Transboundary Fisheries Management under Uncertainty

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1 Introduction

Open access harvesting and development of more and more efficient fishing methods have resulted in overcapitalization of fisheries and depletion of fish stocks, reducing the profitability of the fishing industry and endangering many fish species. Disputes over the management of fish stocks have been heated, and the problems in marine resource management have over the years received increasing attention among policy makers. Conflicts in fisheries management are difficult enough to resolve within a single jurisdiction. The difficulties are compounded when management authority is divided among separate jurisdictional regions whose interests diverge. Nations involved in transboundary fisheries have recognized a mutual advantage in cooperative management of their resources. Negotiations over harvest allotments have nevertheless proved to be arduous, characterized by periods of stalemate and interrupted by “fish wars” that have left fish stocks decimated and fishing industry unprofitable.

How can one explain the persistence of “fish wars” and identify institutional frameworks that might result in more successful management of transboundary fisheries? One challenge to transboundary fisheries management is that there is no international jurisdiction with the authority to enforce agreements. Cooperative solutions have to be self-enforcing. The theory of non-cooperative games has provided insights into the transboundary management problem and the dynamics of negotiations in search of cooperative agreements. Munro

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(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) studies how critical the number of agents sharing a fish stock is for realizing the cooperative solution supported by the threat of reversion to non-cooperative harvest. 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) address the related question of the management of straddling fish stocks subject to multinational harvest in the high seas.

Agreements on joint management generally define the amount of harvest in each part of the transboundary fishery. Given the stock available in the beginning of the fishing season, choosing the harvest levels equals choosing the abandonment level, the stock of fish left behind after harvest. The abandonment level, called the escapement, determines the economic and biological development of a fishery. Intricacies arise when stock recruitment varies stochastically or harvests and escapements are observed with error. Parties negotiating over cooperative management can no longer directly observe adherence to the agreement by the other fleets. Laukkanen (2003) studies the case of stochastic variation in stock recruitment in a transboundary setting where two fisheries operate in a gauntlet. The stock available to the first fishery in the sequence depends on both the escapement from the subsequent fishery that targets the spawning stock, and on a stochastic shock on recruitment. Laukkanen describes an agreement that supports cooperative harvesting in a sequential fishery in the presence of recruitment uncertainty. This paper will extend the work to considering the case of escapement uncertainty. The paper provides further insights into why “fish wars” persist, and suggest ways in which cooperative agreements might be designed to overcome the difficulties in transboundary fisheries management.

2 The Bioeconomic Model

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, hereafter referred to as an agent. The fish migrate only slowly between the areas. Each agent harvests only the portion of the stock present in its fishing zone. The growth of the stock depends on the aggregate size of the stock. Such interdependency arises for example when the 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 density, that is, the biomass 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 of the same size throughout the fishing season. Without loss of generality we define the area that the stock occupies as the unit area. We assume that the area remains constant throughout the fishing season. The area is divided between the 2 agents. The aggregate stock available to harvest in the beginning of a fishing season is X^t. The stock X^t is uniformly distributed over the area. Agent *i* has access to the stock $\gamma_i X^t$, where γ_i is agent *i*'s share of the area where the stock is located.[1] By assumption, the fish do not migrate from one agent's area to another during the fishing season. Each agent then controls the abandonment level, or escapement, in his area. After the fishing season the stock grows and redistributes itself over the entire area.

Assume that the growth of the fish stock is defined by how much is left behind in total after harvesting. In the absence of uncertainty the fish population changes from one period to the next as follows:

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

where $R\left(\sum_{i=1}^{N} S_{i,t}\right)$ is a differentiable and strictly concave recruitment function and $\sum_{i=1}^{N} S_{i,t}$ is the aggregate escapement. Ignoring natural mortality during the fishing season, the harvest in area *i* is the initial stock minus the escapement: $H_{i,t} = \gamma_i X^t - S_{i,t}$. The relation of the aggregate escapement to initial stock and aggregate harvest is $\sum_{i=1}^{N} S_{i,t} = \sum_{i=1}^{N} \gamma_i X^t - \sum_{i=1}^{N} H_{i,t} = X^t - \sum_{i=1}^{N} H_{i,t}$.

[1] 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. The stock redistributing itself in the same way after each fishing period suffices.

Let x denote the size of the stock available to Agent i at any moment in time, c the constant unit cost of fishing effort, and p the constant price of catch. Assuming that the harvest follows the Schaefer production function, the marginal cost of harvest for each agent is c/x. The profits in period t to Agent i from harvesting the stock from $\gamma_i X$ down to S_i are

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

The present value of harvest is $\sum_{t=0}^{\infty} \delta^t \pi_{i,t}$, where δ^t denotes the common discount factor δ raised to the tth power. Each agent can either act alone to maximize the flow of profits from his share of the fishery or, given the interdependence of the fisheries through the shared stock, cooperate to maximize the joint profit and bargain for a fair share of that profit. The action available to Agent i is setting the escapement $S_{i,t}$ which, given the initial stock, determines the harvest quota $H_{i,t}$.

We extend Hannesson's (1997) model of a transboundary fishery to consider two sources of uncertainty: (i) stochastic variation in stock recruitment and (ii) inaccurate implementation of target escapements. Consider first case (i), a random shock $\theta_{R,t}$ on recruitment. Stock recruitment is

(1b) $$X^{t+1} = \theta_{R,t} R\left(\sum_{i=1}^{N} S_{i,t} \right),$$

where $R\left(\sum_{i=1}^{N} S_{i,t} \right)$ is the expected or average spawning stock – recruitment relation, and $\{\theta_{R,t}\}$ is a sequence of independent identically distributed random variables with unit mean. Each

$\theta_{R,t}$ is a shock to the recruitment that the agents cannot observe directly. The random multipliers $\theta_{R,t}$ are distributed on some finite interval $[a_R, b_R]$, where $0 < a_R < 1 < b_R < \infty$, with a common cumulative distribution function F_R and continuous density f_R, with $b_R R'(0) > 1$ and $lim_{s \to \infty} a_R R'(s) < 1$. Uncertainty enters the present value of harvest through X^t. The agents now maximize their expected discounted net revenue $E\left[\sum_{t=0}^{\infty} \delta^t \pi_{i,t}\right]$.

In case (ii) we allow for uncertainty in the implementation of the fishery manager's target escapement level. We define $S_{i,t}^T$ as the target escapement for fishery *i* set by the fishery manager. We assume a multiplicative implementation shock θ_i on the target escapement. The θ_i are distributed on some finite interval $[a_i, b_i]$, where $0 < a_i < 1 < b_i < \infty$, again with a common cumulative distribution function F_i and continuous density f_i. The realized escapement is defined as $S_{i,t}^R = \theta_{i,t} S_{i,t}^T$. The stock in the beginning of period $t+1$ is

(2) $$X^{t+1} = R\left(\sum_{i=1}^{N} S_i^R\right) = R\left(\sum_{i=1}^{N} \theta_i S_i^T\right).$$

Uncertainty now enters in the period *t* profits to Agent *i*. The expected profits when the target escapement is set at S_i^T are given by

$$E[\pi_i^t] = E\left[p\left(\gamma_i X^t - \theta_{i,t} S_{i,t}\right) - c\left(ln\, \gamma_i X^t - ln\, \theta_{i,t} S_{i,t}\right)\right].$$

We will next consider the implications of non-cooperative harvest in the shared fishery with (i) stochastic shock on recruitment and (ii) stochastic shock on escapement. We will then proceed to describe a cooperative agreement that can be supported in the presence of uncertainty. We will conclude with a numerical example of such agreement.

3 Non-cooperation in the stochastic transboundary fishery

We first examine non-cooperative harvesting, where each agent makes his harvest decision without considering its effect on the other agent's expected payoff. There are no negotiations or understandings between the agents. Each agent maximizes his expected payoff, taking as given the other fleets' escapements which he can only infer from his knowledge of the other fleets' objective functions. Agent *i* will participate in harvest in period *t* only if his marginal net revenue $p - c/\gamma_i X$ at the outset of harvest is positive. We will assume that $\gamma_i \theta_R R\left(\sum_{i=1}^{N} S_i\right) > c/p$ for all $\theta_R \in [a_R, b_R]$ and for all *i* for the case of recruitment uncertainty (i), and that $\gamma_i R\left(\sum_{i=1}^{N} \theta_i S_i\right) > c/p$ for all $\theta_i \in [a_i, b_i]$ for the case of escapement uncertainty (ii). All the agents will then harvest at any state of nature. We first describe the case of recruitment uncertainty, then the case of escapement uncertainty.

3.1 Recruitment uncertainty

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

(3) $$EV_i = E\left[\sum_{t=0}^{\infty} \delta^t \left\{ p\left[\gamma_i \theta_R R\left(\sum_{j=1}^{N} S_{j,t-1}\right) - S_{i,t}\right] - c\left[ln\, \gamma_i \theta_R R\left(\sum_{j=1}^{N} S_{j,t-1}\right) - ln\, S_{i,t}\right]\right\}\right].$$

The first order condition for maximizing (3) subject to $X_{t+1} = \theta_R R\left(\sum_{i=1}^{N} S_{i,t}\right)$ is

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

We call the escapement that solves equation (4) the non-cooperative escapement S_i^N. These escapements give rise to the expected non-cooperative equilibrium profits $E\pi_i^N$. Note that the predictions from the model where each fishery has control of the portion of the stock feeding in its area are less pessimistic that those from the sequential fishery models by Hannesson (1995), McKelvey (1997), and Laukkanen (2003). The agents do not harvest all the way down to the zero marginal profit level c/p but instead partially account for the effect of their harvest on the stock available next year. As in Reed's (1978, 1979) analysis, the random multipliers cancel out and no uncertainty is hence present in the first order conditions.

We next study how the solution to equation (3) compares to the sole owner optimum where one manager controls the entire fishery resource. The expected payoff EV_{TOT} is the sum of the *N* agents' payoffs,

$$(5) \qquad EV_{TOT} = E\left[\sum_{t=0}^{\infty}\delta^t \sum_{i=1}^{N}\left\{p\left[\gamma_i\theta_R R\left(\sum_{j=1}^{N} S_{j,t-1}\right) - S_{i,t}\right] - c\left[ln\,\gamma_i\theta_R R\left(\sum_{j=1}^{N} S_{j,t-1}\right) - ln\,S_{i,t}\right]\right\}\right].$$

The first order condition for the sole owner optimal S_i that maximizes equation (5)

$$(6) \qquad p - \frac{c}{S_{i,t}} = \delta\sum_{j=1}^{N}\gamma_j R'\left(\sum_{j=1}^{N} S_{j,t-1}\right)\left\{p - \frac{c}{\gamma_j R\left(\sum_{j=1}^{N} S_{j,t-1}\right)}\right\}.$$

We denote the S_i that solves (6) by $S^0{}_i$. The random multipliers again cancel out. The individual agent's first order condition in (4) balances the marginal benefit of an additional unit of harvest this year to the benefit forgone by the agent next year due to reduced recruitment. An individual agent fails to account for the effect of reduced recruitment on the benefits accruing to the other agents harvesting the stock. The society's first order condition in (6) instead accounts for the effect of one agent's additional harvest on the benefits to all agents in the following year. Since $p - c/S_i$ is increasing in S_i, the S_i solving (4) is smaller than the S_i solving (6). An individual agent harvesting independently of the others leaves a suboptimal escapement from the point of view of the fishery as a whole.

3.2 Escapement uncertainty

Agent *i*'s expected payoff now is

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

By assumption, at time *t* the current stock X_t is known but $X_{t+j}, j \geq 1$ is not. That is, $\theta_{i,t}$ is realized after the period *t* target escapement $S^T_{i,t}$ has been set.

Fishery manager *i*'s problem is to maximize (7) by choice of a target escapement $S_{i,t}^{T}$, subject to $X_{t+1} = R\left(\sum_{i=1}^{N}\theta_i S_i^T\right)$. The first order condition for maximizing (7) is

$$(8) \qquad p - \frac{c}{S_{i,t}^{T}} = E\left[\delta\theta_{i,t}\gamma_i R'\left(\sum_{j=1}^{N}\theta_{j,t}S_{j,t}^{T}\right)\left\{p - \frac{c}{\gamma_i R\left(\sum_{j=1}^{N}\theta_{j,t}S_{j,t}^{T}\right)}\right\}\right].$$

We call the target escapement that solves (8) the non-cooperative target escapement $S_{i,t}^{TN}$.

Society's objective is to maximize the total expected payoff, which is the sum of the individual agents' payoffs:

$$(9) \qquad EV_{TOT} = E\left[\sum_{t=0}^{\infty}\delta^t \sum_{i=1}^{N}\left\{p\left[\gamma_i X_t - \theta_{i,t}S_{i,t}^{T}\right] - c\left[\ln\gamma_i X_t - \ln\theta_{i,t}S_{i,t}^{T}\right]\right\}\right]$$

subject to $X_{t+1} = R\left(\sum_{i=1}^{N}\theta_i S_i^T\right)$. The first order condition for the maximization problem is

$$(10) \qquad p - \frac{c}{S_{i,t}^{T}} = E\left[\delta\theta_{i,t}R'\left(\sum_{j=1}^{N}\theta_{j,t}S_{j,t}^{T}\right)\sum_{j=1}^{N}\gamma_j\left(p - \frac{c}{\gamma_j R\left(\sum_{j=1}^{N}\theta_{j,t}S_{j,t}^{T}\right)}\right)\right].$$

The escapement that solves (10) is denoted by $S_{i,t}^{TO}$. The first order conditions to the individual agent's and society's problems are similar to the recruitment uncertainty case. In expectation, an individual agent only accounts for the effect of his harvest this season on his own expected payoff next year through reduced recruitment. If the fishery instead were managed by a sole owner, he would balance the benefit from additional harvest this year with expected loss to all the fishing areas in the next period.

We next study whether preplay communication, without commitment, enables the agents to manage the resource more successfully. Assume that the agents confer, and agree on a cooperative management scheme that yields higher expected payoffs to each agent.

Hannesson (1997) provides a deterministic model to study cooperative harvesting supported by the threat of reverting to non-cooperative harvesting if defection is detected. Uncertainty in recruitment or implementation of target escapements complicates the enforcement of harvesting agreements since agents are no longer able to observe the actions of their competitors. We next examine conditions under which cooperative harvesting can be sustained as a self-enforcing equilibrium when stock fluctuations are incorporated into the model.

4 Cooperative harvesting

Suppose now that the agents confer and negotiate on a cooperative harvesting strategy that allows them to better use the productive potential of the fishery resource. Assume that they agree on constrained Pareto efficient cooperative escapement levels that maximize the joint benefit from the fishery, subject to the constraint that it is in each agent's interest to adhere to the agreement. Since each fleet harvests in a distinct fishing area, the agents cannot observe the escapement left by the other fleet. The stock available for harvest can be small either because someone cheated, or because there was a negative shock on the recruitment or escapement. 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, following Green and Porter (1984), we consider an agreement where the agents settle on the threat strategies of reversion to the non-cooperative (target) escapements S_i^N (S_i^{TN}) for $T-1$ periods if violations of the agreement are detected.

Formally, suppose that the agents decide to cooperate and agree on a trigger strategy of reverting to the non-cooperative target escapements S_i^N (S_i^{TN}) 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 will return to cooperative target escapement levels.

The agents commence harvesting in accordance with their cooperative target escapement levels S_i^C $\left(S_i^{T,C}\right)$ in a Nash equilibrium in trigger strategies. They continue to do so until 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^N $\left(S_i^{TN}\right)$ regardless of what $S_{j,t}$ and X^t are. At the conclusion of the $T-1$ punishment periods, cooperation is resumed. Once resumed, cooperation prevails until the next time that $X < \overline{X}$.

Formally, 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 defined by

$$\begin{cases} S_i^C \left(S_i^{TC}\right) \text{if } t \text{ is normal} \\ S_i^N \left(S_i^{TN}\right) \text{if } t \text{ is reversionary.} \end{cases}$$

We again first depict the agreement for the case of recruitment uncertainty, and then for the case of escapement uncertainty.

4.1 Recruitment uncertainty

The escapement left by agent *i* in period *t* determines the agent's current payoff and the probability of triggering a punishment phase. The expected payoff from leaving an escapement S_i in period *t*, after the current stock X^t has been observed is

$$\begin{aligned} EV_i^C\left(X^t\right) = \pi_i\left(X^t, S_i\right) + P\left[\theta_R R\left(\sum_j S_j\right) \geq \overline{X}\right] \delta EV_i^C\left(\tilde{X}^{t+1} \middle| \tilde{X}^{t+1} \geq \overline{X}\right) \\ + P\left[\theta_R R\left(\sum_j S_j\right) < \overline{X}\right] \delta EV_i^*\left(\tilde{X}^{t+1} \middle| \tilde{X}^{t+1} < \overline{X}\right) \end{aligned} \quad (11)$$

The notation in equation (11) is as follows:

$P\left[\theta_R R\left(\sum_j S_j\right) \geq \overline{X}\right]$ the probability of the stock next year being at or above the trigger level

$\pi_i\left(X^t, S_{i,t}\right) = p\left[\gamma_i X^t - S_{i,t}\right] - c\left[\ln \gamma_i X^t - \ln S_{i,t}\right]$

$$EV_i^C\left(\tilde{X}^{t+1}\middle|\tilde{X}^{t+1}\geq\overline{X}\right)=E\left[\pi_i\left(\tilde{X}^t,S_{i,t}\right)\right]+P\left[\theta_R R\left(\sum_j S_j,t\right)\geq\overline{X}\right]\delta^T EV_i^C\left(\tilde{X}^{t+1}\middle|\tilde{X}^{t+1}\geq\overline{X}\right)$$

$$+P\left[\theta_R R\left(\sum_j S_{j,t}\right)<\overline{X}\right]\delta^T EV_i^*\left(\tilde{X}^{t+1}\middle|\tilde{X}^{t+1}<\overline{X}\right)$$

$$EV_i^*\left(\tilde{X}^{t+1}\middle|\tilde{X}^{t+1}<\overline{X}\right)=\omega_{1,i}^p+\sum_{\tau=1}^{T-2}\delta^\tau\omega_{2,i}^p+\delta^{T-1}\omega_{3,i}^p+P\left[\theta_R R\left(\sum_j S_j\right)\geq\overline{X}\right]\delta^T EV_i^C\left(\tilde{X}^{t+1}\middle|\tilde{X}^{t+1}\geq\overline{X}\right)$$

$$+P\left[\theta_R R\left(\sum_j S_j\right)<\overline{X}\right]\delta^T EV_i^*\left(\tilde{X}^{t+1}\middle|\tilde{X}^{t+1}<\overline{X}\right)$$

$$\omega_{1,i}^p=E\left\{p\left[\gamma_i\theta_R R\left(\sum_{j=1}^N S_{j,t-1}\right)-S_{i,t}^*\right]-c\left[\ln\gamma_i\theta_R R\left(\sum_{j=1}^N S_{j,t-1}\right)-\ln S_{i,t}^*\right]\middle|\theta_R R\left(\sum_{j=1}^N S_{j,t-1}\right)<\overline{X}\right\}$$

$$\omega_{2,i}^p=E\left\{p\left[\gamma_i\theta_R R\left(\sum_{j=1}^N S_{j,t-1}^*\right)-S_{i,t}^*\right]-c\left[\ln\gamma_i\theta_R R\left(\sum_{j=1}^N S_{j,t-1}^*\right)-\ln S_{i,t}^*\right]\right\}$$

$$\omega_{3,i}^p=E\left\{p\left[\gamma_i\theta_R R\left(\sum_{j=1}^N S_{j,t-1}^*\right)-S_{i,t}\right]-c\left[\ln\gamma_i\theta_R R\left(\sum_{j=1}^N S_{j,t-1}^*\right)-\ln S_{i,t}\right]\right\}$$

We first solve for $EV_i^*\left(\tilde{X}^{t+1}\middle|\tilde{X}^{t+1}<\overline{X}\right)$ and insert the solution into the equation for $EV_i^C\left(\tilde{X}^{t+1}\middle|\tilde{X}^{t+1}\geq\overline{X}\right)$. We then derive a closed form solution for $EV_i^C\left(\tilde{X}^{t+1}\middle|\tilde{X}^{t+1}\geq\overline{X}\right)$. Finally, we insert $EV_i^C\left(\tilde{X}^{t+1}\middle|\tilde{X}^{t+1}\geq\overline{X}\right)$ and $EV_i^*\left(\tilde{X}^{t+1}\middle|\tilde{X}^{t+1}<\overline{X}\right)$ into (11), from which we solve for the optimal $S_{i,t}$ under cooperation in trigger strategies.

With $P\left[\theta_R R\left(\sum_j S_j\right)<\overline{X}\right]=F\left[\overline{X}/R\left(\sum_j S_j\right)\right]$, where $F(\theta_R)$ is the distribution of θ_R, $EV_i^*\left(\tilde{X}^{t+1}\middle|\tilde{X}^{t+1}<\overline{X}\right)$ can be written as

$$EV_i^*\left(\tilde{X}^{t+1}\middle|\tilde{X}^{t+1}<\overline{X}\right)$$

$$=\frac{\omega_{1,i}^p+\sum_{\tau=1}^{T-2}\delta^\tau\omega_{2,i}^p+\delta^{T-1}\omega_{3,i}^p+\left[1-F\left[\overline{X}/R\left(\sum_j S_j\right)\right]\right]\delta^T EV_i^C\left(\tilde{X}^{t+1}\middle|\tilde{X}^{t+1}\geq\overline{X}\right)}{1-F\left[\overline{X}/R\left(\sum_j S_j\right)\right]\delta^T}\tag{12}$$

Inserting (12) into the equation for $EV_i^C\left(\tilde{X}^{t+1}\middle|\tilde{X}^{t+1}\geq\overline{X}\right)$, writing out $\sum_{\tau=1}^{T-2}\delta^\tau\omega_{2,i}^p$ using the formula for the geometric sum, and solving for $EV_i^C\left(\tilde{X}^{t+1}\middle|\tilde{X}^{t+1}\geq\overline{X}\right)$ yields

(13) $$EV_i^C\left(\tilde{X}^{t+1}\middle|\tilde{X}^{t+1}\geq\overline{X}\right)=\frac{E\left[\pi_i\left(\tilde{X}^t,S_{i,t}\right)\right]+\delta F\left[\overline{X}/R\left(\sum_j S_j\right)\right]\left\{\omega_{1,i}^p+\frac{\omega_{2,i}^p\left(\delta-\delta^{T-1}\right)}{1-\delta}+\delta^{T-1}\omega_{3,i}^p-\delta^{T-1}E\left[\pi_i\left(\tilde{X}^t,S_{i,t}\right)\right]\right\}}{1-\delta+\left(\delta-\delta^T\right)F\left[\overline{X}/R\left(\sum_j S_j\right)\right]}$$

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

(14) $$EV_i^C\left(\tilde{X}^{t+1}\middle|\tilde{X}^{t+1}\geq\overline{X}\right)=\frac{E\left[\pi_i\left(\tilde{X}^t,S_{i,t}\right)\right]-\omega_{2,i}^p+F\left[\overline{X}/R\left(\sum_j S_j\right)\right]\left\{\delta\left(\omega_{1,i}^p-\omega_{2,i}^p\right)+\delta^T\left[\omega_{3,i}^p-E\left[\pi_i\left(\tilde{X}^t,S_{i,t}\right)\right]\right]\right\}}{1-\delta+\left(\delta-\delta^T\right)F\left[\overline{X}/R\left(\sum_j S_j\right)\right]}+\frac{\omega_{2,i}^p}{1-\delta}.$$

The agents' expected cooperative payoff in (14) consists of the noncooperative payoff, plus the one period gain from cooperation and payoffs from transition to and from punishment period appropriately discounted.

By assumption, the agents observe period *t* stock before setting their period *t* target escapement. Using (14) and (12), the expected payoff from leaving an escapement S_i in period *t*, after the current stock X^t has been observed becomes

(14b) $$EV_i^C\left(X^t\right)=EV_i^C\left(\tilde{X}^{t+1}\middle|\tilde{X}^{t+1}\geq\overline{X}\right)+\pi_i\left(X^t,S_i\right)-E\left[\pi_i\left(\tilde{X}^t,S_{i,t}\right)\right].$$

Where to put Si? Check dynamic programming, G&P paper etc.

The agents' actions are not observed. After stock observation, each agent chooses the target escapement that maximizes his expected payoff under cooperation in trigger strategies, $EV_i^C\left(X^t\right)$. Given $S_{j\neq i}$, $\overline{X}$, and *T*, Agent *i*'s optimal cooperative escapement S_i^C must satisfy

$$EV_i^C\left(S_i^C,S_{j\neq i}\right)\geq EV_i^C\left(S_i,S_{j\neq i}^C\right)\text{ for all }S_i.$$

Assuming an interior solution, the necessary condition for maximizing $EV_i^C\left(X^t\right)$ is $\partial EV_i^C\left(S_i^C,S_{j\neq i}^C\right)/\partial S_i=0$.

We next turn into how the countries set T and $\overline{X}$ in an optimal manner, given that for any T, $\overline{X}$ pair each fishery's optimal escapement under cooperation is $S_i = \underset{S_i}{arg\,max}\, EV_i^C$.

Countries negotiate on the length of the punishment phase, determined by T, and the trigger stock level $\overline{X}$, knowing that each country sets its escapement to maximize EV_i^C. Formally, T and $\overline{X}$ are set to maximize the expected joint payoff

$$(15) \qquad J\left(S_1, S_2, \overline{X}, T, X^0\right) = \sum_{i=1}^{2} \alpha_i EV_i^C\left(S_i, \underset{j \neq i}{S}, \overline{X}, T, X^0\right),$$

subject to each S_i maximizing $EV_i^C\left(X^t\right)$. Each agent must also obtain at least his expected non-cooperative payoff. The α_i in (15) are the weights to each country's payoff in the joint maximization problem. A cooperative solution that satisfies (15) for all i is a self-enforcing equilibrium, and the strategies are subgame perfect.

If the cooperative solution is such that $P\left[\theta_R R\left(\sum_j S_j\right) < \overline{X}\right] > 0$, punishment phases of reversion to non-cooperative harvests are observed with a positive probability even if the countries agree on a cooperative harvesting strategy. These periods are necessary to support the cooperative agreement. The cooperative solution is not renegotiation proof. At the outset of a punishment phase, the countries could presumably confer and decide to continue cooperative harvest. However, this would unravel the rational for cooperation and it will thus be in each country's interest to follow the agreement in punishment periods as well.

4.2 Escapement uncertainty

We next describe the trigger stock agreement for the case of escapement uncertainty. For now we suppose that the uncertainty on the escapement is exogenous. An agent's action is setting the target escapement. Others cannot observe the action because of the disparity between the target and the realized escapement. Because of the implementation uncertainty, agents do not know whether low stock level is due to someone cheating or low escapement due to bad luck.

With a cooperative agreement in trigger strategies similar to the one above, the functional equation for agent *i*'s expected payoff can be written as

(16)
$$EV_i^C\left(X, S_i\right) = E\pi_i\left(X, \theta_i S_i\right) + P\left[R\left(\sum_j \theta_j S_j\right) \geq \overline{X}\right]\delta EV_i^C\left(\tilde{X}, S_i\right)$$
$$+ P\left[R\left(\sum_j \theta_j S_j\right) < \overline{X}\right]\delta EV_i^*\left(\tilde{X}, S_i\right)$$

The notation is as follows:

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

$$EV_i^C\left(\tilde{X}, S_i\right) = E\left[\pi_i\left(\tilde{X}, \theta_i S_i\right) \middle| \tilde{X} \geq \overline{X}\right] + P\left[R\left(\sum_j \theta_j S_j\right) \geq \overline{X}\right]\delta EV_i^C\left(\tilde{X}, S_i\right)$$
$$+ P\left[R\left(\sum_j \theta_j S_j\right) < \overline{X}\right]\delta EV_i^*\left(\tilde{X}, S_i\right)$$

$$EV_i^*\left(\tilde{X}, S_i\right) = \omega_{1,i}^p + \sum_{\tau=1}^{T-2} \delta^\tau \omega_{2,i}^p + \delta^{T-1}\omega_{3,i}^p$$
$$+ P\left[R\left(\sum_j \theta_j S_j\right) \geq \overline{X}\right]\delta^T EV_i^C\left(\tilde{X}, S_i\right) + P\left[R\left(\sum_j \theta_j S_j\right) < \overline{X}\right]\delta^T EV_i^*\left(\tilde{X}, S_i\right)$$

$$\omega_{1,i}^p = E\left\{p\left[\gamma_i R\left(\sum_{j=1}^N \theta_j S_j\right) - \theta_i S_i^{TN}\right] - c\left[\ln\gamma_i R\left(\sum_{j=1}^N \theta_j S_j\right) - \ln\theta_i S_i^{TN}\right] \middle| R\left(\sum_{j=1}^N \theta_j S_j\right) < \overline{X}\right\}$$

$$\omega_{2,i}^p = E\left\{p\left[\gamma_i R\left(\sum_{j=1}^N \theta_j S_j^{TN}\right) - \theta_i S_i^{TN}\right] - c\left[\ln\gamma_i R\left(\sum_{j=1}^N \theta_j S_j^{TN}\right) - \ln\theta_i S_i^{TN}\right]\right\}$$

$$\omega_{3,i}^p = E\left\{p\left[\gamma_i R\left(\sum_{j=1}^N \theta_j S_j^{TN}\right) - \theta_i S_i\right] - c\left[\ln\gamma_i R\left(\sum_{j=1}^N \theta_j S_j^{TN}\right) - \ln\theta_i S_i\right]\right\}$$

We next solve for EV_i^C following the same procedure as in the recruitment uncertainty case. The probability of reversion can be written as $P\left[R\left(\sum_j \theta_j S_j\right) < \overline{X}\right] = F\left[\overline{X}; S_1, S_2\right]$, where is the distribution of $R\left(\sum_j \theta_j S_j\right)$. Solving for EV_i^*, inserting the solution into the equation for EV_i^C and solving for EV_i^C yields

(17)

$$EV_i^C(X,S_i)=\frac{E\pi(X,\theta_i S_i)+F[\overline{X};S_1,S_2]\delta\left[\omega_{1,i}^p+\sum_{\tau=1}^{T-2}\delta^\tau\omega_{2,i}^p+\delta^{T-1}\omega_{3,i}^p-\delta^{T-1}E\pi(X,\theta_i S_i)\right]}{1-\delta+(\delta-\delta^T)F[\overline{X};S_1,S_2]}$$

As above, writing out the geometric sum $\sum_{\tau=1}^{T-2}\delta^\tau\omega_{2,i}^p$ and adding and subtracting $\omega_{2,i}^p$ in the numerator yields

(18)

$$EV_i^C=\frac{E\pi_i\left(X^t,\theta_i S_i\right)-\omega_{2,i}^p+F[\overline{X};S_1,S_2]\left[\delta\left(\omega_{1,i}^p-\omega_{2,i}^p\right)+\delta^T\left(\omega_{3,i}^p-E\pi_i\left(X^t,\theta_i S_i\right)\right)\right]}{1-\delta+(\delta-\delta^T)F[\overline{X};S_1,S_2]}+\frac{\omega_{2,i}^p}{1-\delta}$$

Again, the agents' expected cooperative payoff consists of the noncooperative payoff, plus the one period gain from cooperation and payoffs from transition to and from punishment period appropriately discounted. Each agent chooses the escapement that maximizes his expected payoff under cooperation in trigger strategies, EV_i^C. Given $S_{j\neq i}$, $\overline{X}$, and *T*, Agent *i*'s optimal cooperative escapement S_i^C must satisfy

$$EV_i^C\left(S_i^C,S_{j\neq i}\right)\geq EV_i^C\left(S_i,S_{j\neq i}^C\right)\text{ for all } S_i.$$

The agents settle on *T* and $\overline{X}$ that maximize $J\left(S_1,S_2,\overline{X},T,X^0\right)=\sum_{i=1}^{2}\alpha_i EV_i^C\left(S_i,\underset{j\neq i}{S},\overline{X},T,X^0\right)$, given that S_i maximizes EV_i^C above.

5 Simulation results on cooperation in trigger strategies

This section provides a numerical example that illustrates the joint management game under uncertainty. The numerical results were computed using Mathematica 4. Table 1 displays the parameter values. The parameter values were chosen to reflect a realistic range. Average recruitment follows the Ricker spawning stock – recruitment relation $R(S)=kSe^{lS}$. Prices was normalized to one. Prices and costs are the same for both countries. We consider the case of uniformly distributed θ_i, $i=1,2,R$. That is,

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

where $a_i = 1 - \varepsilon_i$ and $b_i = 1 + \varepsilon_i$.

We proceed by computing the optimal (target) escapements S_i (S_i^T) for each $T, \overline{X}$ pair. The optimal agreement is the set $\{T, \overline{X}, S_1^T, S_2^T\}$ that maximizes the expected joint payoff $J(T, \overline{X}, S_1^T, S_2^T, X_0)$ in (15). We used a simulation period of 50 years. The S_i are no smaller than S_i^N and no larger than $\gamma_i R_u$, where R_u is the upper bound to recruitment. Since probability of reversion is 0 for values of $\overline{X}$ less than $a_R R[\Sigma S_i^N]$ ($R[\Sigma a_i S_i^N]$), and 1 for values of $\overline{X}$ greater than R_u, it is sufficient to consider trigger stocks between $a_R R[\Sigma S_i^N]$ ($R[\Sigma a_i S_i^N]$) and R_u. The initial stock was set equal to the expected stock at the non-cooperative (target) escapements. The weight α_i on each agent's payoff is 0.5. We computed the non-cooperative globally optimal outcomes and the trigger stock agreement for three values of ε: $\varepsilon = 0.1$, $\varepsilon = 0.3$, and $\varepsilon = 0.5$.

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

Table 1. Example parameters

6 Conclusion

We examine cooperative and non-cooperative harvesting in a stochastic transboundary fishery shared by N agents. Even when each agent has full control of the harvest and escapement in a part of the area that the entire stock occupies, the non-cooperative escapement levels will be 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 all the agents cooperate, reversionary periods may occur with a positive probability. Although the agents know that a low stock level reflects a stochastic shock to recruitment, 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 or low escapements have been observed. However, all parties realize that renegotiating would unravel the rational for cooperation.

An important extension would be to study the agreement numerically to illustrate the characteristics of the cooperative harvesting game. Further, it would be of interest to study the impacts of different degrees of uncertainty and the effect of the number of agents sharing the fishery on the likelihood of sustaining cooperative harvest levels. Finally, the model could be extended to allow for uncertainty in implementing the agreed upon escapement levels.

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