T\right)\Big|_{\widetilde{X}^C\geq\overline{X}} + P\left(\widetilde{X}^C<\overline{X}\right)\delta^T EV_i^*\left(\widetilde{X}^C,S_i^T\right)\Big|_{\widetilde{X}^C<\overline{X}} \tag{8c}$$

are the expected cooperative and reversionary payoffs evaluated at time t when the future stock $\widetilde{X}^C$ is unknown. The terms in the expected reversionary payoff $EV_i^*\left(\widetilde{X}^C,S_i^T\right)\Big|_{\widetilde{X}^C<\overline{X}}$ are

$$\omega_{1,i}=E\left[p\left(\gamma_i\widetilde{X}^C-\theta_i S_i^{T*}\right)-c\left(ln\,\gamma_i\widetilde{X}^C-ln\,\theta_i S_i^{T*}\right)\right]_{\widetilde{X}^C<\overline{X}} \tag{8d}$$

$$\omega_{2,i}=E\left[p\left(\gamma_i\widetilde{X}^N-\theta_i S_i^{T*}\right)-c\left(ln\,\gamma_i\widetilde{X}^N-ln\,\theta_i S_i^{T*}\right)\right] \tag{8e}$$

$$\widetilde{X}^N=R\left(\sum\nolimits_j\theta_j S_j^{T*}\right) \tag{8f}$$

$$\omega_{3,i}=E\left[p\left(\gamma_i\widetilde{X}^N-\theta_i S_i^T\right)-c\left(ln\,\gamma_i\widetilde{X}^N-ln\,\theta_i S_i^T\right)\right]. \tag{8e}$$

In the first period of a reversionary phase the agents revert to their non-cooperative target escapements S_i^{T*}. The expected profit $\omega_{1,i}$ in the first reversionary period is conditioned on the stock falling below the trigger stock level, $\widetilde{X}^C<\overline{X}$. For the following $T-2$ periods stock recruitment is $\widetilde{X}^N$ and the agents receive the expected non-cooperative profit $\omega_{2,i}$. In period

$t+T-1$ the agents resume the cooperative target escapements which at the non-cooperative stock recruitment $\widetilde{X}^N$ yield the expected profit $\omega_{3,i}$.

We first solve for $EV_i^*\left(\widetilde{X}^C, S_i^T\right)\Big|_{\widetilde{X}^C<\overline{X}}$ in (8c) and insert the solution into the equation for $EV_i^C\left(\widetilde{X}^C, S_i^T\right)\Big|_{\widetilde{X}^C\geq\overline{X}}$ in (8b). We then derive a closed form solution for $EV_i^C\left(\widetilde{X}^C, S_i^T\right)\Big|_{\widetilde{X}^C\geq\overline{X}}$. We next insert $EV_i^C\left(\widetilde{X}^C, S_i^T\right)\Big|_{\widetilde{X}^C\geq\overline{X}}$ and $EV_i^*\left(\widetilde{X}^C, S_i^T\right)\Big|_{\widetilde{X}^C<\overline{X}}$ into (8) and solve for the optimal target escapement S_i^T under cooperation in trigger strategies.

The probability of reversion $P\left(\widetilde{X}^C<\overline{X}\right)$ is given by the distribution of $\widetilde{X}^C$ at $\overline{X}$, defined by $F\left(\overline{X}, S_1^T, S_2^T\right)$. The distribution of the random variable $\widetilde{X}^C = R\left(\sum_j \theta_j S_j^C\right)$ is derived from the distributions of the θ_i, $i=1,2$. Appendix 2 presents the derivation for uniformly distributed random multipliers θ_i. The expected payoff $EV_i^*\left(\widetilde{X}^C, S_i^T\right)\Big|_{\widetilde{X}^C<\overline{X}}$ in (8c) can then be written as

$$(9)\quad EV_i^*\left(\widetilde{X}^C, S_i^T\right)\Big|_{\widetilde{X}^C<\overline{X}} = \frac{\omega_{1,i}^p + \sum_{\tau=1}^{T-2}\delta^\tau \omega_{2,i}^p + \delta^{T-1}\omega_{3,i}^p + \left[1-F\left(\overline{X}, S_1^T, S_2^T\right)\right]\delta^T EV_i^C\left(\widetilde{X}^C, S_i^T\right)\Big|_{\widetilde{X}^C\geq\overline{X}}}{1-F\left(\overline{X}, S_1^T, S_2^T\right)\delta^T}$$

Inserting (9) into equation (8b), writing out $\sum_{\tau=1}^{T-2}\delta^\tau \omega_{2,i}^p$ using the formula for the geometric sum, and solving for $EV_i^C\left(\widetilde{X}^C, S_i^T\right)\Big|_{\widetilde{X}^C\geq\overline{X}}$ yields

(10)

$$EV_i^C\left(\widetilde{X}^C, S_i^T\right)\Big|_{\widetilde{X}^C\geq\overline{X}} = \frac{E\pi_i\left(\widetilde{X}^C, \theta_i S_i^T\right) + \delta F\left(\overline{X}, S_1^T, S_2^T\right)\left\{\omega_{1,i}^p + \frac{\omega_{2,i}^p\left(\delta-\delta^{T-1}\right)}{1-\delta} + \delta^{T-1}\omega_{3,i}^p - \delta^{T-1}E\pi_i\left(\widetilde{X}^C, \theta_i S_i^T\right)\right\}}{1-\delta+\left(\delta-\delta^T\right)F\left(\overline{X}, S_1^T, S_2^T\right)}$$

Adding and subtracting $\omega_{2,i}^p$ in the numerator yields

$$(11)\quad EV_i^C\left(\widetilde{X}^C, S_i^T\right)\Big|_{\widetilde{X}^C \geq \overline{X}} = \frac{E\pi_i\left(\widetilde{X}^C, \theta_i S_i^T\right) - \omega_{2,i}^p + F\left(\overline{X}, S_1^T, S_2^T\right)\left\{\delta\left(\omega_{1,i}^p - \omega_{2,i}^p\right) + \delta^T\left[\omega_{3,i}^p - E\pi_i\left(\widetilde{X}^C, \theta_i S_i^T\right)\right]\right\}}{1-\delta + \left(\delta - \delta^T\right)F\left(\overline{X}, S_1^T, S_2^T\right)} + \frac{\omega_{2,i}^p}{1-\delta}.$$

Agent *i*'s expected cooperative payoff in (11) is the sum of the expected payoff under non-cooperation, and the expected per period gain from cooperation plus the expected payoff accruing from transition to and from punishment period.

By assumption, the agents observe the current stock before setting their period *t* target escapement. Equation (8) yields the expected payoff from leaving an escapement S_i^T in period *t,* evaluated after the current stock X has been observed. Inserting (9) and (11) into (8) yields

$$(12)\qquad EV_i^C\left(X, S_i^T\right) = EV_i^C\left(\widetilde{X}^C, S_i^T\right)\Big|_{\widetilde{X}^C \geq \overline{X}} + E\pi_i\left(X, S_i^T\right) - E\pi_i\left(\widetilde{X}^C, S_i^T\right).$$

The agents' actions are not observed. After measuring the current stock X, each agent chooses the target escapement that maximizes his expected cooperative payoff in (12). Given $S_{j\neq i}^T$, $\overline{X}$, and *T,* Agent *i*'s optimal cooperative target escapement S_i^{TC} must satisfy

$$(13)\qquad EV_i^C\left(X, S_i^{TC}\right) \geq EV_i^C\left(X, S_i^T\right) \text{ for all } S_i^T.$$

Assuming an interior solution, the first order condition for maximizing $EV_i^C\left(X, S_i^T\right)$ is $\partial EV_i^C\left(X, S_i^T\right)/\partial S_i^T = 0$. The first order condition can be written as

$$(14)\qquad \begin{aligned} p - \frac{c}{S_i^T} &= \left(1 - F\left(\overline{X}, S_1^T, S_2^T\right)\right)\delta E\left[\frac{\partial \widetilde{X}^C}{\partial S_i^T}\gamma_i\left(p - \frac{c}{\gamma_i \widetilde{X}^C}\right)\right] \\ &+ F\left(\overline{X}, S_1^T, S_2^T\right)\left[\delta\frac{\partial w_1}{\partial S_i^T} + \delta^T E\left[\frac{\partial \widetilde{X}^C}{\partial S_i^T}\gamma_i\left(p - \frac{c}{\gamma_i \widetilde{X}^C}\right)\right]\right] \\ &- \frac{\partial F\left(\overline{X}, S_1^T, S_2^T\right)}{\partial S_i^T}\frac{\left(\delta - \delta^T\right)\cdot\left(E\pi_i\left(\widetilde{X}^C, \theta_i S_i^T\right) - \omega_{2,i}^p\right)}{1-\delta + \left(\delta - \delta^T\right)F\left(\overline{X}, S_1^T, S_2^T\right)} \\ &+ \frac{\partial F\left(\overline{X}, S_1^T, S_2^T\right)}{\partial S_i^T}\frac{(1-\delta)\left(\delta\left(\omega_{1,i}^p - \omega_{2,i}^p\right) + \delta^T\left[\omega_{3,i}^p - E\pi_i\left(\widetilde{X}^C, \theta_i S_i^T\right)\right]\right)}{1-\delta + \left(\delta - \delta^T\right)F\left(\overline{X}, S_1^T, S_2^T\right)} \end{aligned}$$

The optimal target escapement again balances the expected marginal benefit of additional harvest to the loss of expected benefits next season, now caused by two factors: reduced recruitment, and an increased probability of entering a punishment phase. With probability $1-F\left(\overline{X},S_1^T,S_2^T\right)$, cooperation continues in the next period. With probability $F\left(\overline{X},S_1^T,S_2^T\right)$, the agents revert to non-cooperative harvest and return to cooperation only in period *T.* The increased probability of reversion is weighed by the expected loss of gains from cooperation relative to non-cooperative harvest, and the expected punishment phase payoff.

We next examine the optimal design of the cooperative agreement. Countries negotiate on the length of the punishment phase and the trigger stock level knowing that each country sets its target escapement to maximize $EV_i^C\left(X,S_i^T\right)$. We next describe how the countries choose the length of the punishment phase *T* and the trigger stock level $\overline{X}$ in an optimal manner, given that for any *T* and $\overline{X}$ pair each fishery manager's optimal target escapement under cooperation is $S_i^T=\arg\max_{S_i^T} EV_i^C\left(X,S_i^T\right)$. Formally, *T* and $\overline{X}$ are set to maximize the expected joint payoff

$$(15)\qquad J\left(X^0,S_1,S_2,\overline{X},T\right)=\alpha EV_1^C\left(X^0,S_1,S_2,\overline{X},T\right)+(1-\alpha)EV_2^C\left(X^0,S_1,S_2,\overline{X},T\right),$$

subject to each S_i^T maximizing $EV_i^C\left(X,S_i^T\right)$, and each agent obtaining at least his expected non-cooperative payoff. The share α in (15) is the weight on Agent 1's payoff in the joint maximization problem. A cooperative solution that maximizes the joint payoff in (15) subject to $S_i^T=\arg\max_{S_i^T} EV_i^C\left(X,S_i^T\right)$ is a self-enforcing equilibrium, and the strategies are subgame perfect. The cooperative solution is not renegotiation proof. At the outset of a punishment phase, the countries could confer and decide to continue cooperative harvest. However, renegotiation would unravel the rational for cooperation. It will then be in each country's interest to follow the agreement in punishment periods as well.

If the cooperative solution is such that $F\left(\overline{X},S_1^{TC},S_2^{TC}\right)>0$, punishment phases of reversion to non-cooperative harvests are observed with a positive probability even if the countries agree on a cooperative harvesting strategy. The punishment periods are necessary to support the cooperative agreement. We next examine how frequently retaliatory periods will occur if two countries have agreed upon a joint harvesting strategy. We determine the expected ratio of cooperative to non-cooperative periods and the expected percentage of time spent in cooperation during a cycle. Denote the number of consecutive periods during which the agents cooperate by *M*. The number of cooperative periods is a random variable whose distribution depends on $F\left(\overline{X}, S_1^{TC}, S_2^{TC}\right)$. The probability of cooperation in a normal period *t* is $1-F\left(\overline{X}, S_1^{TC}, S_2^{TC}\right)$ and the probability of reversion is $F\left(\overline{X}, S_1^{TC}, S_2^{TC}\right)$. The probability of cooperation in *M* successive periods then is $\left[1-F\left(\overline{X}, S_1^{TC}, S_2^{TC}\right)\right]^M$, and the probability of cooperation lasting exactly *M* periods is $\left[1-F\left(\overline{X}, S_1^{TC}, S_2^{TC}\right)\right]^M F\left(\overline{X}, S_1^{TC}, S_2^{TC}\right)$. Given the distribution of *M*, the expected number of successive cooperative periods is given by $\sum_{M=0}^{\infty} M\left[1-F\left(\overline{X}, S_1^{TC}, S_2^{TC}\right)\right]^M F\left(\overline{X}, S_1^{TC}, S_2^{TC}\right)$. With the length of the punishment phase $T-1$, the expected ratio of cooperative periods to punishment periods, denoted by *Q,* is

$$(16) \qquad Q = \frac{1}{T-1} \sum_{M=0}^{\infty} M\left[1-F\left(\overline{X}, S_1^{TC}, S_2^{TC}\right)\right]^M F\left(\overline{X}, S_1^{TC}, S_2^{TC}\right).$$

The expected percentage of time spent in cooperation, denoted by *R,* becomes

$$(17) \qquad R = 100 \sum_{M=0}^{\infty} \frac{M}{M+T-1}\left[1-F\left(\overline{X}, S_1^{TC}, S_2^{TC}\right)\right]^M F\left(\overline{X}, S_1^{TC}, S_2^{TC}\right).$$

5 A Numerical Illustration of Cooperation in Trigger Strategies

5.1 Parameter Values and Functional Forms

This section presents a numerical example that illustrates the joint management game. Table 1 displays the parameter values. The parameter values were chosen to reflect a realistic range. Prices and costs are the same for both countries. Prices are normalized to one. Average recruitment follows the Ricker spawning stock – recruitment relation $R(S) = kSe^{lS}$. We consider the case of uniformly distributed random multipliers θ_i, $i = 1,2$. The probability density function for θ_i is

$$(18) \qquad f_i(\theta_i) = \begin{cases} \dfrac{1}{b_i - a_i} & \text{for } \mathrm{a_i} \le \theta_\mathrm{i} \le b_i \\ 0 & \text{elsewhere,} \end{cases}$$

where $a_i = 1 - \varepsilon_i$ and $b_i = 1 + \varepsilon_i$. The mean of θ_i is 1 and the variance is $\sigma_i^2 = \varepsilon_i^2 / 3$. We explore small, moderate, and large fluctuations in realized escapements, corresponding to values of ε_i ranging through $\varepsilon_i = 0.1$, $\varepsilon_i = 0.3$, and $\varepsilon_i = 0.5$. The coefficient of variation ranges from 0.18 ($\varepsilon_i = 0.1$) to 0.41 ($\varepsilon_i = 0.5$).

[Table 1 here]

5.2 Computation of the Joint Management Game

The numerical results were computed using Mathematica 4.0. The optimal agreement is the set $\{T, \overline{X}, S_1^T, S_2^T\}$ that maximizes the expected joint payoff $J(X_0, T, \overline{X}, S_1^T, S_2^T)$ in (15). We proceeded by searching over T and $\overline{X}$ and computing the individually optimal target escapements S_i^T for each $T, \overline{X}$ pair. We considered values of T ranging from 2 to 51 years and values of $\overline{X}$ ranging from $R\left(\sum_{i=1}^{2} a_i S_i^*\right)$ to the maximum of the recruitment function $R(S)$, denoted by X_{max}. In terms of the expected payoffs a punishment phase of 50 years is practically equivalent to a punishment phase of infinite length. The probability of reversion is 0 for values of $\overline{X}$ less than $R\left(\sum_{i=1}^{2} a_i S_i^*\right)$ and 1 for values of $\overline{X}$ greater than X_{max}. Examining the set $T \in [2,51]$, $\overline{X} \in \left[R\left(\sum_{i=1}^{2} a_i S_i^*\right), X_{\max}\right]$ thus suffices to consider all possible agreement outcomes. The initial stock was set equal to the expected stock at the non-cooperative target escapements. The weight α on Agent i's payoff was 0.5. The proportion of the stock that each agent controls, γ_i, varied between 0.1 and 0.9.

We computed the optimal target escapements and the agents' expected benefits in the non-cooperative equilibrium, in the globally optimal equilibrium, and under the trigger stock agreement. The optimal trigger stock agreement is in addition characterized by the optimal length of the punishment phase and the optimal trigger stock. The length of the punishment phase and the trigger stock in turn determine the ratio of cooperative periods to punishment periods, and the percentage of time spent in cooperation. Tables 2 and 3 display the full results. Figures 1 to 6 illustrate the optimal agreement.

In order to compare the prospects of cooperation in the presence of two different types of uncertainty, we also computed the non-cooperative, globally optimal and trigger stock equilibria with stochastic variation in recruitment. Tables 4 to 6 report the full results for the recruitment uncertainty case. Figures 7 to 15 illustrate the optimal agreement. Table 7 compares the implications of the two sources of variation for implicit cooperation in trigger strategies.

5.3 The Optimal Agreement under Implementation Uncertainty

The cooperative agreement in trigger strategies is supported as a self-enforcing equilibrium for a limited range of parameter values (Figures 1 and 2). The equilibrium in trigger strategies only exists when implementation shocks are small or moderate ($\varepsilon = 0.1$, $\varepsilon = 0.3$), and when the stock is relatively evenly split between the two agents ($\gamma_1 = 0.4$ to $\gamma_1 = 0.6$). When large fluctuations are possible ($\varepsilon = 0.5$), the agents are better off harvesting in accordance with their non-cooperative strategies. With large implementation shocks, the likelihood of a low stock level launching a punishment phase is noticeable, and cooperation becomes a volatile exercise. The target escapement needed to balance the tradeoff between the expected current period profit and the probability of triggering a punishment phase is so large that the non-cooperative target escapement yields higher expected payoffs. A fishery with a large share of the stock is also better off following its individual harvesting strategy. It controls the size of the stock available in its fishing zone in the next period to a considerable extent even if it operates on its own. Setting a large target escapement in order to account for an increased probability of triggering a reversionary phase is not profitable.

[Figures 1 and 2]

The probability of reversion is markedly above 0 for all parameter values (Figures 3 and 4). When implementation shocks are moderate ($\varepsilon = 0.3$) and the agents control uneven shares of the fishery ($\gamma_1 = 0.4$, 0.6), the probability of reversion is 0.02. The probability of reversion increases to 0.07 when the agents control equal shares of the fishery. The probability of reversion is even higher with small implementation shocks ($\varepsilon = 0.1$), ranging from 0.05 when the shares differ, to 0.13 when agents control equal shares of the fishery. When the shares differ, the target escapements are close to the non-cooperative target escapements. With equal shares, both agents gain noticeably more from cooperation, but the target escapements are also markedly larger than in the case of unequal shares. The temptation to decrease the target escapement is notable, and a higher probability of reversion is needed to support cooperation.

[Figures 3 and 4]

The length of the punishment phase is greater when implementation shocks are moderate ($\varepsilon = 0.3$) than when the shocks are small ($\varepsilon = 0.1$). As a result, the ratio of cooperative to non-cooperative periods and the percentage of time spent in cooperation are higher when fluctuations are small, regardless of the higher probability of reversion (Figures 5 and 6). The agents cooperate as much as 75 % of time when fluctuations are small, as opposed to at most 57 % of time when fluctuations are moderate. Some asymmetry makes cooperation more likely. For both small and moderate amounts of implementation uncertainty, the percentage of time spent in cooperation is greater when the agents' shares of the fishery differ than when the shares are equal.

[Figures 5 and 6]

The expected payoffs under trigger strategies are greater than the non-cooperative ones but smaller than those obtaining under the globally optimal policy. Even when the target escapements are close to the globally optimal levels ($\varepsilon_i = 0.1$), punishment strategies are applied as much as 47 % of time in a cycle. The frequent punishment phases decrease the expected payoffs. Because each fishery controls a part of the stock and partially accounts for the effect of current harvest on future stock levels, the differences between the expected payoffs under the three different management scenarios are not substantial (Figures 1 and 2). The gains from cooperation are more pronounced when non-cooperative harvest entails harvesting down to the zero marginal profit level, as in high seas fisheries where competing fleets harvest in one area. The shared fishery model allows for partial ownership of the resource, and the consequences of uncoordinated harvest are less detrimental than in the case of simultaneous harvest by competing fleets.

5.4 The Optimal Agreement under Recruitment Uncertainty

The biological model with stochastic recruitment is

$$X^{t+1} = \theta_{R,t} R\left(\sum_{i=1}^{2} S_{i,t}^{T}\right), \tag{19}$$

where the $\theta_{R,t}$ are uniformly distributed random variables with probability density function

$$f_R(\theta_R) = \begin{cases} \dfrac{1}{b_R - a_R} & \text{for } \mathrm{a_R} \leq \theta_\mathrm{R} \leq b_R \\ 0 & \text{elsewhere,} \end{cases} \tag{20}$$

where $a_R = 1 - \varepsilon_R$ and $b_R = 1 + \varepsilon_R$. The mean of θ_R is 1 and the variance is $\sigma_R^2 = \varepsilon_R^2 / 3$. The non-cooperative, globally optimal and trigger stock equilibria with a multiplicative shock on recruitment are derived similarly to the implementation uncertainty case. The expected payoffs and the agents' first order conditions under recruitment uncertainty are as in the implementation uncertainty model, but stochastic variation is only present in stock recruitment as defined by equation (19). The cumulative distribution function of $X = \theta_R R(S_1 + S_2)$ is $F_X(x, S_1, S_2) = F_R(x / R(S_1 + S_2))$, where $F_R(\cdot)$ is the cumulative distribution of θ_R. The details of the derivation are available from the author upon request.

The cooperative equilibrium in trigger strategies is supported for small, moderate, and large fluctuations in recruitment ($\varepsilon = 0.1, \varepsilon = 0.3$, and $\varepsilon = 0.5$). The initial stock determines whether a period is cooperative or reversionary. When stochastic shocks occur in recruitment only, the stock is a function of one random variable. When target escapements are implemented with error, the stock is a function of two random variables. For identically distributed recruitment and implementation shocks, the variance of the stock is smaller under recruitment uncertainty than under implementation uncertainty, and cooperation is easier to sustain. (Tables 4 to 6, figures 7 to 9).

[Figures 7 to 9]

When fluctuations in recruitment are large or small ($\varepsilon = 0.5, 0.1$), cooperation can be sustained for the same range of share parameters γ_1 as in the case of escapement uncertainty ($\gamma_1 = 0.4$ to $\gamma_1 = 0.6$). When recruitment uncertainty is moderate ($\varepsilon = 0.3$), cooperation can be sustained for a somewhat wider range of share parameters (from $\gamma_1 = 0.3$ to $\gamma_1 = 0.7$). Why is asymmetry less detrimental for cooperation when fluctuations are moderate than when they are large or small? An agent with a large share of the fishing area has considerable control of the stock available in its fishing zone in the next period. In the case of stochastic recruitment, the expected payoff increases as fluctuations become larger. At moderate levels of uncertainty, the gains from cooperation are sufficiently large to make cooperation profitable even for an agent with a large share of the stock. However, the probability of reversion that is necessary to sustain cooperation also increases as fluctuations become larger. When large recruitment shocks occur ($\varepsilon = 0.5$), the tradeoff between the expected payoff from the individual harvesting strategy and the cooperative target escapement that is required to account for the increased probability of a reversionary phase becomes too large for an agent with a sizeable share of the stock.

The probability of entering a reversionary period is close to zero for large and moderate fluctuations ($\varepsilon = 0.5, 0.3$), but considerably higher when fluctuations are small ($\varepsilon = 0.1$). The length of the punishment phase ranges from 2 to 21 periods. The range of T is similar for small, moderate and large fluctuations (Figures 10 to 12). Even though the punishment phases are relatively short when fluctuations are small, the percentage of time spent in cooperation is markedly lower for small fluctuations than for large and moderate fluctuations: The agents cooperate 48 to 55 % of time when fluctuations are small, as opposed to as much as 92 to 97 % of time when fluctuations are moderate and 86 to 99 % of time when fluctuations are large. Why does more uncertainty make cooperation more likely in the case of recruitment uncertainty? The expected payoffs increase in the size of the fluctuations. The agents have more to gain from cooperation, and the agreement is easier to sustain. Regardless of the amount of uncertainty, the percentage of time spent in cooperation is higher when the agents control equal shares of the stock than when the shares differ. Uneven shares give rise to markedly uneven relative gains from cooperation. As a result, the probability of reversion and the length of the punishment phase that are necessary to sustain cooperation are greater. (Figures 10 to 15).

[Figures 10 to 15]

[Table 7]

6 Conclusion

We examine cooperative and non-cooperative harvesting in a stochastic transboundary fishery shared by two agents. We consider the effects of both implementation and recruitment uncertainty on implicit cooperation in the management of the transboundary fishery. Even when each agent controls harvest in his share of the area that the fish stock occupies, the non-cooperative target escapements are suboptimal. We define conditions under which cooperative harvesting can be sustained as a self-enforcing equilibrium when the actions of the agents are not observed. Even when the agents cooperate, reversionary periods occur with a positive probability. While the agents know that a low stock level may reflect a negative shock rather than cheating on behalf of the competitor, it is rational to participate in reversionary periods. Otherwise, there would be no incentive to cooperate. The equilibrium is subgame perfect but not renegotiation proof. Supposedly the agents could renegotiate and agree to continue cooperation after low stock levels have been observed. However, the parties realize that renegotiating would unravel the rational for cooperation.

The numerical example shows that the trigger stock agreement can be implemented for a range of parameter values. The agreement can only be supported as a self-enforcing equilibrium when uncertainty is not too pronounced. Even when the cooperative agreement in trigger strategies does obtain, a substantial part of time in each cycle is spent in reversion to the punishment strategies. In the presence of implementation uncertainty, the agents may have to apply the reversionary strategies as much as 72 % of time in a cycle in order to support the implicit cooperative agreement. Furthermore, the trigger stock agreement only obtains when the agents control close to equal shares of the fishery. The numerical results indicate that the implications of recruitment uncertainty for implicit cooperation in transboundary fisheries management are less detrimental than those of implementation uncertainty. The agreement is supported for larger fluctuations, and less frequent punishment phases suffice to enforce the agreement. The parties engage in cooperative play as much as 99 % of time in a cycle.

Recruitment uncertainty arises from environmental factors that are only partially and indirectly controlled by management efforts. Implementation uncertainty instead occurs when management provisions fail to have the intended consequences. While noise and uncertain states of nature can contribute to implementation uncertainty, its basis is in how fishers react to management actions (Peyton 1987, White and Mace 1988). Rice and Richards (1996) argue that management system performance can be improved to reduce implementation uncertainty. Our results indicate that controlling implementation uncertainty would facilitate cooperation in transboundary fisheries management and improve the economic performance of shared fisheries. Addressing implementation uncertainty in each participating country can help create an environment where non-binding cooperation will succeed.

This paper focuses on the effects of implementation uncertainty on international cooperation. Comparison of the implications of implementation uncertainty and recruitment uncertainty on international cooperation indicates different sources of uncertainty have different effects on the chances of non-binding cooperation. Future work would include investigating the prospects of international cooperation in fisheries management in the presence of more than one source of variation.

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Appendix 1. Derivation of the individually optimal and globally optimal target escapements under non-cooperation.

Agent *i*'s objective is to maximize his expected payoff

(A1.1) $$EV_i^* = E\left[\sum_{t=0}^{\infty}\delta^t\left\{p\left(\gamma_i X_t - \theta_{i,t} S_{i,t}^T\right) - c\left[\ln\gamma_i X_t - \ln\theta_{i,t} S_{i,t}^T\right]\right\}\right]$$

subject to

(A1.2) $$X_{t+1} = R\left(\sum_{j=1}^{2}\theta_{j,t} S_{j,t}^T\right).$$

By assumption, X_0 is known and given at $t = 0$, and X_t is known at time *t* but X_{t+j}, $j \geq 1$ is not. The $\theta_{i,t}$ are realized after the period *t* target escapement $S_{i,t}^T$ has been set.

Given the period *t* stock X_t, fishery manager *i*'s problem is to maximize (A1.1) subject to (A1.2) by choice of the target escapement $S_{i,t}^T$. The dynamic programming equation for the manager's problem is

(A1.3) $$V(X_t) = \max_{S_{i,t}^T} E\left[p\left[\gamma_i X_t - \theta_{i,t} S_{i,t}^T\right] - c\left[\ln\gamma_i X_t - \ln\theta_{i,t} S_{i,t}^T\right]\right] + \delta E\left[V(X_{t+1})\right]$$

subject to the stock equation (A1.2).

The first order necessary condition for the problem on the right hand side of (A1.3) is

(A1.4) $$E\left[\left\{-p\theta_{i,t} + \frac{c}{S_{i,t}^T}\right\}\right] + \delta E\left[\frac{\partial X_{t+1}}{\partial S_{i,t}^T} V'(X_{t+1})\right] = 0$$

Applying the Benveniste-Scheinkman formula to evaluate $V'(X_{t+1})$ gives

(A1.5) $$V'(X_{t+1}) = \frac{\partial \pi_i}{\partial X_{t+1}}\left(X_{t+1}, S_i^T\right) = p\gamma_i - \frac{c}{X_{t+1}}.$$

Substituting (A1.5) into the first order necessary condition in (A1.4) and using the stock equation in (A1.2) gives the stochastic Euler equation

$$E\left[\left\{-p\theta_{i,t} + \frac{c}{S^T_{i,t}}\right\}\right] + E\left[\delta\theta_{i,t} R'\left(\sum_{j=1}^{2}\theta_{j,t}S^T_{j,t}\right)\left\{p\gamma_i - \frac{c}{R\left(\sum_{j=1}^{N}\theta_{j,t}S^T_{j,t}\right)}\right\}\right] = 0 \quad \leftrightarrow$$

(A1.6) $$p - \frac{c}{S^T_{i,t}} = E\left[\delta\theta_{i,t} R'\left(\sum_{j=1}^{2}\theta_{j,t}S^T_{j,t}\right)\gamma_i\left\{p - \frac{c}{\gamma_i R\left(\sum_{j=1}^{N}\theta_{j,t}S^T_{j,t}\right)}\right\}\right]$$

The global fishery manager's objective is to maximize the total expected payoff, which is the sum of the individual agents' payoffs

(A1.7) $$EV_{TOT} = E\left[\sum_{t=0}^{\infty}\delta^t \sum_{i=1}^{2}\left\{p\left[\gamma_i X_t - \theta_{i,t}S^T_{i,t}\right] - c\left[\ln\gamma_i X_t - \ln\theta_{i,t}S^T_{i,t}\right]\right\}\right]$$

subject to the stock equation in (A1.2).

The dynamic programming equation for the society's problem is

(A1.8) $$V(X_t) = \max_{S^T_{i,t}} E\left[\sum_{j=1}^{2}\left\{p\left[\gamma_j X_t - \theta_{j,t}S^T_{j,t}\right] - c\left[\ln\gamma_j X_t - \ln\theta_{j,t}S^T_{j,t}\right]\right\} + \delta E\left[V\left(X_{t+1}\right)\right]\right].$$

The first order necessary condition for maximizing the right hand side of (A1.8) is

(A1.9) $$E\left[\left\{-p\theta_{i,t}+\frac{c}{S_{i,t}^{T}}\right\}\right]+\delta E\left[\frac{\partial X_{t+1}}{\partial S_{i,t}^{T}}V'(X_{t+1})\right]=0 .$$

Applying the Benveniste-Scheinkman formula to evaluate $V'(X_{t+1})$ and using (A1.2) now gives

(A1.10) $$V'(X_{t+1})=\sum_{j=1}^{2}\frac{\partial\pi_j}{\partial X_{t+1}}\left(X_{t+1},S_j^T\right)=\sum_{j=1}^{2}p\gamma_j-\frac{c}{X_{t+1}} .$$

Substituting (A1.10) into (A1.9) gives the stochastic Euler equation

$$E\left[-p\theta_{i,t}+\frac{c}{S_{i,t}^{T}}\right]+\delta E\left[\theta_{i,t}R'\left(\sum_{j=1}^{2}\theta_{j,s}S_{j,s}^{T}\right)\sum_{j=1}^{2}\left(p\gamma_j-\frac{c}{R\left(\sum_{j=1}^{2}\theta_{j,s}S_{j,s}^{T}\right)}\right)\right]=0 \leftrightarrow$$

(A1.11) $$p-\frac{c}{S_{i,t}^{T}}=\delta E\left[\theta_{i,t}R'\left(\sum_{j=1}^{2}\theta_{j,t}S_{j,t}^{T}\right)\sum_{j=1}^{2}\gamma_j\left(p-\frac{c}{\gamma_j R\left(\sum_{j=1}^{2}\theta_{j,t}S_{j,t}^{T}\right)}\right)\right].$$

Appendix 2. Derivation of the probability distribution function of $X = R(\theta_1 S_1 + \theta_2 S_2)$.

We start out with a pair of independent random variables $\theta = [\theta_1, \theta_2]'$ with a bivariate density $f_\theta(\theta_1, \theta_2) = f_1(\theta_1) f_2(\theta_2) = \frac{1}{(b_1 - a_1)(b_2 - a_2)}$. We consider the case where the stochastic multipliers θ_i have equal support: $a_1 = a_2 = a$ and $b_1 = b_2 = b$. We undertake deriving the distribution of $X = R(\theta_1 S_1 + \theta_2 S_2)$. We first derive the distribution of $Y_1 = \theta_1 S_1 + \theta_2 S_2$ using the algorithm described in De Groot (1986) for computing the distribution of a function of two random variables. The algorithm describes a transformation from $\Re^2$ to $\Re^2$, whereas we are interested in a transformation from $\Re^2$ to $\Re^1$. To this end, we construct a dummy random variable $Y_2 = \theta_2$ and derive the distribution of $\boldsymbol{Y} = [Y_1, Y_2]' = S\theta$, where $S = \begin{bmatrix} S_1 & S_2 \\ 0 & 1 \end{bmatrix}$. Integrating out Y_2 from the distribution of $\boldsymbol{Y}$ yields the distribution of Y_1. Given the distribution of Y_1, it is straightforward to derive the distribution of $X = R(Y_1) = R(\theta_1 S_1 + \theta_2 S_2)$.

The density g_Y of $\boldsymbol{Y}$ is defined as $g_Y(\mathbf{Y}) = f(Z\mathbf{Y})|J(\mathbf{Y})|$, where Z is the inverse of S and $Z\mathbf{Y}$ is the inverse map $\theta = [\theta_1, \theta_2]' = \mathbf{z}(\mathbf{Y}) = Z\mathbf{Y}$, and $J(y)$ denotes the Jacobian matrix of **z(Y)** and $|J(\boldsymbol{Y})|$ denotes the Jacobian determinant. (see De Groot 1986). We have $Z = \begin{bmatrix} \frac{1}{S_1} & -\frac{S_2}{S_1} \\ 0 & 1 \end{bmatrix}$. The Jacobian matrix is simply Z and the Jacobian determinant is $|J(\boldsymbol{Y})| = \frac{1}{S_1}$. The density g_Y of $\boldsymbol{Y}$ then becomes

(A2.1)

$$g_Y(\mathbf{Y}) = f(Z\mathbf{Y})|J(\mathbf{Y})|$$

$$= f\left(\frac{Y_1}{S_1} - \frac{S_2 Y_2}{S_1}, Y_2\right)\frac{1}{S_1} = f_1\left(\frac{Y_1 - S_2 Y_2}{S_1 - S_2}\right) f_2(Y_2)\frac{1}{S_1} = \frac{1}{(b-a)^2 S_1} \qquad \text{for } \boldsymbol{Y} \in T,$$

where T is the range of the function $\mathbf{Y} = S\theta$, and $g(\mathbf{Y}) = 0$ otherwise.

The distribution $g_Y(\mathbf{Y})$ in (A2.1) is the joint distribution of $(Y_1, Y_2) = (S_1\theta_1 + S_2\theta_2, \theta_2)$. The distribution of Y_1 is obtained by integrating out Y_2. In order to obtain the limits of integration, we first have to determine the range *T* of the function $\boldsymbol{Y} = [Y_1, Y_2]' = S\theta$. Figure A2.1 shows *T,* which is a trapezoid. We depict Y_1 on the horizontal axis and Y_2 on the vertical axis. In order to determine the shape of *T,* we fix $y_2 = Y_2 = \theta_2 \in [a, b]$ and examine which values Y_1 can take. For $Y_2 = a$, Y_1 ranges from $a(S_1 + S_2)$ to $bS_1 + aS_2$. For $Y_2 = b$, Y_1 ranges from $aS_1 + bS_2$ to $b(S_1 + S_2)$. The range *T* is defined by the trapezoid with the corners at $(a(S_1 + S_2), a)$, $(bS_1 + aS_2, a)$, $(b(S_1 + S_2), b)$, $(aS_1 + bS_2, b)$. We integrate out Y_2 for every value of y_1 in the support of the marginal, which is $[a(S_1 + S_2), b(S_1 + S_2)]$. As we can see from Figure A2.1, the integral has to be computed in three pieces. Two cases arise depending on whether (i) $aS_1 + bS_2 \leq bS_1 + aS_2$ or (ii) $aS_1 + bS_2 > bS_1 + aS_2$.

Consider first case (i). The interval associated with y_2 on the vertical axis is

I $\quad a \leq y_2 \leq a + \frac{1}{S_2}(y_1 - a(S_1 + S_2)) \qquad$ for $y_1 \in [a(S_1 + S_2), aS_1 + bS_2]$

II $\quad a \leq y_2 \leq b \qquad$ for $y_1 \in [aS_1 + bS_2, bS_1 + aS_2]$

III $\quad a + \frac{1}{S_2}(y_1 - (bS_1 + aS_2)) \leq y_2 \leq b \qquad$ for $y_1 \in [bS_1 + aS_2, b(S_1 + S_2)]$.

Integrating out Y_2 yields the density of Y_1:

(A2.2) $g_1(y_1) = \int_{a2}^{a + \frac{1}{S_2}(y_1 - a(S_1 + S_2))} \frac{1}{(b-a)^2 S_1} dy_2 = \frac{1}{(b-a)^2 S_1 S_2}(y_1 - a(S_1 + S_2))$ for $y_1 \in [a(S_1 + S_2), aS_1 + bS_2]$

$$= \int_a^b \frac{1}{(b-a)^2 S_1} dy_2 = \frac{1}{(b-a)S_1}$$ for $y_1 \in [aS_1 + bS_2, bS_1 + aS_2]$

$$= \int_{a+\frac{1}{S_2}(y_1-(bS_1+aS_2))}^{b} \frac{1}{(b-a)^2 S_1} dy_2 \ = \frac{1}{(b-a)^2 S_1 S_2}\left(b(S_1+S_2)-y_1\right) \quad \text{for}$$

$y_1 \in [bS_1 + aS_2, b(S_1 + S_2)]$

In case (ii), $a_1 S_1 + b_2 S_2 > b_1 S_1 + a_2 S_2$. The interval associated with y_2 on the vertical axis is

I $\quad a \le y_2 \le a + \frac{1}{S_2}\left(y_1 - a(S_1 + S_2)\right) \quad$ for

$y_1 \in [a(S_1 + S_2), bS_1 + aS_2]$

II $\quad a + \frac{1}{S_2}\left(y_1 - (bS_1 + aS_2)\right) \le y_2 \le a + \frac{1}{S_2}\left(y_1 - a(S_1 + S_2)\right) \quad$ for

$y_1 \in [bS_1 + aS_2, aS_1 + bS_2]$

III $\quad a + \frac{1}{S_2}\left(y_1 - (bS_1 + aS_2)\right) \le y_2 \le b \quad$ for

$y_1 \in [aS_1 + bS_2, b(S_1 + S_2)]$.

Integrating out Y_2 as above yields

(A2.3) $g_1(y_1) \ = \frac{1}{(b-a)^2 S_1 S_2}\left(y_1 - a(S_1 + S_2)\right) \quad$ for $y_1 \in [a(S_1 + S_2), bS_1 + aS_2]$

$$= \int_{a+\frac{1}{S_2}(y_1-(bS_1+aS_2))}^{a+\frac{1}{S_2}(y_1-a(S_1+S_2))} \frac{1}{(b-a)^2 S_1} dy_2 = \frac{1}{(b-a)S_2} \quad \text{for } y_1 \in [b_1 S_1 + a_2 S_2, a_1 S_1 + b_2 S_2]$$

$$= \frac{1}{(b-a)^2 S_1 S_2}\left(b(S_1 + S_2) - y_1\right) \quad \text{for } y_1 \in [aS_1 + bS_2, b(S_1 + S_2)].$$

The cumulative distribution function for Y_1 is obtained by integrating the probability density function. In case (i), $aS_1 + bS_2 \leq bS_1 + aS_2$, the cumulative distribution function is

(A2.4) $$G_1(y_1) = \int_{a(S_1+S_2)}^{y_1} \frac{1}{(b-a)^2 S_1 S_2}(y - a(S_1+S_2))dy = \frac{(a(S_1+S_2)-y_1)^2}{2(a-b)^2 S_1 S_2}$$

for $y_1 \in [a(S_1+S_2), aS_1 + bS_2]$

$$= \frac{S_2}{2S_1} + \int_{aS_1+bS_2}^{y_1} \frac{1}{(b-a)S_1}dy = \frac{S_2}{2S_1} + \frac{1}{(b-a)S_1}[y_1 - (aS_1 + bS_2)]$$

for $y_1 \in [aS_1 + bS_2, bS_1 + aS_2]$

$$= \frac{S_2}{2S_1} + \frac{1}{(b-a)S_1}[bS_1 + aS_2 - (aS_1 + bS_2)] + \int_{bS_1+ab_2}^{y_1} \frac{1}{(b-a)^2 S_1 S_2}(b(S_1+S_2) - y)dy$$

$$= \frac{-2a(b-a)S_1S_2 - b^2S_1^2 - 2bS_1(aS_2 - y_1) - (y_1 - bS_2)^2}{2(b-a)^2 S_1 S_2}$$

for $y_1 \in [aS_1 + bS_2, b(S_1+S_2)]$.

In case (ii), $aS_1 + bS_2 > bS_1 + aS_2$, the cumulative distribution function is

(A2.5) $$G_1(y_1) = \int_{a(S_1+S_2)}^{y_1} \frac{1}{(b-a)^2 S_1 S_2}(y_1 - a(S_1+S_2))dy_1 = \frac{(a(S_1+S_2)-y_1)^2}{2(a-b)^2 S_1 S_2}$$

for $y_1 \in [a(S_1+S_2), bS_1 + aS_2]$

$$= \frac{(aS_1 + aS_2 - bS_1 - aS_2)^2}{2(a-b)^2 S_1 S_2} + \int_{bS_1+aS_2}^{y_1} \frac{1}{(b-a)S_2}dy_1$$

$$= \frac{S_1}{2S_2} + \frac{1}{(b-a)S_2}[y_1 - (bS_1 + aS_2)] \qquad \text{for } y_1 \in [bS_1 + aS_2, aS_1 + bS_2]$$

$$= \frac{S_1}{2S_2} + \frac{1}{(b-a)S_2}\left[aS_1 + bS_2 - (bS_1 + aS_2)\right] + \int_{aS_1+bS_2}^{y_1} \frac{1}{(b-a)^2 S_1 S_2}\left(b(S_1 + S_2) - y\right)dy$$

$$= \frac{-2a(b-a)S_1S_2 - b^2S_1^{\ 2} - 2bS_1(aS_2 - y_1) - (y_1 - bS_2)^2}{2(b-a)^2 S_1 S_2}$$

for $y_1 \in [aS_1 + bS_2, bS_1 + bS_2]$.

Given the distribution of $Y_1 = \theta_1 S_1 + \theta_2 S_2$, the cumulative distribution function of $X = R(\theta_1 S_1 + \theta_2 S_2) = R(Y_1)$ can be written as

(A2.6) $$F_X(x) = \Pr(X \le x) = \Pr(R(Y_1) \le x) = \Pr\left(Y_1 \le R^{-1}(x)\right) = G_1\left(R^{-1}(x)\right)$$

provided that the inverse $R^{-1}(x)$ exists. The density of X is recovered by differentiating F_x, which yields

(A2.7) $$f_x(x) = g_1\left(R^{-1}(x)\right)\frac{\partial R^{-1}(x)}{\partial x}.$$

Appendix 3. First order conditions for non-cooperative and cooperative target escapements under recruitment uncertainty.

Agent *i*'s first order condition for the optimal non-cooperative target escapement S_i^{T*} :

(A3.1) $$p-\frac{c}{S_{i,t}}=\delta\gamma_i R'\left(\sum_{j=1}^{N}S_{j,t}\right)\left\{p-\frac{c}{\gamma_i R\left(\sum_{j=1}^{N}S_{j,t}\right)}\right\}=0$$

The first order condition for the sole owner optimal target escapements S_i^O:

(A3.2) $$p-\frac{c}{S_{i,t}}=\delta\sum_{j=1}^{N}\gamma_j R'\left(\sum_{j=1}^{N}S_{j,t-1}\right)\left\{p-\frac{c}{\gamma_j R\left(\sum_{j=1}^{N}S_{j,t-1}\right)}\right\}.$$

The payoffs and the agents' first order conditions under the trigger stock agreement are written as in the case of implementation uncertainty, but stochastic variation is only present in stock recruitment as defined in equation (19). The cumulative distribution function of $X=\theta_R R(S_1+S_2)$ is given by $F_X(x,S_1,S_2)=F_R(x/R(S_1+S_2))$, where $F_R(\cdot)$ is the cumulative distribution of θ_R.

Table 1. Example parameters

Parameter	Value
p	1
c	6.8
k	4.5
l	$-1.8\ 10^{-2}$
δ	0.95

Table 2. Agreement on joint management under implementation uncertainty. $\varepsilon = 0.1$

γ_1	S_1^{TC}	S_2^{TC}	S_1^{T*}	S_2^{T*}	$\overline{X}$	T	F	EV_1^C	EV_2^C	EV_1^*	EV_2^*	Q	R
0.1			7	27						3	812		
0.2			8	24						69	674		
0.3			9	22						163	548		
0.4	11	19	11	18	76	3	0,0552	262	443	258	439	8,0	75
0.5	18	18	14	14	83	4	0,1302	364	364	346	346	2,2	53
0.6	19	11	18	11	76	3	0,0552	443	262	439	258	8,0	75
0.7			22	9						548	163		
0.8			24	8						674	69		
0.9			27	7						812	3		

$S_1^O = S_2^O = 18.34$. $EV_1^O = EV_2^O = 367$ at $\gamma_1 = \gamma_2 = 0.5$.

Table 3. Agreement on joint management under implementation uncertainty. $\varepsilon = 0.3$

γ_1	S_1^{TC}	S_2^{TC}	S_1^{T*}	S_2^{T*}	$\overline{X}$	T	F	EV_1^C	EV_2^C	EV_1^*	EV_2^*	Q	R
0.1			7	27						1	800		
0.2			8	24						65	665		
0.3			9	21						158	541		
0.4	11	18	11	18	75	22	0,0194	253	434	252	433	2,41	57
0.5	16	16	14	14	74	25	0,0740	348	348	340	340	0,52	28
0.6	18	11	18	11	75	22	0,0194	434	253	433	252	2,00	57
0.7			21	9						541	158		
0.8			24	8						665	65		
0.9			27	7						800	1		

$S_1^O = S_2^O = 18.23$. $EV_1^O = EV_2^O = 361$ at $\gamma_1 = \gamma_2 = 0.5$

Table 4. Agreement on joint management under recruitment uncertainty. $\varepsilon = 0.1$

γ_1	S_1^{TC}	S_2^{TC}	S_1^{T*}	S_2^{T*}	$\overline{X}$	T	F	EV_1^C	EV_2^C	EV_1^*	EV_2^*	Q	R
0.1			7	27						3	814		
0.2			8	25						69	676		
0.3			9	22						164	550		
0.4	12	20	11	18	76	4	0,16	264	440	259	440	1,75	48
0.5	18	18	14	14	77	7	0,069	359	359	347	347	2,25	55
0.6	20	12	18	11	76	4	0,16	440	264	440	259	1,75	48
0.7			22	9						550	164		
0.8			25	8						676	69		
0.9			27	7						814	3		

$S_1^O = S_2^O = 18.36$. $EV_1^O = EV_2^O = 368$ at $\gamma_1 = \gamma_2 = 0.5$

Table 5. Agreement on joint management under recruitment uncertainty. $\varepsilon = 0.3$

γ_1	S_1^{TC}	S_2^{TC}	S_1^{T*}	S_2^{T*}	$\overline{X}$	T	F	EV_1^C	EV_2^C	EV_1^*	EV_2^*	Q	R
0.1			7	27						5	816		
0.2			8	25						71	678		
0.3	10	25	9	22	59	21	0.00054	179	559	166	552	93	96
0.4	13	21	11	18	58	8	0,0032	278	452	261	442	45	92
0.5	16	16	14	14	57	2	0,0066	362	362	349	349	150	97
0.6	21	13	18	11	58	8	0,0032	452	278	442	261	45	92
0.7	25	10	22	9	59	21	0.00054	559	179	552	166	93	96
0.8			25	8						678	71		
0.9			27	7						816	5		

$S_1^O = S_2^O = 18.36$. $EV_1^O = EV_2^O = 370$ at $\gamma_1 = \gamma_2 = 0.5$

Table 6. Agreement on joint management under recruitment uncertainty. $\varepsilon = 0.5$

γ_1	S_1^{TC}	S_2^{TC}	S_1^{T*}	S_2^{T*}	$\overline{X}$	T	F	EV_1^C	EV_2^C	EV_1^*	EV_2^*	Q	R
0.1			7	29						9	819		
0.2			8	25						75	682		
0.3			9	22						170	556		
0.4	10	20	11	18	41	9	0,0073	276	449	265	446	17	86
0.5	16	16	14	14	40	4	0,00035	364	364	353	353	952	99
0.6	20	10	18	11	41	9	0,0073	449	276	446	265	17	86
0.7			22	9						556	170		
0.8			25	8						682	75		
0.9			29	7						819	9		

$S_1^O = S_2^O = 18.36$. $EV_1^O = EV_2^O = 374$ at $\gamma_1 = \gamma_2 = 0.5$

Table 7. Comparison of the implications of implementation and recruitment uncertainty for the prospects of cooperation in trigger strategies

Source of uncertainty / Agreement characteristics	Implementatation shock	Recruitment shock
Range of shocks $\varepsilon_i, \varepsilon_R$ for which agreement sustained	Small, moderate	Small, moderate, large
Range of shares γ_i for which agreement sustained	0.4 to 0.6	0.4 to 0.6 when shocks small or large 0.3 to 0.7 when shocks moderate
Probability of reversion (*F*)	0.019 to 0.13	0.00035 to 0.0073 when shocks moderate or large 0.069 to 0.16 when shocks small
	The smaller the shocks, the higher is *F*	
	F is higher when shares even	No monotonic relationship between shares and *F*
Length of the punishment phase (*T-1*)	2 to 24	3 to 20
	T greater when shocks moderate	Range of *T* similar for different degrees of uncertainty
Percentage of time in cooperation (*R*)	28 to 75 %	48 to 99 %
	R high when shocks small	*R* low when shocks small, high when shocks large
	R high when shares differ	*R* high when shares equal
Maximum percentage of time in cooperation	75 %, small fluctuations	99 %, large fluctuations
Maximum percentage of time in non-cooperation	72 % , moderate fluctuations	52%, small fluctuations

Fig. 1. Agents' expected payoffs under non-cooperation and under the trigger stock agreement. Implementation uncertainty, $\varepsilon = 0.1$

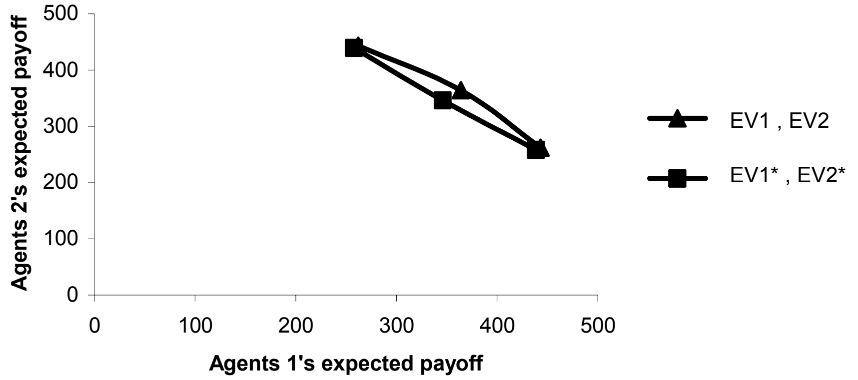


Fig. 2. Agents' expected payoffs under non-cooperation and under the trigger stock agreement. Implementation uncertainty, $\varepsilon = 0.3$

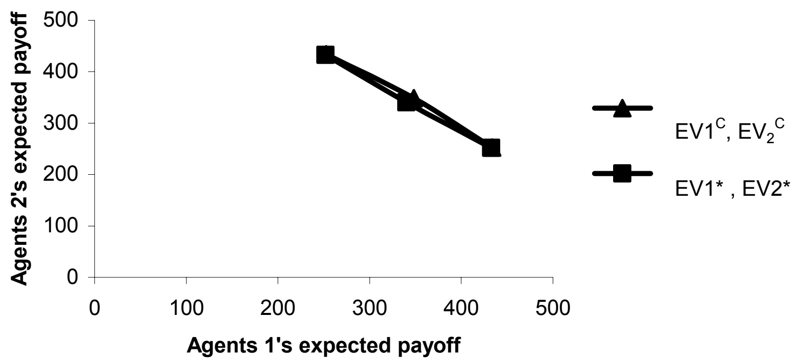


Fig. 3. The optimal length of punishment phase and the optimal probability of reversion. Implementation uncertainty, $\varepsilon = 0.1$

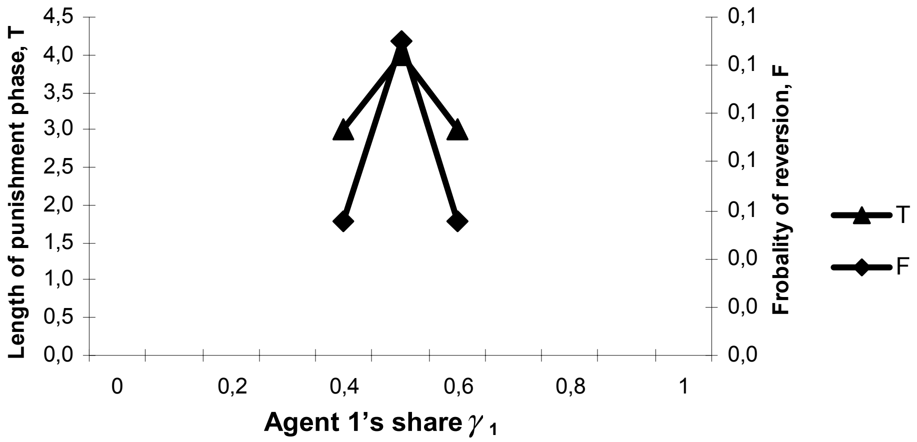


Fig.4. The optimal length of punishment phase and the optimal probability of reversion. Implementation uncertainty, $\varepsilon = 0.3$.

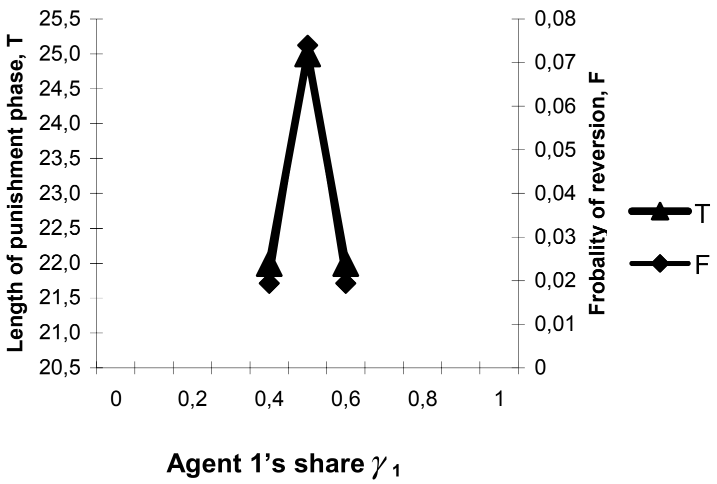


Fig. 5. The expected ratio of cooperative to punishment periods and the percentage of time spent in cooperation. Implementation uncertainty, $\varepsilon = 0.1$.

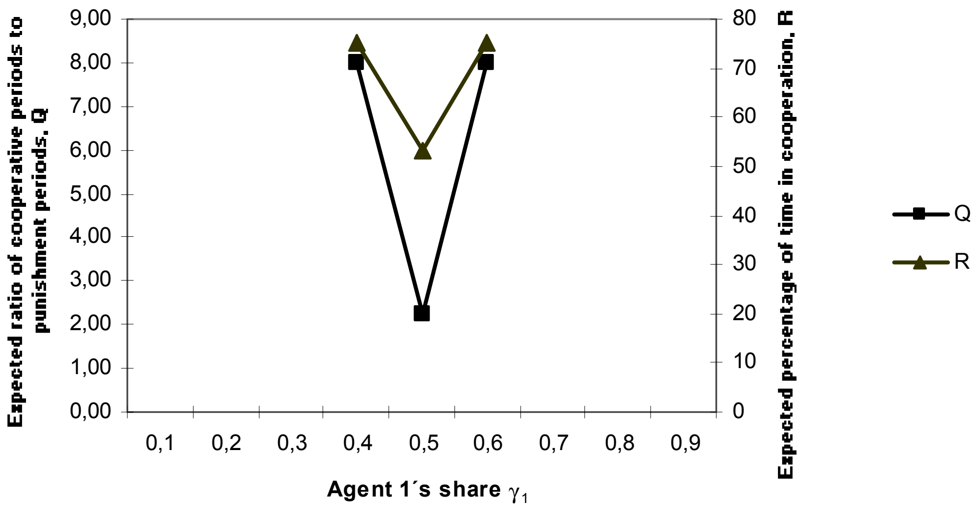


Fig. 6. The expected ratio of cooperative to punishment periods and the percentage of time spent in cooperation. Implementation uncertainty, $\varepsilon = 0.3$.

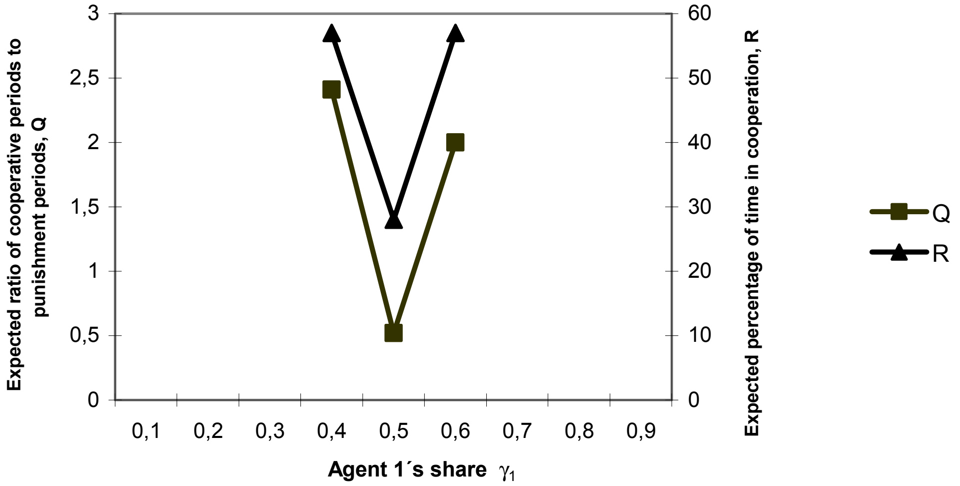


Fig. 7. Agents' expected payoffs under non-cooperation and under the trigger stock agreement. Recruitment uncertainty, $\varepsilon = 0.1$

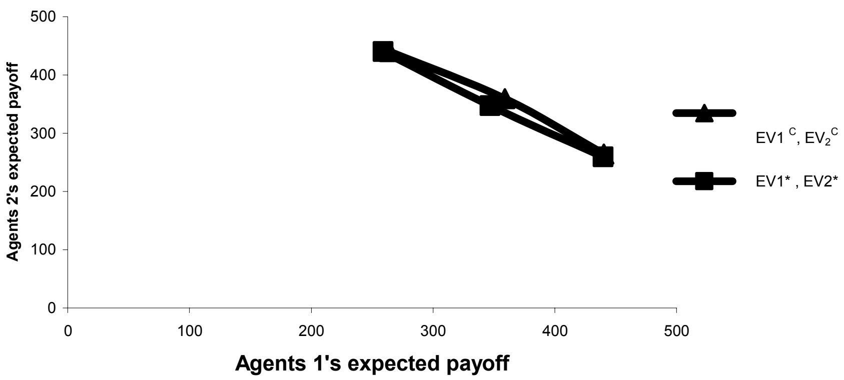


Fig. 8. Agents' expected payoffs under non-cooperation and under the trigger stock agreement. Recruitment uncertainty, $\varepsilon = 0.3$.

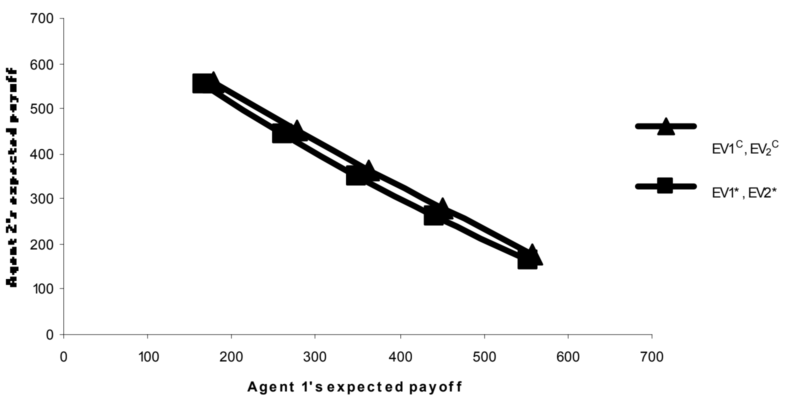


Fig. 9. Agents' expected payoffs under non-cooperation and under the trigger stock agreement. Recruitment uncertainty, $\varepsilon = 0.5$.

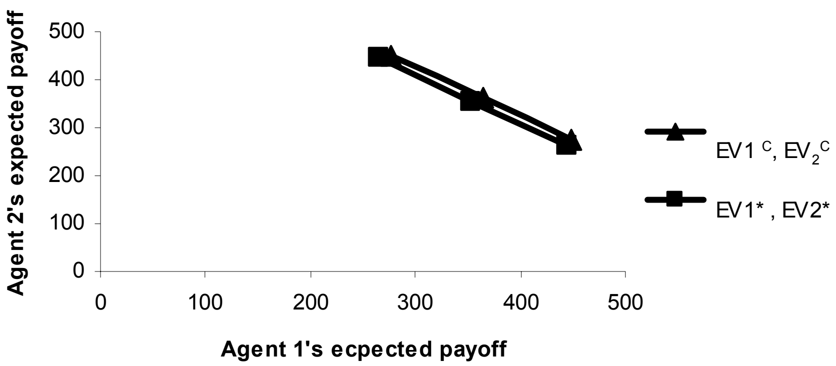


Fig. 10. The optimal length of punishment phase and the optimal probability of reversion. Recruitment uncertainty, $\varepsilon = 0.1$.

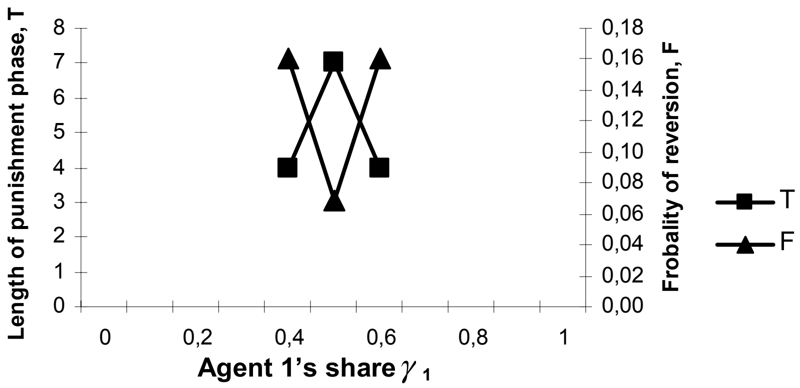


Fig.11. The optimal length of punishment phase and the optimal probability of reversion. Recruitment uncertainty, $\varepsilon = 0.3$.

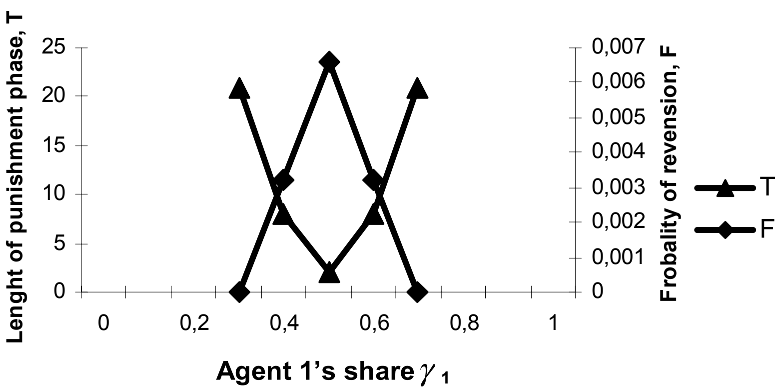


Fig.12. The optimal length of punishment phase and the optimal probability of reversion. Recruitment uncertainty, $\varepsilon = 0.5$.

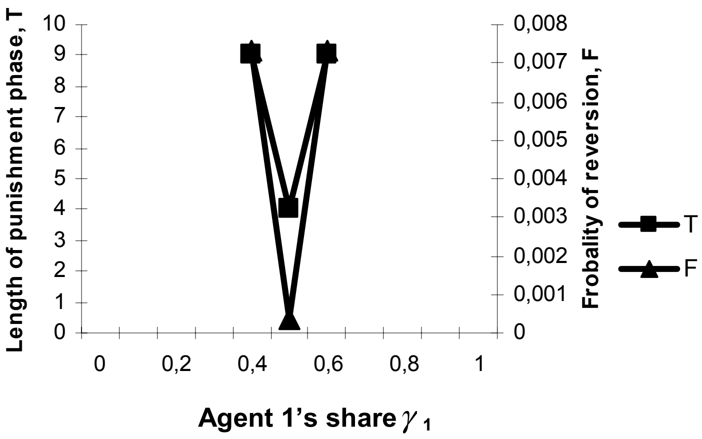


Fig.13. The expected ratio of cooperative to punishment periods and the percentage of time spent in cooperation. Recruitment uncertainty, $\varepsilon = 0.1$.

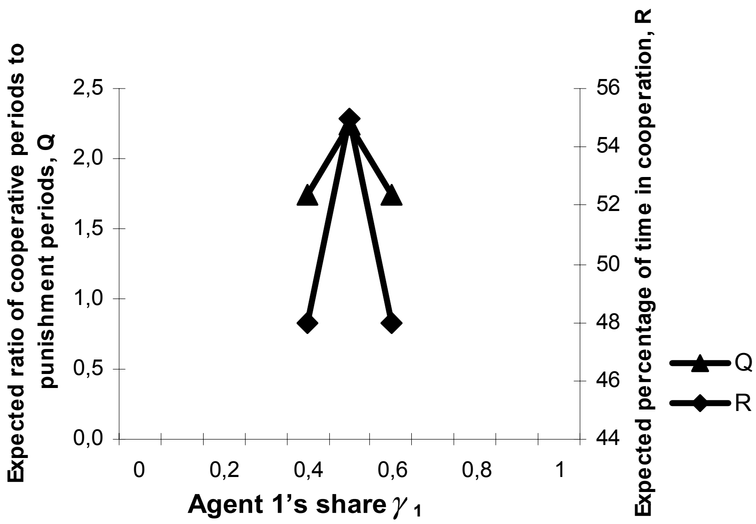


Fig.14. The expected ratio of cooperative to punishment periods and the percentage of time spent in cooperation. Recruitment uncertainty, $\varepsilon = 0.3$.

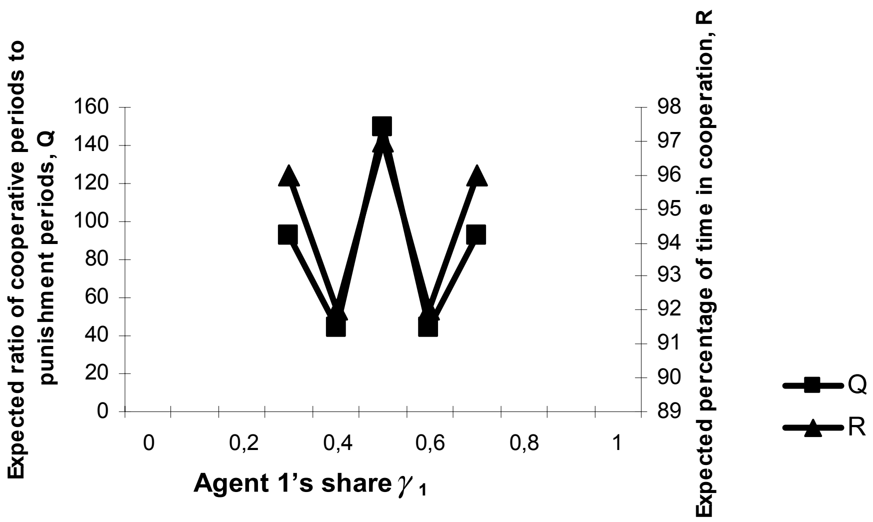


Fig.15. The expected ratio of cooperative to punishment periods and the percentage of time spent in cooperation. Recruitment uncertainty, $\varepsilon = 0.5$.

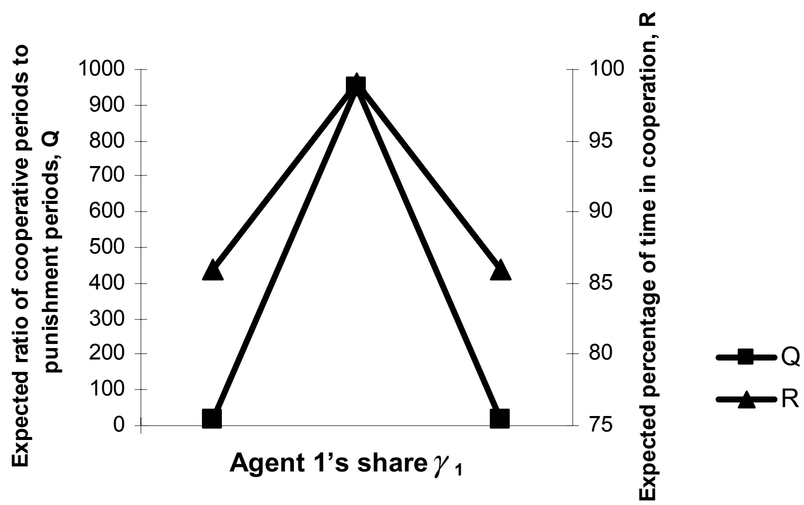
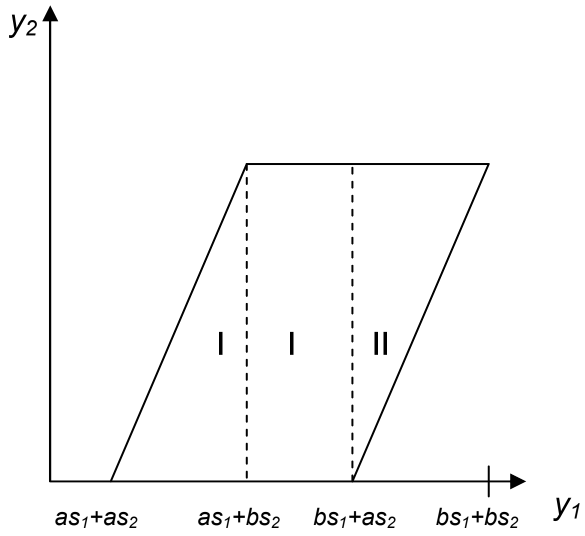
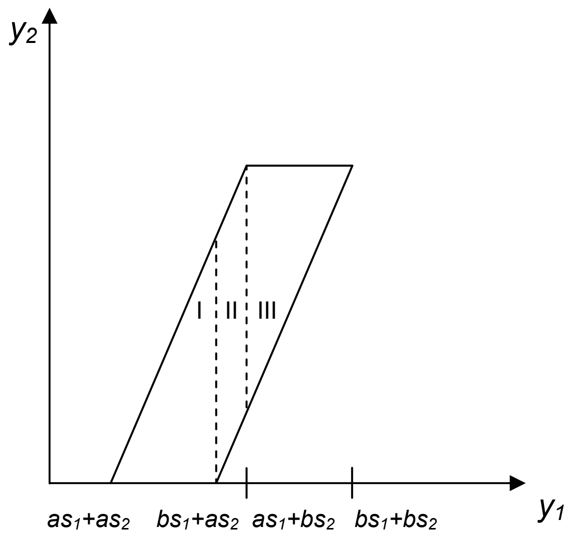


Figure A2.1. Limits of integration for integrating out Y_2.

(i) $as_1 + bs_2 \leq bs_1 + as_2$



(ii) $as_1 + bs_2 > bs_1 + as_2$



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(l) This paper was presented at the Workshop "Growth, Environmental Policies and Sustainability" organised by the Fondazione Eni Enrico Mattei, Venice, June 1, 2001

(li) This paper was presented at the Fourth Toulouse Conference on Environment and Resource Economics on "Property Rights, Institutions and Management of Environmental and Natural Resources", organised by Fondazione Eni Enrico Mattei, IDEI and INRA and sponsored by MATE, Toulouse, May 3-4, 2001

(lii) This paper was presented at the International Conference on "Economic Valuation of Environmental Goods", organised by Fondazione Eni Enrico Mattei in cooperation with CORILA, Venice, May 11, 2001

(liii) This paper was circulated at the International Conference on "Climate Policy – Do We Need a New Approach?", jointly organised by Fondazione Eni Enrico Mattei, Stanford University and Venice International University, Isola di San Servolo, Venice, September 6-8, 2001

(liv) This paper was presented at the Seventh Meeting of the Coalition Theory Network organised by the Fondazione Eni Enrico Mattei and the CORE, Université Catholique de Louvain, Venice, Italy, January 11-12, 2002

(lv) This paper was presented at the First Workshop of the Concerted Action on Tradable Emission Permits (CATEP) organised by the Fondazione Eni Enrico Mattei, Venice, Italy, December 3-4, 2001

(lvi) This paper was presented at the ESF EURESCO Conference on Environmental Policy in a Global Economy "The International Dimension of Environmental Policy", organised with the collaboration of the Fondazione Eni Enrico Mattei , Acquafredda di Maratea, October 6-11, 2001

(lvii) This paper was presented at the First Workshop of "CFEWE – Carbon Flows between Eastern and Western Europe", organised by the Fondazione Eni Enrico Mattei and Zentrum fur Europaische Integrationsforschung (ZEI), Milan, July 5-6, 2001

(lviii) This paper was presented at the Workshop on "Game Practice and the Environment", jointly organised by Università del Piemonte Orientale and Fondazione Eni Enrico Mattei, Alessandria, April 12-13, 2002

(lix) This paper was presented at the ENGIME Workshop on "Mapping Diversity", Leuven, May 16-17, 2002

(lx) This paper was presented at the EuroConference on "Auctions and Market Design: Theory, Evidence and Applications", organised by the Fondazione Eni Enrico Mattei, Milan, September 26-28, 2002

(lxi) This paper was presented at the Eighth Meeting of the Coalition Theory Network organised by the GREQAM, Aix-en-Provence, France, January 24-25, 2003

(lxii) This paper was presented at the ENGIME Workshop on "Communication across Cultures in Multicultural Cities", The Hague, November 7-8, 2002

(lxiii) This paper was presented at the ENGIME Workshop on "Social dynamics and conflicts in multicultural cities", Milan, March 20-21, 2003

(lxiv) This paper was presented at the International Conference on "Theoretical Topics in Ecological Economics", organised by the Abdus Salam International Centre for Theoretical Physics - ICTP, the Beijer International Institute of Ecological Economics, and Fondazione Eni Enrico Mattei – FEEM Trieste, February 10-21, 2003

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