DEPARTMENT OF AGRICULTURAL AND RESOURCE ECONOMICS AND POLICY
DIVISION OF AGRICULTURE AND NATURAL RESOURCES
UNIVERSITY OF CALIFORNIA AT BERKELEY

WORKING PAPER NO. 918

COOPERATIVE AND NON-COOPERATIVE HARVESTING IN A STOCHASTIC SEQUENTIAL FISHERY

by

Marita Laukkanen

California Agricultural Experiment Station
Giannini Foundation of Agricultural Economics
November 2000

COOPERATIVE AND NON-COOPERATIVE HARVESTING IN A STOCHASTIC SEQUENTIAL FISHERY*

Marita Laukkanen
Email laukkane@are.berkeley.edu
Department of Agricultural and Resource Economics
University of California
207 Giannini Hall
Berkeley, CA 94720

Abstract

We examine cooperative harvesting in a sequential fishery with stochastic shocks in recruitment. Two fleets harvest in a stochastic interception fishery. We analyze cooperative management as a non-cooperative game, where deviations from cooperative harvesting are deterred by the threat of harvesting at non-cooperative levels for a fixed number of periods whenever the initial stock falls below a trigger level. We illustrate the sequential harvesting game with an application to the Northern Baltic salmon fishery. Cooperative harvesting yields participants substantial gains in terms of expected payoffs. The greatest gains accrue to the fleet harvesting the spawning stock, the actions of which are not observed by the competitor. An explanation for the prevalence of fish wars is provided in that even if a cooperative agreement is reached, shocks in recruitment trigger phases of non-cooperative harvesting. Further, the cooperative solution can only be maintained when stock uncertainty is not too prevalent.

Keywords: fisheries management, shared resources, sequential fishery, non-cooperative games, stochastic recruitment.

* This study has benefited enormously from ongoing discussions with Larry Karp and from helpful comments from Jeffrey LaFrance. All remaining errors are the author's sole responsibility.

1. Introduction

Migratory fish stocks breed in one area, move to another to grow, and return to their breeding area to spawn. During their migration the stocks are harvested in a sequence of fisheries. Each fishery affects the stock available to the next fishery in the gauntlet and therefore its economic performance. For example, salmon spawn in rivers, feed in the open sea, and return to their home rivers to spawn. Southern bluefin tuna spend most of their juvenile phase along the coast of Australia, then migrate to the high seas between South Africa and New Zealand. Pacific Halibut travel along the coast of Canada and the United States. If a single authority controls each fishery, two basic management options arise: each fishery manager can either maximize the return from his own fishery, or cooperate with other fleets in order to maximize the aggregate return, and bargain for a share of that return. In a cooperative solution, agents negotiate over the amount of fish they leave behind. When recruitment is deterministic, they can monitor adherence to the agreement through the stock available at the outset of harvest. Hannesson (1995) studies the case of two sequential fisheries, and examines cooperative management as a self-enforcing equilibrium supported by the threat of harvesting non-cooperatively forever if deviations are detected. Otherwise, transboundary management of sequential fisheries has received little attention. McKelvey (1997) considers side payments in a sequential fishery. Kaitala and Pohjola (1988) address the related problem of joint harvest in a single fishery simultaneously exploited by two agents.

Stochastic fluctuations in stock recruitment complicate the joint management problem. When recruitment depends on both the spawning stock level and unobserved shocks, the agent who harvests the initial stock cannot infer the amount of fish left behind by the other agent. Cooperative harvesting equilibria supported by the threat non-cooperative harvesting ad infinitum break down. We study an agreement designed to overcome this problem and maintain coordinated harvest as a self-enforcing equilibrium in the case of stochastic recruitment. We incorporate stock uncertainty into Hannesson's (1995) setting and apply the model of non-cooperative collusion developed by Green and Porter (1984) to a sequential fishery. We consider two fleets, each controlled by a sole authority acting independently. Differing from Green and Porter (1984), one agent's action follows that of the other.

The sustainability of a cooperative solution is an empirical question. We apply the model to data for the northern Baltic salmon fishery. The numerical results indicate that by cooperating both parties could obtain substantial gains in expected payoffs. For most parameter values, the agreement is characterized by an arbitrarily small likelihood of reversion to a punishment phase. For a range of parameter values, the optimal length of the punishment phase is practically infinite.

2. The Model

Assume that a fish stock migrates between two areas. It breeds in Area 2, and migrates to Area 1 to feed. Agent 1 harvests in the feeding area. At the outset of the season in year t he has access to the initial stock X^t, which he harvests down to the escapement level S_1^t. The escapement left behind by Agent 1 migrates to Area 2, where Agent 2 harvests the stock down to the escapement S_2^t. The escapement left behind by Agent 2 spawns, producing recruitment of young fish that in turn migrate to Area 1 to feed. The stock available to Agent 1 in year $t+1$ is given by

$$(1) \qquad X^{t+1} = \theta^t R\left(S_2^t\right),$$

where $R\left(S_2^t\right)$ is the expected or average spawning stock - recruitment relation, and $\{\theta^t\}$ is a sequence of independent identically distributed random variables with unit mean. Each θ^t is a shock to the recruitment the agents cannot observe directly. The random multipliers θ^t are distributed on some finite interval $[a,b]$, where $0<a<1<b<\infty$, with a common cumulative distribution function F and continuous density f. The recruitment relation $R\left(S_2^t\right)$ is differentiable and strictly concave, and $bR'(0)>1$ and $\lim_{S_2 \to \infty} aR'(S_2)<1$. There will then be finite population levels

$$u = \max\left\{bR\left(S_2^t\right) : bR\left(S_2^t\right) \geq z, z \geq 0\right\}$$

and

$$l = \max\left\{aR\left(S_2^t\right) : aR\left(S_2^t\right) \geq z, z \geq 0\right\}$$

such that the population will enter and stay within the interval $[l,u]$, on which in will have a stationary limiting distribution (Reed 1978 and Reed 1979).

Let x denote the current size of the exploited stock at any moment in time, c_i the constant unit cost of fishing effort for agent *i*, and p_i the constant price of catch. Assuming that the harvest follows the Schaefer production function, the marginal cost of harvest for each agent is given by c_i / x. The profits in period t to Agent 1 from harvesting the stock from X^t down to S_1^t are given by

$$(2) \qquad \pi_1^t = \int_{S_1^t}^{X^t} \left(p_1 - \frac{c_1}{x} \right) dx = p_1\left(X^t - S_1^t\right) - c_1\left(\ln X^t - \ln S_1^t\right).$$

The period t profits to Agent 2 from harvesting the spawning stock from S_1^t to S_2^t are

$$(3) \qquad \pi_2^t = \int_{S_2^t}^{S_1^t} \left(p_2 - \frac{c_2}{x} \right) dx = p_2\left(S_1^t - S_2^t\right) - c_2\left(\ln S_1^t - \ln S_2^t\right).$$

The agents are risk neutral and maximize their expected discounted net revenue $E\left[\sum_{t=0}^{\infty} \delta^t \pi_i^t\right]$, where δ is the common discount factor.

The actions available to each agent in period t are setting the escapement levels, S_1^t for Agent 1 and S_2^t for Agent 2. Agent 1's strategy $s_1^t : R_+^{2t+1} \to R_+$ defines Agent 1's escapement as a function of past and present recruitments and Agent 1's past escapements by $s_1^t\left(X^0,\ldots,X^t,S_1^0,\ldots,S_1^{t-1}\right) = S_1^t$. The choice of domain reflects the fact that Agent 1 does not observe escapements left behind by Agent 2 but only perceives the initial stock level X^t at the beginning of the fishing season. Agent 2's strategy $s_2^t : R_+^{2t+1} \to R_+$ defines Agent 2's escapement level as a function of past and present Agent 1 escapements and past Agent 2 escapements by $s_2^t\left(S_1^0,\ldots,S_1^t,S_2^0,\ldots,S_2^{t-1}\right) = S_2^t$. Agent 2, unlike Agent 1, observes the competitor's escapement S_1^t. A contingent strategy for agent i is an infinite sequence $s_i = \{s_i^0, s_i^1, \ldots\}$. A Nash equilibrium is a strategy profile $(s_{1\circ}, s_{2\circ})$ that satisfies

$$E_{s_1, s_{2\circ}}\left[\sum_{t=0}^{\infty} \delta^t \pi_1\left(s_1^t, X^t\left(s_{2\circ}^{t-1}\right)\right)\right] \leq E_{s_{1\circ}, s_{2\circ}}\left[\sum_{t=0}^{\infty} \delta^t \pi_1\left(s_{1\circ}^t, X^t\left(s_{2\circ}^{t-1}\right)\right)\right]$$

(4)

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

for each agent i and all feasible strategies s_i.

Reed (1979) showed that a constant escapement policy maximizes the expected discounted net revenue from a stochastic fishery in the case of the Schaefer production function. If it were possible for Agent i to manage the resource as a sole owner, the first order condition for the sole owner optimal escapement level would be

(5) $$p_i - c_i / S_i = \delta R'(S_i)[p_i - c_i / R(S_i)].$$

Let S_i^* denote the solution to (5). Agent $i's$ sole owner optimal escapement S_i^o would be $S_i^o = S_i^*$ if $X > S_i^*$, and $S_i^o = 0$ otherwise. Assuming that S_i^* is always feasible in that $\theta^t R(S_i^*) \geq S_i^*$ for all $\theta^t \in [a,b]$, the stochastic and deterministic models then yield the same sole owner optimal escapement (see also Clark 1990).

3. Non-cooperation in a stochastic sequential fishery

We next 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. We confine our attention to interior solutions where both agents participate in uncoordinated harvest in every state of nature. Each agent sets his escapement to maximize the expected present value of his profits, taking as given the other fleet's escapement which he can only infer from his knowledge of the other fleet's objective function. The optimal escapements are constrained by the non-negativity and feasibility constraints $0 \le S_1^t \le X^t$ and $0 \le S_2^t \le S_1^t$.

The lowest profitable escapement levels are the zero marginal profit levels c_1 / p_1 and c_2 / p_2. Agent 1 will harvest in period t only if his marginal net revenue $p_1 - c_1 / X^t$ at the outset of harvest is positive. Agent 2 will only harvest if $p_2 - c_2 / S_1^t$ is positive. We assume that $\theta^t R(c_2 / p_2) > c_1 / p_1$ for all $\theta^t \in [a,b]$, and that $c_1 / p_1 > c_2 / p_2$. Both agents then harvest at any state of nature. The expected discounted payoffs in period t are

(6a) $$EV_1(X^t, S_1^t) = p_1(X^t - S_1^t) - c_1(\ln X^t - \ln S_1^t) + \delta EV_1[\theta^t R(S_2^t), S_1^{t+1}]$$

(6b) $$V_2(S_1^t, S_2^t) = p_2[S_1^t - S_2^t] - c_2[\ln S_1^t - \ln S_2^t] + \delta V_2(S_1^{t+1}, S_2^{t+1}).$$

With $X^t > c_1 / p_1$ and S_2^t given it is optimal for Agent 1 to harvest to the zero marginal profit level $S_1^t = c_1 / p_1$, which maximizes short-term profit. Similarly, with $S_1^t > c_2 / p_2$ and S_1^{t+1} given, Agent 2's optimal escapement is $S_2^t = c_2 / p_2$.[1]

The competitive harvesting game has a stationary equilibrium in the strategies

$$\begin{cases} S_1^N = c_1 / p_1 \\ S_2^N = c_2 / p_2. \end{cases}$$

These escapements give rise to the expected non-cooperative equilibrium profits $E\pi_1^N$ and π_2^N. The escapements are below optimal levels, since the agents do not account for

---

[1] If $c_1 / p_1 \le c_2 / p_2$, Agent 1 will maximize his expected payoff by excluding Agent 2: Agent 1 will be able to harvest down to a stock level that is unprofitable for Agent 2, and force Agent 2 to leave an escapement $S_2^t = S_1^t$. Agent 1 will then maximize (6a) subject to the constraint $S_1^t \le c_2 / p_2$. Similarly, if $bR(c_2 / p_2) \le c_1 / p_1$, Agent 2 will exclude Agent 1 by harvesting down to an escapement producing recruitment at which it is not profitable for Agent 1 to harvest, forcing Agent 1 to leave an escapement $\theta^t R(S_2^t)$. Agent 2 will then maximize (6b) subject to the constraint $bR(S_2^t) \le c_1 / p_1$. If $\theta^t R(c_2 / p_2) \le c_1 / p_1$ only for some $\theta^t < b$, Agent 2 will only be able to exclude Agent 1 in bad seasons.

the effect of their harvest on the fish stock. Any fish in excess of S_1^N left behind by Agent 1 would be harvested by Agent 2, while a spawning stock larger than S_2^N left behind by Agent 2 would only benefit Agent 1.

We study whether preplay communication, without commitment, enables the agents to manage the resource more successfully. Assume that the agents confer, and agree on some cooperative escapement levels other than S_i^N that yield higher expected payoffs to each agent. Hannesson (1995) examines the case where cooperative harvesting is supported by the threat of reverting to non-cooperative harvesting forever if defection is detected. Stock uncertainty complicates the enforcement of harvesting agreements since agents are no longer able to directly 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 Management

Assume that the agents negotiate and agree on a constrained Pareto efficient joint harvesting strategy, with escapement levels S_1^C and S_2^C such that $S_1^C > S_1^N$ and $S_2^C > S_2^N$. If side payments are not possible, each agent must harvest to earn a profit. Cooperative escapements give rise to the expected single-period profits $E\pi_1^C$ and π_2^C, where $E\pi_1^C > E\pi_1^N$ and $\pi_2^C > \pi_2^N$. The agents settle on the threat strategies of reversion to the non-cooperative escapements S_1^N and S_2^N for $T-1$ periods if violations of the agreement occur.[2] Since Agent 1 only observes recruitment X', which depends on both stochastic shocks and Agent 2's escapement, a trigger level $\overline{X}$ is set which recruitment has to exceed for Agent 1 to continue cooperation. Agent 2 observes S_1' and hence Agent 1's adherence to the agreement.

Suppose the agents then commence harvesting in accordance with their cooperative escapement levels S_1^C and S_2^C in a Nash equilibrium in trigger strategies. They continue to do so until recruitment X' falls below the trigger level $\overline{X}$, or Agent 1

[2] Using non-cooperative escapements as threats is plausible because of their Nash equilibrium property.

leaves an escapement S_1^t below the cooperative level S_1^C. Then $T-1$ periods of punishment phase follow, during which the agents harvest to the non-cooperative escapements S_1^N and S_2^N regardless of what S_1^t and X^t are. At the conclusion of the $T-1$ punishment periods, agents resume cooperative harvesting. Cooperation prevails until the next time that $X < \overline{X}$ or $S_1 < S_1^C$. Assuming that $S_2^N < S_1^N$ and $S_1^N < \theta R\left(S_2^N\right)$ for all $\theta \in [a,b]$, both agents continue to harvest in the punishment phase.

Formally, the agreement is defined as follows. The game has *normal* and *reversionary* stages. Agent 1 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. Agent 2 regards period t as *normal* if

(a) $S_1^t \geq S_1^C$ and $t=0$ or *t-1* was normal,

(b) $S_1^{t-(T-1)} < S_1^C$ and $t-T$ was normal,

and *reversionary* otherwise. The agents act sequentially. Their strategies are defined by

$$\begin{cases} S_i^C \text{ if } t \text{ is normal} \\ S_i^N \text{ if } t \text{ is reversionary.} \end{cases}$$

We first determine the conditions under which cooperation is optimal for Agent 1. Table 4.1 summarizes the definitions used in the discussion.[3] Agent 1 cooperates in a normal period t if the expected value $EV_1^C\left(S_1^C, X^t\right)$ of doing so is greater than that of cheating, $EV_1^N\left(S_1^N, X^t\right)$. Formally, cooperation in a normal period t is optimal if $EV_1^N\left(S_1^N, X^t\right) \leq EV_1^C\left(S_1^C, X^t\right)$ for $X^t \geq \overline{X}$. In order for the threat of reversion to the non-cooperative Nash equilibrium escapement S_1^N to be credible, it must also be optimal for Agent 1 to harvest down to S_1^N when $X^t \leq \overline{X}$. We must thus have $EV_1^N\left(S_1^N, X^t\right) \geq EV_1^C\left(S_1^C, X^t\right)$ for $X^t \leq \overline{X}$. At $X^t = \overline{X}$, the two conditions yield

(7) $$EV_1^N\left(S_1^N, \bar{X}\right) = EV_1^C\left(S_1^C, \bar{X}\right).$$

Condition (7) determines a trigger stock level $\bar{X}$ for any given S_1^C, S_2^C, and T such that Agent 1 will adhere to the agreement, and harvest cooperatively in normal periods but revert to punishment phase at low stock levels.

[Table 4.1 here]

To write out (7), we first write out Agent 1's expected payoffs from cheating and from cooperating. The expected payoff from deviating and harvesting down to S_1^N is

(8) $$EV_1^N\left(S_1^N, X'\right) = \pi_1\left(S_1^N, X'\right) + \sum_{\tau=1}^{T-1} \delta^\tau \omega_1 + \delta^T EV_1^C\left(S_1^C, \tilde{X}^C\right).$$

The current period payoff from deviating is $\pi_1\left(S_1^N, X'\right)$. Agent 2 detects cheating with certainty and commences retaliation, harvesting to his non-cooperative escapement S_2^N. Non-cooperative harvest then continues through $T-1$ reversionary periods with the expected profits ω_1. In reversionary periods it is optimal for Agent 1 to apply his Nash harvesting strategy. The expected payoff from resuming cooperation in period $t+T$ is $EV_1^C\left(S_1^C, \tilde{X}^C\right)$, with Agent 2 first returning to cooperation in period $t+T-1$.[4]

Agent 1's expected payoff from cooperating and leaving S_1^C in normal periods is

[3] In order to avoid cumbersome notation, we suppress S_2 and T in Agent 1's expected payoffs here. Agent 1's payoff will depend on these variables, but they are not choice variables for him once the agreement has been negotiated.

[4] In a more symmetric structure Agent 1 would first return to cooperation if he deviated first. However, only Agent 1 observes the initial stock level. Agent 2 would not know whether Agent 1 is cheating or punishing Agent 2 after observing a low stock level. Agent 1 would always pretend that the latter be the case.

$$
(9) \qquad \begin{aligned} EV_1^C\left(S_1^C, X^t\right) &= \pi_1\left(S_1^C, X^t\right) + \left[1 - F\left(\overline{X} / R\left(S_2^C\right)\right)\right]\delta EV_1^C\left(S_1^C, \tilde{X}^C \mid \tilde{X}^C \geq \overline{X}\right) \\ &+ F\left(\overline{X} / R\left(S_2^C\right)\right)\left\{\delta\gamma_1 + \sum_{\tau=2}^{T} \delta^\tau \omega_1 + \delta^{T+1} EV_1^C\left(S_1^C, \tilde{X}^C\right)\right\}. \end{aligned}
$$

In period t Agent 1 obtains the cooperative profit $\pi_1\left(S_1^C, X^t\right)$. If X^{t+1} exceeds the trigger stock $\overline{X}$, cooperative harvest continues with the expected payoff $EV_1^C\left(S_1^C, \tilde{X}^C \mid \tilde{X}^C \geq \overline{X}\right)$. If X^{t+1} is below $\overline{X}$, a reversionary phase begins. In the first retaliatory period, Agent 1 obtains the expected profit γ_1, followed by $T-1$ punishment periods with expected profits ω_1. Cooperation resumes in period $t+T+1$, with expected payoff $EV_1^C\left(S_1^C, \tilde{X}^C\right)$.

Using (8) and (9), at $X^t = \overline{X}$ equation (7) can be written as

$$
(10) \qquad \begin{aligned} \pi_1\left(S_1^N, \overline{X}\right) - \pi_1\left(S_1^C, \overline{X}\right) &= \left[1 - F(\cdot)\right]\delta EV_1^C\left(S_1^C, \tilde{X}^C \mid \tilde{X}^C \geq \overline{X}\right) \\ &+ F(\cdot)\left[\delta\gamma_1 + \frac{\delta^2 - \delta^{T+1}}{1-\delta}\omega_1 + \delta^{T+1} EV_1^C\left(S_1^C, \tilde{X}^C\right)\right] \\ &- \left[\frac{\delta - \delta^T}{1-\delta}\omega_1 + \delta^T EV_1^C\left(S_1^C, \tilde{X}^C\right)\right]. \end{aligned}
$$

Equation (10) states that Agent 1 only prefers cooperation if the probability $F\left(\overline{X} / R\left(S_2^C\right)\right)$ of entering a reversionary phase is sufficiently low.

We next consider next Agent 2's problem. Table 4.2. summarizes the notation. Agent 2's actions are not observed directly. Unlike Agent 1, Agent 2 then faces a continuous choice of escapements S_2 in normal periods. The escapement determines his current payoff and the probability of cooperative versus reversionary play in the next period. Given S_1^C, $\overline{X}$ and T, Agent 2's chooses a cooperative escapement S_2 that maximizes his expected payoff from cooperative harvesting. Let S_2^C denote Agent 2's optimal choice. Let $EV_2^P\left(S_1^N, S_2^N\right)$ denote Agent 2's expected payoff at the beginning of a punishment phase. Agent 2's expected payoff $EV\left(S_1^C, S_2\right)$ then satisfies the functional equation

$$(11)\qquad EV_2^C(S_1^C,S_2)=\pi_2(S_1^C,S_2)+[1-F(\overline{X}/R(S_2))]\delta EV_2^C(S_1^C,S_2) + F(\overline{X}/R(S_2))\delta EV_2^P(S_1^N,S_2^N)$$

$$=\pi_2(S_1^C,S_2)+[1-F(\overline{X}/R(S_2))]\delta EV_2^C(S_1^C,S_2) + F(\overline{X}/R(S_2))\delta\Big[\sum_{\tau=0}^{T-2}\delta^\tau\omega_2+\delta^{T-1}\pi_2(S_1^N,S_2) + \delta^T\{[1-F(\overline{X}/R(S_2))]EV_2^C(S_1^C,S_2)+F(\overline{X}/R(S_2))EV_2^P(S_1^N,S_2^N)\}\Big]$$

In a normal period t Agent 2 harvests Agent 1's cooperative escapement S_1^C. If $X^{t+1}>\overline{X}$, cooperation continues in the next period. If $X^{t+1}<\overline{X}$, Agent 1 harvests down to S_1^N, and $T-1$ reversionary periods with the non-cooperative profit ω_2 follow. In reversionary periods it is optimal for Agent 2 to harvest to S_2^N. In period $t+T$, Agent 2 first returns to cooperative harvesting, with the profit $\pi_2(S_1^N,S_2)$. Depending on X^{t+1}, cooperative harvesting resumes in period $t+T+1$, or another reversionary phase is entered.

[Table 4.2 here]

Solving (12) for Agent 2's expected discounted payoff $EV_2(S_1^C,S_2)$ yields

$$(12)\qquad EV_2(S_1^C,S_2)=\frac{\pi_2(S_1^C,S_2)-\omega_2-F(\overline{X}/R(S_2))\delta^T[\pi_2(S_1^C,S_2)-\pi_2(S_1^N,S_2)]}{1-\delta+(\delta-\delta^T)F(\overline{X}/R(S_2))}+\frac{\omega_2}{1-\delta}.$$

The details of the derivation are presented in Appendix 1. Agent 2's expected discounted payoff consists of the non-cooperative profits, plus the single-period gain from harvesting cooperatively, appropriately discounted. The gain from cooperation is adjusted for Agent 2's loss from first returning to cooperation after a reversionary phase.

Given S_1^C, $\overline{X}$, and T, Agent 2's optimal cooperative escapement S_2^C must satisfy

$$(13)\qquad EV_2^C(S_1^C,S_2)\le EV_2^C(S_1^C,S_2^C)\text{ for all }S_2.$$

Assuming an interior solution, the necessary condition for (14) is $\partial EV(S_1^C, S_2^C)/\partial S_2 = 0$, which from (13) equals

$$(14) \qquad 0 = \left[\frac{\partial}{\partial S_2}\pi_2(S_1^C, S_2^C)\right]\left[1-\delta+(\delta-\delta^{T+1})F(\overline{X}/R(S_2^C))\right]$$
$$+ f(\overline{X}/R(S_2^C))\frac{\overline{X}R'(S_2^C)}{R(S_2^C)^2}\left\{(\delta-\delta^{T+1})\left[\pi_2(S_1^C, S_C^2)-\pi_2(S_1^N, S_2^C)\right]\right\}.$$

Agent 2's optimal cooperative escapement S_2^C balances the marginal benefit of additional harvest with the marginal increase in the risk of losses resulting from a switch reversionary play. Equation (14) implies $\partial\pi_2(S_1^C, S_2)/\partial S_2\big|_{S_2=S_2^C} < 0$. Since $\partial^2\pi_2(S_1^C, S_2)/(\partial S_2)^2 < 0$, comparing (14) to the condition that determines Agent 2's non-cooperative escapement level, $\partial\pi_2(S_1^C, S_2)/\partial S_2\big|_{S_2=S_2^N} = 0$, we see that the cooperative escapement always exceeds the non-cooperative one.

The parties confer prior to commencement of harvest, and agree on T and S_1^C that maximize a weighted sum of their expected payoffs, subject to the trigger stock equation (10) and Agent 2's first order condition (14). Given T and S_1^C, equations (10) and (14) determine $\overline{X}$ and S_2^C. The cooperative equilibrium is constrained by the requirement that each agent obtain at least his expected non-cooperative payoff. Formally, suppose that the agents negotiate in period 0 after the stock X^0 has been observed. Let α be the weight on Agent 1's expected payoff and $(1-\alpha)$ that on Agent 2's expected payoff. The objective is to choose S_1^C and T that maximize the expected joint payoff

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

subject to conditions (10) and (14). For any S_1^c and T, the constraints determine S_2^c and $\overline{X}$.[5] A cooperative solution characterized by T, $\overline{X}$, S_1^c, and S_2^c such that conditions (10) and (14) hold is a self-enforcing equilibrium, and the strategies are subgame perfect.[6] Varying with the weight on each agent's preferences, there are an infinite number of joint value maximizing cooperative solutions.

We next determine the expected fraction of time spent in cooperation during a cycle, denoted by M, and the expected ratio of cooperative to non-cooperative periods, denoted by N. If cooperation lasts i periods and a punishment phase $T-1$ periods, the fraction of a cycle spent in cooperation is $i/(T-1+i)$. Given that period $t-1$ was normal, the probability of reversion in period t is $F(S_2^c, \overline{X})$ and the probability of cooperation $1-F(S_2^c, \overline{X})$. The expected fraction of time spent in cooperation during a cycle is

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

The expected number of cooperative periods in a cycle is $\sum_{i=0}^{\infty} i\left[1-F\left(S_2^c, \overline{X}\right)\right]^i F\left(S_2^c, \overline{X}\right)$. The expected ratio of cooperative periods to punishment periods then is

$$(17) \qquad N = \frac{1}{T-1}\sum_{i=0}^{\infty} i\left[1-F\left(S_2, \overline{X}\right)\right]^i F\left(S_2, \overline{X}\right).$$

5. Empirical Illustration: the Northern Baltic Salmon Fishery

We illustrate the joint management game with an application to the Northern Baltic salmon fishery. The Northern Baltic salmon stock is harvested sequentially by

---

[5]Mirrlees (1999) points out difficulties that may arise in solving a maximization problem of the type discussed here. Using the Lagrangian method of constrained optimization is only legitimate when for any $\{S_1, \overline{X}, T\}$ there is a unique S_2 that maximizes $EV_2(S_1, S_2, \overline{X}, T)$. If this is not warranted, an analogue of the Kuhn-Tucker method depicted by Mirrlees (1999) may be used to solve the problem.

[6] The equilibrium is not renegotiation proof, since the agents could negotiate if low stock levels have been observed, and resume cooperative behavior, avoiding the punishment stage.

commercial offshore and inshore fleets. Stock recruitment fluctuates, mostly due to the M-74 disease. Economically sound cooperative agreements have not been reached. The computations indicate that the cooperative solution we propose could be sustained for a range of parameter values. Since we consider a simplified model of the fishery, our application is primarily used to illustrate the sequential harvesting game rather than to prescribe policy in a specific fishery.

The offshore fishery corresponding to Agent 1 in our previous discussion harvests the stock first. The inshore fishery corresponds to Agent 2. The structure of the Northern Baltic salmon fishery is more complicated than the basic case analyzed above.[7] Only a fraction σ of the offshore escapement moves inshore to spawn, while a fraction β remains offshore till the next season. A recreational river fishery harvests the stock left behind by the inshore fishery. River harvest share is small compared to that of the commercial offshore and inshore fisheries, and was here assumed to remain constant. Only a proportion v of the stock is wild salmon that reproduce.

Table 5.1 displays the parameter values. By assumption, average recruitment follows the Ricker recruitment relation $R(S_2) = k(v\,S_2 - H_3)\exp[l(vS_2 - H_3)]$, where H_3 is harvest of spawning salmon in the river fishery and k and l parameters, estimated by Romakkaniemi (1997). In addition to natural reproduction, constant stockings I maintain the stock. The stock available to Agent 1 in year t is $X^{t+1} = I + \beta S_1^t + \theta^t R(S_2^t)$. We consider the case of θ uniformly distributed:

$$(18)\qquad f(\theta) = \begin{cases} \dfrac{1}{b-a} & \text{for a} \le \theta \le b \\ 0 & \text{elsewhere,} \end{cases}$$

where $a = 1-\varepsilon$ and $b = 1+\varepsilon$, with $0 < \varepsilon \le 1$. The mean of this distribution is 1 and the variance $\sigma_\varepsilon^2 = \varepsilon^2 / 3$. We let $\varepsilon = 0.5$ in the base case.

[Table 5.1 here]

[7] The description of the fishery follows Laukkanen (1999).

Adjusted for stockings and a part of offshore escapement remaining offshore till the next season, Agent 1's participation constraint is $I + \beta c_1 / p_1 + aR(c_2 / p_2) > c_1 / p_1$ and Agent 2's $\sigma c_1 / p_1 > c_2 / p_2$. Since the population is partially maintained by stockings, the parameters in Table 5.1 satisfy the participation constraints for all $0 < \varepsilon \leq 1$. The value of S_2^C is no smaller than S_2^N and no larger than σS_1^C, the part of the cooperative offshore escapement moving inshore. The value of S_1^C is no larger than the maximum offshore escapement with no Agent 1 harvest, $[I + u]/(1 - \beta)$, where u is the upper bound to recruitment. Since the probability of reversion is 1 for values of $\overline{X}$ larger than u, it suffices to consider trigger stocks $\overline{X}$ between 0 and u. The optimal agreement was computed by maximizing J subject to these constraints, with the weight α on Agent 1's payoff varying between 0 and 1 in steps of 0.1.

Figures 5.1 to 5.3 illustrate the optimal agreement. Table A.1 in Appendix 2 displays the full set of results. The cooperative solution can be sustained for any weights on the two agents' payoffs. Each agent must obtain at least his non-cooperative payoff. In addition, the optimal agreement has to satisfy the individual optimality conditions (10) and (14). Each agent's payoff enters the joint maximization problem through these constraints even with a zero weight on it in the objective function. Thus, both agents gain from cooperation no matter the weights on their payoffs.

Agent 1's expected payoff increases monotonically with its weight, whereas Agent 2 is better off when some weight is given to the competitor's payoff. The trigger stock $\overline{X}$ set by Agent 1 decreases in α, as Agent 1's gains from cooperation increase. Agent 2's gains and thus his optimal escapement decrease in α. Since the probability of reversion increases in $\overline{X}$ and decreases in S_2^C, it needs not be monotonic in α. Giving some weight to Agent 1 may then decrease the probability of reversion and increase Agent 2's expected payoff, as in our example.

For any weights α, Agent 2 has the greatest relative gains from cooperation with expected payoffs 10 to 14 times his non-cooperative payoff. Agent 1 is at most able to double his expected payoff. Agent 2's relative advantage is explained by the asymmetric structure of the game. Since Agent 2's actions are not observed, he can choose S_2^C

optimally given the values of S_1^C, $\overline{X}$, and T. Agent 1 only has the choice between leaving S_1^C and S_1^N. Since Agent 1's deviations are observed directly, the optimal deviation is always to harvest down to S_1^N.

[Figure 5.1 here]

The probability $F(S_2, \overline{X})$ of entering a reversionary period is close to zero for all weights α. The optimal length of the punishment phase is finite, ranging from 2 to 11 years. The smaller the weight on Agent 1's payoff, the longer is the punishment phase. The expected fraction of time spent in cooperation, *M*, increases from 0.89 to 0.99 as the weight on Agent 1's preferences increases and the probability of reversion decreases. The expected ratio of time in cooperation to time in punishment, *N*, increases rapidly as the probability of reversion decreases, ranging from 26 to 2,800.

[Figures 5.2 and 5.3 here]

5.1 The Effect of Stock Uncertainty on the Optimal Agreement

We next examine the sensitivity of the optimal agreement to the level of stock uncertainty. In addition to $\varepsilon = 0.5$, we computed the optimal agreement at $\varepsilon = 0.2$, $\varepsilon = 0.6$ and $\varepsilon = 0.8$. Figures 5.4 and 5.5 compare the results at $\varepsilon = 0.2$ and $\varepsilon = 0.5$ (see also Table A.2 in Appendix 2). The agreement at $\varepsilon = 0.2$ is similar to that at $\varepsilon = 0.5$, but the expected payoffs vary more with the weight on the agents' payoffs. The lower degree of uncertainty gives Agent 2 less freedom in choosing his optimal escapement, decreasing the relative advantage of Agent 2 over Agent 1. At large weights on Agent 1's payoff, Agent 1 gains more from cooperation, obtaining expected payoffs over five times his non-cooperative payoff. Agent 2 gains less. No cooperative solution agreeable to both agents exists at $\varepsilon = 0.6$ or $\varepsilon = 0.8$.[8] Large variations in stock recruitment make Agent 2's

---

[8] Equations (10) and (14) were not satisfied simultaneously for any values of $0 \le \alpha \le 1$

optimal escapement small. Agent 1 then is better off cheating and harvesting down to his non-cooperative escapement. Agreements on cooperation break down.

[Figures 5.4 and 5.5 here]

5.2 Alternative Parameter Values

The economic characteristics of the offshore and inshore fleets in the Northern Baltic salmon fishery differ markedly. Furthermore, only a fraction of the offshore escapement moves inshore to spawn. To study the extent to which our results were driven by the economic differences of the fisheries, we computed the optimal agreement for an alternative set of parameter values. We used the Baltic salmon fishery data but changed the inshore price equal to the offshore price, and set the inshore fishing costs 20% below the offshore costs. [9] The fraction of spawners was set equal to one. Stockings were still included in the stock equation. The alternative parameter values satisfy the regulatory conditions of section 3 for any ε. The results for the alternative parameter values were similar to those for the actual Northern Baltic salmon fishery data. We next summarize the results. The full results for the alternative parameters are available from the author upon request.

Cooperation was again sustained no matter the weights on the agents' payoffs, with Agent 1's expected payoff practically the same for any weight α. Agent 1's gains from cooperation were now negligible. With Agent 2's prices and costs similar to those of Agent 1, Agent 2's harvest share under non-cooperation is small. Thus Agent 1 who harvests the stock first faces little competition, operating practically as a sole harvester. The cooperative agreement then yields Agent 1 little additional profit. The punishment phase was practically infinite for most values of α, at 160 periods, with a probability of reversion arbitrarily close to zero. Cooperation could again only be sustained at moderate levels of uncertainty. Both agents' gains from cooperation decreased with stock uncertainty.

---

[9] In the actual data the offshore price is 15 % higher than the inshore price, and the offshore unit costs 70 % higher than those inshore.

5.3 Implicit versus Explicit Enforcement: Joint Management with Stock Monitoring

An interesting policy question is whether an agreement with no escapement uncertainty is more stable than the trigger stock solution. Are there gains from explicit enforcement in the form of measuring the spawning stock? To study joint management with stock monitoring, we applied Hannesson's (1995) cooperative management model to the Northern Baltic salmon fishery data. We modified the model to include stochastic shocks in recruitment. Figure 5.6 displays the results (see also Table A.3 in Appendix 2). Each agent's escapement is now observed. Differing from the trigger stock agreement, constrained by equations (10) and (14), cooperation can only be sustained for a narrow range of weights on the agents' payoffs. For small weights α on Agent 1's payoff, the expected joint value is maximized when Agent 1 is excluded from harvest. In the absence of side payments, Agent 1 will not agree to giving up harvest. Similarly, Agent 2 is optimally excluded for high values of α, which he will not agree to without side payments. The expected payoffs from cooperation differ little from those characterizing the agreement without monitoring. Agent 1 benefits from stock measurements, while Agent 2 looses the relative advantage arising from the asymmetric structure of the game and would therefore be better off with unobserved escapements. The qualitative results for joint management with stock monitoring at the alternative parameter values were similar to those for the actual Northern Baltic salmon fishery data. Cooperation was again only agreeable for a narrow range of weights on the two agents' payoffs. Agent 1 would again benefit from monitoring the competitor's escapements, while Agent 2 would be better off with unobserved spawning stocks.

[Figure 5.6 here]

The result that implicit cooperative agreements can only be supported when stock uncertainty is not too prevalent explains why cooperative harvesting is rare. Explicit enforcement in the form of stock monitoring is a joint management alternative that can be sustained even when variation in recruitment is large.

6. Conclusion

We examine cooperative and non-cooperative harvesting in a stochastic sequential fishery, and define conditions under which cooperative harvesting can be sustained as a self-enforcing equilibrium when the actions of one harvester are not observed. Even when both agents cooperate, reversionary periods may occur with a positive probability. Although the agent harvesting first knows that a low stock level reflects a stochastic shock to recruitment, it is rational to participate in reversionary periods. Otherwise, the agent harvesting the spawning stock would have 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, both parties realize that renegotiating would unravel the rational for cooperation.

We illustrate the sequential harvesting game with an empirical example based on data for the Northern Baltic salmon fishery. The cooperative solution was supported at moderate levels of stock uncertainty. Both agents gained from cooperation, but the agent whose actions are not observed had the greatest gains. The finding that cooperation can only be sustained when stock uncertainty is not too prevalent sheds light on why we rarely observe cooperation in transboundary fisheries. The policy alternative of measuring the spawning stock provides a cooperative solution that both parties can agree to regardless of the extent of stock uncertainty. The agents do not benefit equally from stock monitoring. The agent harvesting the initial stock gains from measuring the spawning stock, while the agent harvesting the spawning stock is better off when his escapement remains unobserved.

Allowing for side payments in cooperative management of a stochastic sequential fishery would be an interesting topic for future study. In particular with notable differences in the sequential fisheries prices and costs, allowing for side payments might yield greater expected joint value and individual payoffs than the trigger stock agreement. Exclusion of one of the fisheries from harvest would preclude monitoring problems – it is more straightforward to control whether a fleet is harvesting than how much it is harvesting. However, joint management with side payments is often politically infeasible, especially if one fishery should optimally be excluded from harvest.

References:

Clark. C. (1990): Mathematical Bioeconomics. Wiley, New York.

Green, E. and Porter, R. (1984): Noncooperative Collusion under Imperfect Price Information. *Econometrica, 52, 87-100.*

Finnish Game and Fisheries Research Institute (FGFRI) (1994): Prices Paid to Fishermen in 1993, Official Statistics of Finland, 1994:5.

Finnish Game and Fisheries Research Institute (FGFRI) (1994): Profiles of Commercial Fishing. Unpublished Manuscript.

Hannesson (1995): Sequential Fishing: Cooperative and Non-cooperative Equilibria. *Natural Resource Modeling, 9, 51-59.*

ICES (1994): Report of the Baltic Salmon and Trout Assessment Group. ICES CM 1994/Assess: 15. Ref. M.

ICES (1995): Report of the Baltic Salmon and Trout Assessment Group. ICES CM 1995/Assess: 16. Ref. M.

Kaitala, V. and Pohjola, M. (1988): Optimal Recovery of a Shared Resource Stock: A Differential Game Model with Efficient Memory Equilibria. *Natural Resource Modeling, 3, 91-119.*

Laukkanen, M. (2001): A Bioeconomic Analysis of the Northern Baltic Salmon Fishery: Coexistence versus Exclusion of Competing Sequential Fisheries. *Environmental and Resource Economics, in Press.*

McKelvey, R. (1997): Game-theoretic Insights into the International Management of Fisheries. *Natural Resource Modeling, 10, 129-171.*

Mirrlees, J. (1999): The Theory of Moral Hazard and Unobservable Behaviour: Part I. *Review of Economic Studies, 66, 3-21.*

Munro, G. (1979): The Optimal Management of Transboundary Renewable Resources, *Canadian Journal of Economics, 12, 355-376.*

Reed, W. J. (1978): The Steady State of a Stochastic Harvesting Model, *Mathematical Biosciences, 41, 273-307.*

Reed, W. J. (1979): Optimal Escapement Levels in Stochastic and Deterministic Harvesting Models, *Journal of Environmental Economics and Management, 6, 350-363.*

Romakkaniemi, A. (1997): Estimates of the Parameters of the Recruitment Function for the Northern Baltic Salmon Stock. Memorandum, Finnish Game and Fisheries Research Institute.

Appendix 1. Closed-form solution for Agent 2' expected cooperative payoff.

The functional equation for Agent 2's expected cooperative payoff is

$$
\begin{aligned}
\text{(A1)}\quad EV_2^C(S_1^C,S_2) &= \pi_2(S_1^C,S_2)+\left[1-F\left(\overline{X}/R(S_2)\right)\right]\delta EV_2^C(S_1^C,S_2)\\
&\quad + F\left(\overline{X}/R(S_2)\right)\delta EV_2^P(S_1^N,S_2^N)\\
&= \pi_2(S_1^C,S_2)+\left[1-F\left(\overline{X}/R(S_2)\right)\right]\delta EV_2^C(S_1^C,S_2)\\
&\quad + F\left(\overline{X}/R(S_2)\right)\delta\left[\sum_{\tau=0}^{T-2}\delta^\tau\omega_2+\delta^{T-1}\pi_2(S_1^N,S_2)\right.\\
&\quad \left.+\delta^T\left\{\left[1-F\left(\overline{X}/R(S_2)\right)\right]EV_2^C(S_1^C,S_2)+F\left(\overline{X}/R(S_2)\right)EV_2^P(S_1^N,S_2^N)\right\}\right]
\end{aligned}
$$

In order to solve equation (A1) for $EV_2^C(S_1^C,S_2)$, we rewrite (A1) as

$$
\begin{aligned}
\frac{1}{\delta}\left[EV_2^C(S_1^C,S_2)-\pi_2(S_1^C,S_2)\right] &= \left[1-F\left(\overline{X}/R(S_2)\right)\right]EV_2^C(S_1^C,S_2)\\
&\quad + F\left(\overline{X}/R(S_2)\right)\left[\sum_{\tau=0}^{T-2}\omega_2+\delta^{T-1}\pi_2(S_1^N,S_2)\right.\\
&\quad \left.+\delta^T\left\{\left[1-F\left(\overline{X}/R(S_2)\right)\right]EV_2^C(S_1^C,S_2)+F\left(\overline{X}/R(S_2)\right)EV_2^P(S_1^N,S_2^N)\right\}\right]
\end{aligned}
$$

We then replace period $t+(T+1)$ expected payoff in equation (A1) by $\frac{1}{\delta}\left[EV_2^C(S_1^C,S_2)-\pi_2(S_1^C,S_2)\right]$ and use the formula for a geometric sum, which yields

$$
\begin{aligned}
\text{(A2)}\quad EV_2^C(S_1^C,S_2) &= \pi_2(S_1^C,S_2)+\left[1-F\left(\overline{X}/R(S_2)\right)\right]\delta EV_2^C(S_1^C,S_2)\\
&\quad + F\left(\overline{X}/R(S_2)\right)\delta\left[\frac{1-\delta^{T-1}}{1-\delta}\omega_2+\delta^{T-1}\pi_2(S_1^N,S_2)+\delta^{T-1}\left\{EV_2^C(S_1^C,S_2)-\pi_2(S_1^C,S_2)\right\}\right]
\end{aligned}
$$

We solve (A2) for $EV_2^C(S_1^C,S_2)$ and simplify the result by adding and subtracting ω_2 in the denominator and rearranging, which yields

$$
\text{(A3)}\quad EV_2^C(S_1^C,S_2)=\frac{\pi_2(S_1^C,S_2)-\omega_2-F\left(\overline{X}/R(S_2)\right)\delta^T\left[\pi_2(S_1^C,S_2)-\pi_2(S_1^N,S_2)\right]}{1-\delta+(\delta-\delta^T)F\left(\overline{X}/R(S_2)\right)}+\frac{\omega_2}{1-\delta}.
$$

Appendix 2. Full results for the empirical illustration.

Table A.1. Agreement on joint management for different values of α.

α	S_1 (kg)	S_2 (kg)	$\overline{X}$ (kg)	T -1	$F(S_2, \overline{X})$	EV_1 (mk)	EV_2 (mk)	J (mk)	M	N
0	10,401,000	3,299,000	1,271,000	11	0.00349	467,171,000	338,843,000	338,843,000	0.88975	26
0.1	10,401,000	3,299,000	1,271,000	11	0.00349	467,171,000	338,843,000	351,676,000	0.88975	26
0.2	10,331,000	3,267,000	1,257,000	10	0.00073	476,027,000	345,987,000	371,995,000	0.96764	137
0.3	10,331,000	3,267,000	1,257,000	10	0.00073	476,027,000	345,987,000	384,999,000	0.96764	137
0.4	10,331,000	3,267,000	1,257,000	10	0.00073	476,027,000	345,987,000	398,003,000	0.96764	137
0.5	8,932,000	2,720,000	1,106,000	4	0.00318	553,735,000	295,527,000	424,631,000	0.94941	78
0.6	8,932,000	2,720,000	1,106,000	4	0.00318	553,735,000	295,527,000	450,452,000	0.94941	78
0.7	8,932,000	2,720,000	1,106,000	4	0.00318	553,735,000	295,527,000	476,273,000	0.94941	78
0.8	7,549,000	2,267,000	908,000	2	0.00018	583,881,000	228,083,000	512,722,000	0.99726	2777
0.9	7,549,000	2,267,000	908,000	2	0.00018	583,881,000	228,083,000	548,301,000	0.99726	2777
1	7,549,000	2,267,000	908,000	2	0.00018	583,881,000	228,083,000	583,881,000	0.99726	2777

M = expected fraction of time spent in cooperation during a cycle

N = expected ratio of time spent in cooperation to time spent in punishment during a cycle

Expected discounted non-cooperative payoffs: $\omega_1/(1-\delta) = 311{,}560{,}000$ mk

$\omega_2/(1-\delta) = 24{,}147{,}800$ mk

Table A.2. Agreement on joint management at $\varepsilon = 0.2$.

α	S_1 (kg)	S_2 (kg)	$\overline{X}$ (kg)	T-1	$F(S_2, \overline{X})$	EV_1 (mk)	EV_2 (mk)	J (mk)	M	N
0	12,100,000	4,221,000	2,209,000	17	2.43E-03	288,216,000	319,951,000	319,951,000	0.88472	24
0.1	12,100,000	4,221,000	2,209,000	17	2.43E-03	288,216,000	319,951,000	316,778,000	0.88472	24
0.2	12,100,000	4,221,000	2,209,000	17	2.43E-03	288,216,000	319,951,000	313,604,000	0.88472	24
0.3	12,100,000	4,221,000	2,209,000	17	2.43E-03	288,216,000	319,951,000	310,431,000	0.88472	24
0.4	7,561,000	2,787,000	1,837,000	1	4.56E-02	658,277,000	110,461,000	329,587,000	0.85246	21
0.5	7,561,000	2,787,000	1,837,000	1	4.56E-02	658,277,000	110,461,000	384,369,000	0.85246	21
0.6	7,561,000	2,787,000	1,837,000	1	4.56E-02	658,277,000	110,461,000	439,150,000	0.85246	21
0.7	7,561,000	2,787,000	1,837,000	1	4.56E-02	658,277,000	110,461,000	493,932,000	0.85246	21
0.8	7,561,000	2,787,000	1,837,000	1	4.56E-02	658,277,000	110,461,000	548,714,000	0.85246	21
0.9	7,561,000	2,787,000	1,837,000	1	4.56E-02	658,277,000	110,461,000	603,495,000	0.85246	21
1	7,561,000	2,787,000	1,837,000	1	4.56E-02	658,277,000	110,461,000	658,277,000	0.85246	21

Expected discounted non-cooperative payoffs: $\omega_1/(1-\delta)$ =124,470,000 mk

$\omega_2/(1-\delta)$=24,147,800 mk

Table A.3. Agreement with monitoring.

α	S_1 (kg)	S_2 (kg)	EV_1 (mk)	EV_2 (mk)	J (mk)
0	X	2,605,010	0	800,162,000	800,162,000
0.1	X	2,605,010	0	800,162,000	720,146,000
0.2	X	2,605,010	0	800,162,000	640,130,000
0.3	X	2,605,010	0	800,162,000	560,113,400
0.4	X	2,605,010	0	800,162,000	480,097,200
0.5	8,643,630	2,697,160	585,075,000	269,923,000	427,499,000
0.6	6,913,430	3,023,680	800,494,000	4,262,460	482,001,000
0.7	5,165,130	2,582,565	686,636,000	0	480,645,200
0.8	5,165,130	2,582,565	686,636,000	0	549,308,800
0.9	5,165,130	2,582,565	686,636,000	0	617,972,000
1	5,165,130	2,582,565	686,636,000	0	686,636,000

Table 4.1. Notation in Agent 1's problem.

$\tilde{X}^C = \theta R(S_2^C)$, $\tilde{X}^N = \theta R(S_2^N)$	Random recruitment with escapements S_2^C and S_2^N
$EV_1^C(S_1^C, X')$	Agent 1's expected payoff from leaving the cooperative escapement S_1^C in a normal period, evaluated after observing X' such that $X' > \overline{X}$
$EV_1^N(S_1^N, X')$	Agent 1's expected payoff from harvesting down to the non-cooperative escapement S_1^N, evaluated after observing X'
$EV_1^C(S_1^C, \tilde{X}^C)$	Agent 1's expected cooperative payoff evaluated prior to observing X', given period *t* was preceded by a normal period
$EV_1^C(S_1^C, \tilde{X}^C \mid \tilde{X}^C \geq \overline{X})$	Agent 1's expected cooperative payoff conditional on $\tilde{X}^C \geq \overline{X}$ evaluated prior to observing X', given period *t-1* was normal
$\gamma_1 = E[\pi_1(S_1^N, \tilde{X}^C) \mid \tilde{X}^C < \overline{X}]$	Agent 1's expected profit in the first period of reversionary play
$\omega_1 = E_\theta \pi_1(S_1^N, \tilde{X}^N)$	Agent 1's expected profit in subsequent reversionary periods
$\Pr(\theta R(S_2) < \overline{X}) = F(\overline{X} / R(S_2))$	Probability of reversionary play

Table 4.2. Notation in Agent 2's problem.

$\omega_2 = \pi_2(S_1^N, S_2^N)$	Agent 2's single period payoff in reversionary periods
$\pi_2(S_1^C, S_2^C)$	Agent 2's single period payoff in cooperative periods. $\pi_2(S_1^C, S_2^C) > \omega_2$
$EV_2(S_1^C, S_2^C)$	Agent 2's expected discounted present value of cooperative harvesting
$EV_2^P(S_1^N, S_2^N)$	Agent 2's expected payoff at the beginning of a punishment phase
$\Pr(\theta R(S_2) < \overline{X}) = F(\overline{X} / R(S_2))$	Probability of reversionary play

Table 5.1. Parameters describing the Northern Baltic salmon fishery

Parameter		Estimate
Price of salmon offshore [a]	p_1	24.32 mk/kg
Price of salmon inshore [a]	p_2	20.56 mk/kg
Unit cost of fishing effort offshore [b]	c_1	$9.62\cdot10^7$ mk
Unit cost of fishing effort inshore [b]	c_2	$2.69\cdot10^7$ mk
Discount factor	δ	0.95
Fraction of S_1' moving inshore [c]	σ	0.44
Fraction of S_1' surviving to next year [c]	β	0.50
Stockings [c]	I	4 170 000 kg
Proportion of wild salmon in stock	v	0.10
Parameters of $R(S_2)$ [d]	k	20.88
	l	-2.76^{-6}
Parameter of the distribution $f(\theta)$	ε	0.5

[a] Derived from *Prices Paid to Fishermen in 1993*. Official Statistics of Finland, 1994:5. FGFRI.
[b] Evaluated from unpublished data in the 1994 FGFRI study *Profiles of Commercial Fishing*.
[c] Derived from ICES 1994 and ICES 1995.
[d] Estimates from Romakkaniemi (1997).

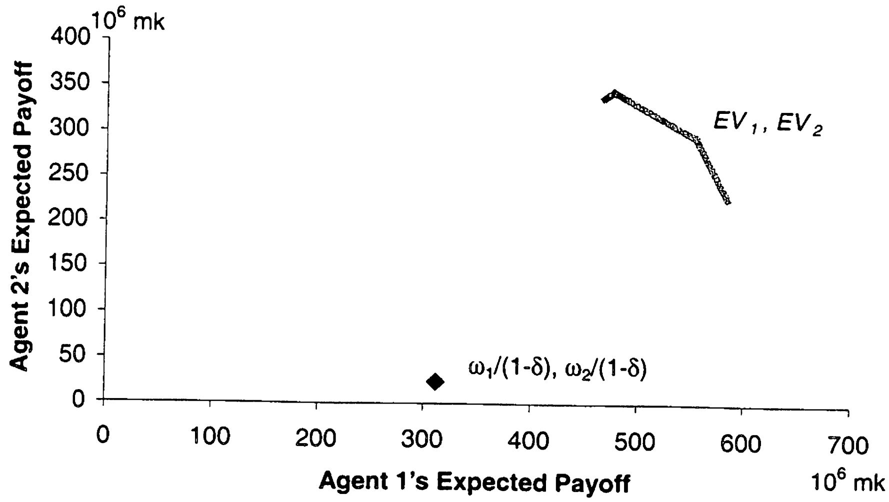

Figure 5.1. Both agents gain from cooperation no matter the value of the weight parameter α. Agent 2 has greater relative gains.[10]

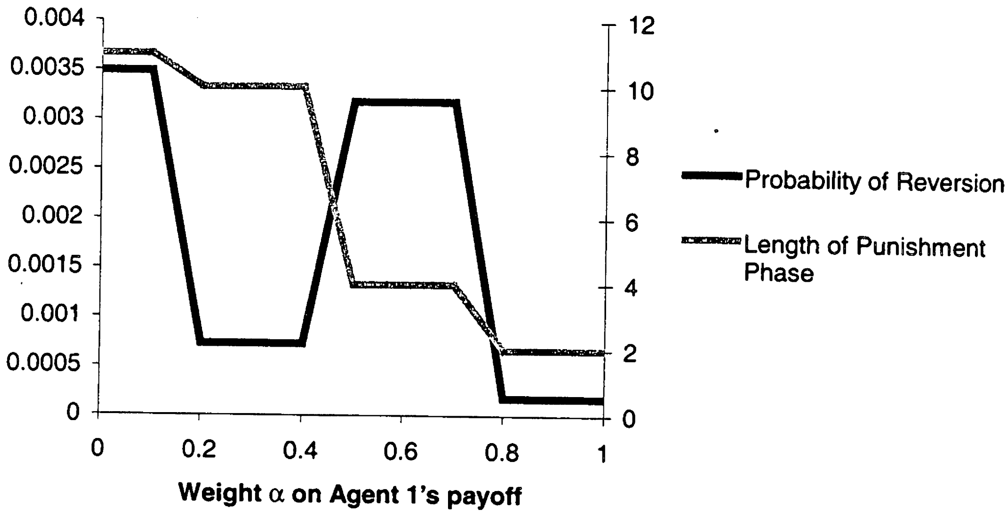

Figure 5.2. The optimal length of the punishment phase decreases in the weight α on Agent 1's payoff. The probability of reversion need not be monotonic in α.

[10] Agent 1's expected discounted non-cooperative payoff is $\omega_1/(1-\delta)$ and that of Agent 2 $\omega_2/(1-\delta)$. In the modified model $\tilde{X}^N$ in $\omega_1 = E_\theta \pi_1(S_1^N, \tilde{X}^N)$ is given by $I + \beta S_1^N + \theta R(S_2^N)$.

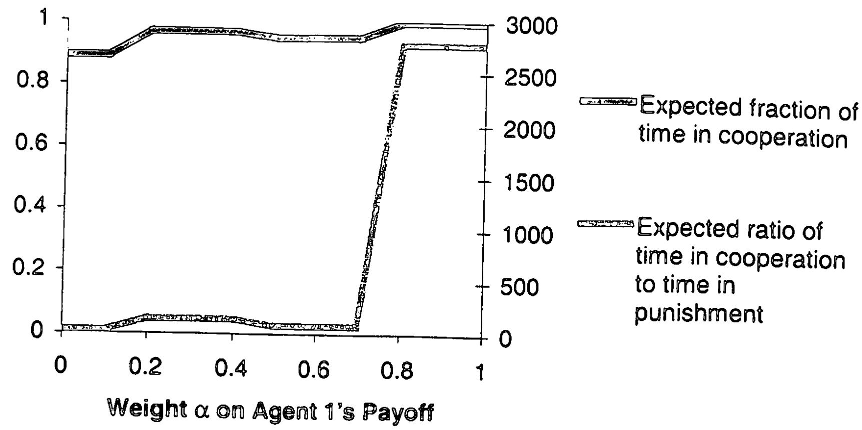

Figure 5.3. The expected fraction of time spent in cooperation is close to one. The expected ratio of time in cooperation to time in punishment increases as the probability of reversion decreases along with the weight on Agent 1's payoff, ranging from 26 to 2800.

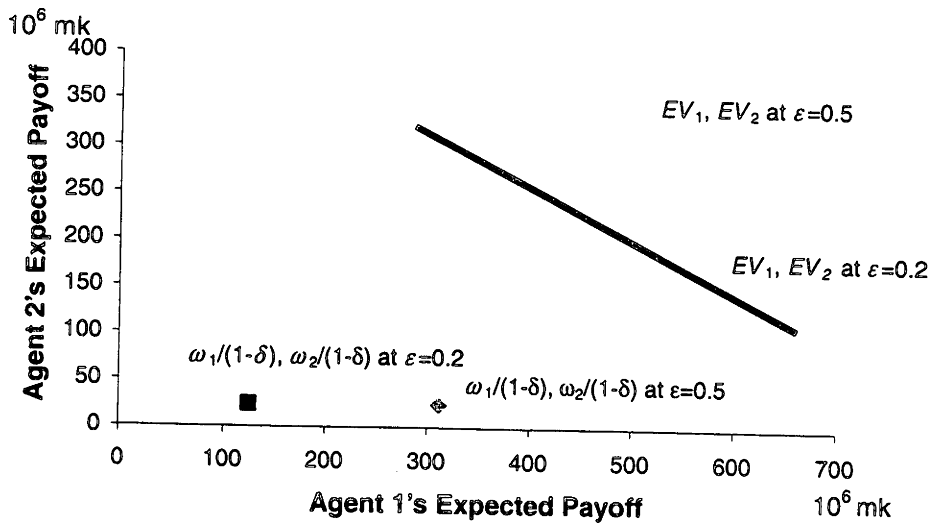

Figure 5.4. With less uncertainty, the agents' expected payoffs vary more as the weights on the payoffs change. At high values of α, smaller amount of stock uncertainty yields Agent 1 greater gains from cooperation.

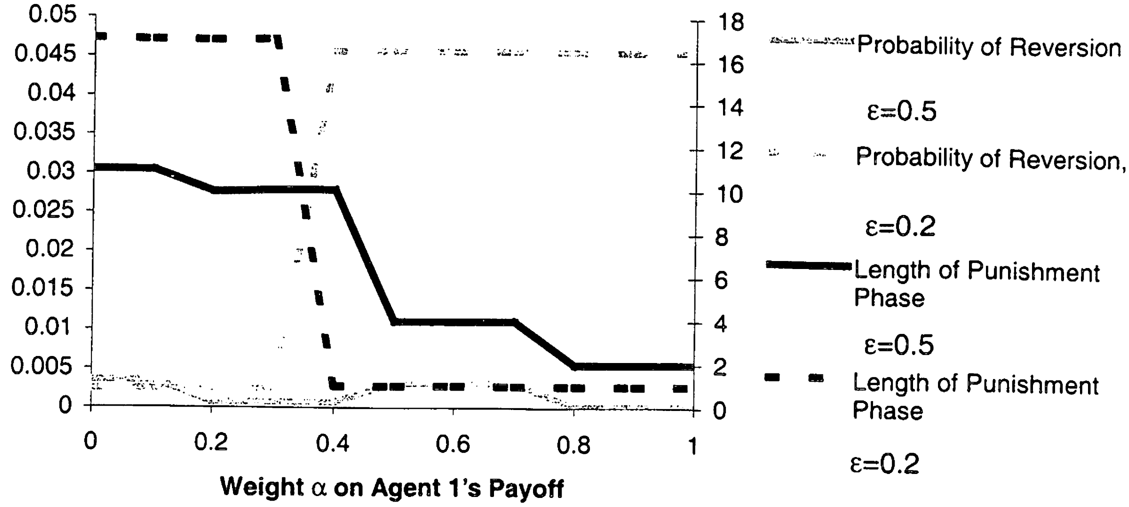

Figure 5.5. Contrary to the case of $\varepsilon = 0.5$, at $\varepsilon = 0.2$ probability of reversion increases in the weight on Agent 1's payoff.

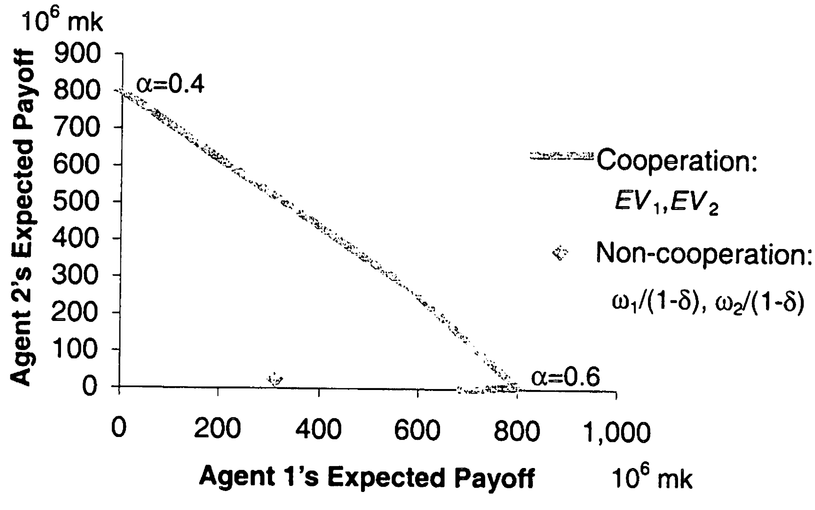

Figure 5.6. Agreement with monitoring. Cooperation can only be sustained for a narrow range of weights on the agents' payoffs. For small values of α expected joint value is maximized when Agent 1 is excluded from harvest, which Agent 1 will not agree to without side payments. Similarly, Agent 2 is optimally excluded for high values of α.