INTERNATIONAL FISHERIES AGREEMENTS WITH A SHIFTING STOCK

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ABSTRACT

When a resource shifts from one player to another, e.g. due to climate change, the conservation incentive of the player losing the resource decreases while the conservation incentive increases for the player at the receiving end. We set up an analytical model to study how the structure of the game changes when the shift occurs either fast or slow, or gradual or abrupt. We also investigate whether there is a self-enforcing agreement that aligns incentives. We find that the longer the expected duration of the shift, the less intensive the exploitation of the resource and the larger the scope for cooperation. In some cases there is no stable agreement, even when there are only two players.

INTRODUCTION

Climate change is expected to put existing International Fisheries Agreements under severe stress [1]. We have already observed this: The recent appearance of Atlantic Mackerel in Icelandic waters has led to the collapse of the existing international fisheries agreement. It has brought the Nordic nations Iceland, Faroese, Norway and the EU to the brink of a new "fish war" and the conflict over the level and distribution of fish quotas has – to date – not been resolved. Similarly, the US-Canadian agreement on the Pacific Salmon fisheries has repeatedly broken down after climatic regime shifts. Here, the two nations could, after some efforts, re-establish cooperative harvesting.

On the one hand, the presumed de-stabilizing effect of climate change is not surprising: a shifting stock distribution will increase the bargaining position of one party while it will decrease the bargaining strength of the other party, so that the first party may want to re-negotiate to obtain a more favorable agreement. On the other hand, it is surprising that this tension is not immediately resolved. The party receiving the resource stock will have more conservation incentives than the party loosing the resource and the former party could just buy out the latter party. In essence, the Coase-Theorem tells us that the allocation of initial property rights should not matter for the possibility to achieve an efficient bargaining solution.

We address this puzzle by developing a tractable model of a dynamic non-cooperative game where the resource is expected to change hands from one player to the next. Contrary to the benchmark game of no shifting stock, we show that agreements are not always stable, even when there are only two players. Moreover, we explicitly consider the impact of quality of the transition dynamics: Is non-cooperative exploitation more aggressive when the change in ownership occurs suddenly or gradually? Can cooperation more easily be achieved when the change in ownership is fast, or when it is slow?

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Although our model is general and our insights can be applied to any renewable resource that changes the hands of its owner, we do couch our discussion in terms of fisheries. This is not only because of the policy relevance of our motivating examples, but also because it helps to fix ideas. There is an immense literature on cooperative and non-cooperative management of international fisheries [for a review see 2, 3]. One starting point is the great "fish wars" paper by Levhari and Mirman [4]. In spite of the time that has passed since its publication, the model still proves to be a valuable workhorse for many applications, ranging from multi-species aspects [5] to the impact of uncertainty [6].

The first paper addressing how climate change might affect the strategies of countries sharing a fish stock with altered habitat or migration routes is from McKelvey et al. [7]. Their model, which is an extension of the classical fish-wars model of Levhari and Mirman [4], is now known as the "split-stream model" and forms the basis of e.g. the paper from Liu et al. [8]. Liu et al. [8] consider the distribution of the Norwegian spring-spawning herring and study partial coalition structures. They conclude cost asymmetry improves the stability of the grand coalition, and non-cooperation gives more conservation incentives to the major player than the minor player. Liu and Heino [9], using the same model, compare management that takes possible climate change effects on the stock distribution into account (proactive management) with management that ignore these effects (reactive management). They find that the players behave symmetrically when practicing reactive management, but proactive management encourages the player losing the stock to act more aggressively. The herring will be in greatest danger when both players own equal shares of the stock. This result has theoretically already been shown by Hannesson [10], who also discusses the effect of stock-dependent costs. When harvesting costs are independent of the stock, a transition of ownership may even lead to an extinction of the stock. In an applied age-structured model of the North-East Arctic cod fishery, Hannesson [11] presents the counter-intuitive result that Norway may benefit when more fish is in Russian waters, because the latter player will then have an increased conservation incentive.

Hannesson [12] studies the topical problem of the Northeast Atlantic mackerel stock under three different hypothesis about what causes the shift in stock distribution. He concludes that the minor player has a stronger bargaining position when the migration pattern is deterministic or purely random. Under a stock-dependent migration, the major player has a threat strategy to fish down the stock to such a low level that it does not spill over to the minor player's zone. Another recent application to the same stock is Ellefsen [13], which confirms that the stability of the agreement is harmed by a new entrant, and the major player in the contract has to pay the most in order to courage the new member into the agreement. Whereas the above studies have to rely on numerical simulations, or discuss steady-state outcomes only, we can derive analytical solutions to the feedback equilibrium by going back to the predecessor of the "split-stream model", the framework introduced by Levhari and Mirman [4].

Furthermore, the papers by Kwon [14] and Breton and Keoula [15, 16] are particularly relevant for our purpose as they study the existence of self-enforcing coalitions in the Levhari-Mirman framework. They find – as it is common in the international agreements literature [17] – coalitions of more than two or three players are generally not stable.[a] Laukkanen [18, 19] studies the case of two countries under uncertainty (albeit in a different model than ours). She concludes that cooperation can be achieved if the uncertainty is not too high and success is more likely the more equal the two players are. Our study differs from the above papers by considering a non-stationary situation.

In short, we contribute to the literature by offering an analytically tractable model of a dynamic game with a shifting resource stock and we explicitly account for the pattern of the transitionary dynamics. Our paper adds these three new insights: First, we show that even when there are only two players, cooperation will not always be sustainable: As the ownership of the stock shifts, the player who receives the stock may not be able to offer enough to offset the losing player's incentives to over-harvest. Second, we show that the scope for cooperation is not constrained by the available harvest shares, so that in contrast to the results from Munro [20], financial side-payments (or issue-linkage in broader terms) would not help to alleviate the strategic tension introduces by the the shifting stock distribution. Third, we show that a fast change in resource ownership is more detrimental than a slow change. For a given expected length of the transition, a more sudden type of change implies a more intense non-cooperative exploitation but increases the chances of obtaining a cooperative solution.

MODEL

The basic setup

We build on the classical model by Levhari and Mirman [4] when there are two players $i = A, B$ applying the same discount factor β. Time is discrete with $t = 0, 1, 2, \ldots$ Players derive utility from consuming the resource according to $u(c_t^i) = \ln(c_t^i)$. It is well known that the Levhari and Mirman [4] game has a unique Nash equilibrium in linear strategies, and we will therefore concentrate on linear strategies. To simplify notation, we denote player A's extraction rate by a_t and player B's extraction rate by b_t (so that $c_t^A = a_t x_t$ and $c_t^B = b_t x_t$). Denote the total extraction rate by d_t (so that $d_t \equiv a_t + b_t$).

The resource develops according to

$$x_{t+1} = M\left((1-d_t)x_t\right)^{\alpha} \qquad \text{(Eq. 1)}$$

The parameter α determines the "renewability" of the resource with $\alpha \in (0, 1)$ and the smaller is α, the stronger is the natural re-growth potential of the resource. M is a scaling parameter which has no effect on the optimal choice of the extraction rate. It ensures that the value-function of the players remains non-negative in all stages of the game.[b] For a constant exploitation rate d, the steady-state value of x is given by $\bar{x} = M\left((1-d)M\right)^{\frac{\alpha}{1-\alpha}}$.

Modeling the shift in ownership

To allow for a general analysis of the effect of an anticipated, but uncertain shift in ownership, we assume that the transition of the resource from player A to player B proceeds in stages. There are a total of T stages, and within each stage τ (where $\tau = 0, 1, \ldots T$) the share of the stock that player A has access to is given by s_τ and the share of the stock that player B has access to is given by $1 - s_\tau$. In other words, the player's harvesting rates in a given stage τ are constrained by $a_\tau \leq s_\tau$ and $b_\tau \leq 1 - s_\tau$.

The duration of each stage is unknown, but there is a constant probability q that the systems stays in the current stage τ and there is a constant probability $1 - q$ that after any given period the next period starts in a new stage with $s_{\tau+1}$. This setup makes the game non-stationary, but within each stage, the problem that the players face is stationary. We make the following assumption about s_τ:

$$s_\tau = \frac{T - \tau}{T} \qquad \text{(Eq. 2)}$$

Note that this implies $s_0 = 1$ and $s_T = 0$, which means that player A is the sole-owner of the resource in the first stage, that the resource shifts monotonically from A to B, and that player B will eventually become the sole-owner of the resource. None of our results depends on the assumption that the share drops linearly.[c]

Denote the expected value of the time that the transition takes by Z. As the duration of each stage τ follows a geometric distribution with mean $\frac{1}{1-q}$, the total expected time that it takes until B is the sole-owner is given by:

$$Z = \frac{T}{1-q} \qquad \text{(Eq. 3)}$$

This implies that the environmental change happens fast when T and q are small. Furthermore, this implies that T is the infimum of Z. However, Z can be very large even if $T = 1$, just q has to be large enough. In this case, one would characterize the environmental change as abrupt or sudden. In contrast, one would speak of a gradual or smooth change when T is large and q is relatively small. To distinguish the speed of change (slow vs. fast) from its character (smooth vs. sudden) we will both analyze the case when we hold Z fixed and change T and q to make the transition more or less smooth, and we hold T fixed and change q to increase or decrease Z.

Before we describe the two-player non-cooperative game with a shift in stock ownership, we characterize two benchmarks when there is no shift in the stock: optimal exploitation, and the standard non-cooperative game between two players.

Benchmark 1: Optimal exploitation

When there are two cooperating players that share the proceeds from optimal harvesting (denote total consumption by d^*), each player's value function is:

$$V^*(x) = \max_{d\leq 1}\left\{\ln\frac{1}{2}dx + \beta V^*\left(M((1-d)x)^{\alpha}\right)\right\} \qquad \text{(Eq. 4)}$$

We can use the 'guess and verify' method to solve for the value function. Conjecturing that $V^* = k^*\ln x + K^*$, where k^* and K^* are undetermined coefficients, we get:

$$k^*\ln x + K^* = \max_{d\leq 1}\left\{\ln\frac{1}{2}dx + \alpha\beta k^*\ln((1-d)x) + \beta(k^*\ln M + K^*)\right\}$$

The first-order-condition (FOC) $\frac{1}{d} = \frac{\alpha\beta k^*}{1-d}$ gives the preliminary function $d = \frac{1}{1+\alpha\beta k^*}$. Inserting confirms our conjecture about V^*:

$$V^*(x) = \underbrace{(1+\alpha\beta k^*)}_{k^*}\ln x \underbrace{-\ln 2 + \alpha\beta k^*\ln(\alpha\beta k^*) - (1+\alpha\beta k^*)\ln(1+\alpha\beta k^*) + \beta(k^*\ln M + K^*)}_{K^*}$$

Equating coefficients gives

$$k^* = \frac{1}{1-\alpha\beta} \qquad K^* = \frac{1}{1-\beta}\left[\frac{\alpha\beta\ln\alpha\beta}{1-\alpha\beta} + \ln(1-\alpha\beta) + \frac{\beta\ln M}{1-\alpha\beta} - \ln 2\right] \qquad \text{(Eq. 5)}$$

First-best total extraction and the optimal steady state resource stock are given by:

$$d^* = (1-\alpha\beta) \qquad \bar{x}^* = M\left(\alpha\beta M\right)^{\frac{\alpha}{1-\alpha}} \qquad \text{(Eq. 6)}$$

Benchmark 2: Nash-equilibrium with no shift and full access for both players

Similarly, we remind the reader of the solution for the standard non-cooperative game without shift in ownership of the stock. When the players use linear strategies, the Bellman equation for player A reads (the case of player B is exactly symmetric here):

$$V^{nc,A}(x) = \max_{a\leq 1-b}\left\{\ln(ax) + \beta V^{nc,A}\left(((1-a-b)x)^{\alpha}\right)\right\} \qquad \text{(Eq. 7)}$$

Conjecturing that the value function $V^{nc,A}$ is of the form $k^{nc}\ln x + K^{nc}$, the problem in (Eq. 7) can be solved. One finds:

$$k^{nc} = \frac{1}{1-\alpha\beta} \qquad K^{nc} = \frac{1}{1-\beta}\left[\frac{\alpha\beta\ln\alpha\beta - \ln(2-\alpha\beta)}{1-\alpha\beta} + \ln(1-\alpha\beta) + \frac{\beta\ln M}{1-\alpha\beta}\right] \qquad \text{(Eq. 8)}$$

Individual equilibrium extraction rate and the steady state resource stock are given by:

$$a^{nc} = \frac{1-\alpha\beta}{2-\alpha\beta} \qquad\qquad \bar{x}^{nc} = M\left(\frac{\alpha\beta}{2-\alpha\beta}M\right)^{\frac{\alpha}{1-\alpha}} \tag{Eq. 9}$$

Note that $k^{nc} = k^*$ but $K^{nc} < K^*$. Furthermore, note that $a^{nc} > \frac{1}{2}d^*$ and thus $\bar{x}^{nc} < \bar{x}^*$.

NON-COOPERATIVE EQUILIBRIUM

In this section we analyze the non-cooperative equilibrium when the resource shifts owner in an uncertain, but anticipated manner. Particular focus will be on the total extraction rate d. In general, player A's and B's value functions are given by:

$$V_\tau^A(x) = \max_{a \le s_\tau} \left\{ \ln ax + \beta \left[qV_\tau^A\left(M((1-d)x)^\alpha\right) + (1-q)V_{\tau+1}^A\left(M((1-d)x)^\alpha\right) \right] \right\} \tag{Eq. 10}$$

$$V_\tau^B(x) = \max_{b \le 1-s_\tau} \left\{ \ln bx + \beta \left[qV_\tau^B\left(M((1-d)x)^\alpha\right) + (1-q)V_{\tau+1}^B\left(M((1-d)x)^\alpha\right) \right] \right\} \tag{Eq. 11}$$

Player A (or player B for that matter) maximizes utility from consuming a share of the resource now and in the future. The player takes into account that with probability q, the environmental regime will stay the same so that the future value of the game, conditional on stock development, is the same as today. With probability $1-q$, however, the environmental regime will change to the next stage and the value of the game is then given by $V_{\tau+1}^A$.

To begin, we consider the general case of player A. The conjecture that $V_\tau^A = k_\tau^A \ln x + K_\tau^A$ leads to the following first-order condition:

$$\frac{1}{a_\tau} = \alpha\beta q k_\tau^A \frac{1}{1-a_\tau-b_\tau} + \alpha\beta(1-q)k_{\tau+1}^A \frac{1}{1-a_\tau-b_\tau}$$

Accordingly, we can solve for player A's best-reply. Noting that her extraction can be limited by the accessible share s_τ, we have:

$$a_\tau = \min\left\{ s_\tau \,;\, \frac{(1-b_\tau)}{1+\alpha\beta(qk_\tau^A + (1-q)k_{\tau+1}^A)} \right\} \tag{Eq. 12}$$

The general case of player B is symmetric, and hence his best-reply is:

$$b_\tau = \min\left\{ 1-s_\tau \,;\, \frac{(1-a_\tau)}{1+\alpha\beta(qk_\tau^B + (1-q)k_{\tau+1}^B)} \right\} \tag{Eq. 13}$$

We now set out to derive the structure of the coefficients k_τ^i and K_τ^i. We start by equating coefficients for player A's value function $V_\tau^A = k_\tau^A \ln x + K_\tau^A$ according to (Eq. 10):

$$\begin{aligned} k_\tau^A \ln x + K_\tau^A = {} & \ln a_\tau x + \alpha\beta q \left[k_\tau^A \left(\ln(1-a_\tau-b_\tau)x + \frac{1}{\alpha}\ln M \right) + \frac{1}{\alpha}K_\tau^A \right] \\ & + \alpha\beta(1-q) \left[k_{\tau+1}^A \left(\ln(1-a_\tau-b_\tau)x + \frac{1}{\alpha}\ln M \right) + \frac{1}{\alpha}K_{\tau+1}^A \right] \\ \Leftrightarrow & \\ k_\tau^A \ln x + K_\tau^A = {} & (1+\alpha\beta(qk_\tau^A + (1-q)k_{\tau+1}^A)\ln x + \ln a_\tau \\ & + \beta\left[qK_\tau^A + (1-q)K_{\tau+1}^A + (qk_\tau^A + (1-q)k_{\tau+1}^A)(\ln M + \alpha \ln(1-a_\tau-b_\tau)) \right] \end{aligned}$$

By equating $k^A_\tau \ln x = (1+\alpha\beta(qk^A_\tau + (1-q)k^A_{\tau+1}))\ln x$, we get the solution for k^A_τ, which is symmetric for player B, and thus we can write the next general form:

$$k^i_\tau = \underbrace{\frac{1}{1-\alpha\beta q}}_{l} + \underbrace{\frac{\alpha\beta(1-q)}{1-\alpha\beta q}}_{m} k^i_{\tau+1} \quad \text{(Eq. 14)}$$

This linear difference equation with constant coefficients can be solved[d] to give:

$$k^i_\tau = \left(\frac{\alpha\beta(1-q)}{1-\alpha\beta q}\right)^{T-\tau}\left[k^i_T - \frac{1}{1-\alpha\beta}\right] + \frac{1}{1-\alpha\beta} \quad \text{(Eq. 15)}$$

As player A will not own anything in the last stage, we have $k^A_T = 0$. This implies that $k^A_\tau = \frac{1}{1-\alpha\beta}\left(1-\left(\frac{\alpha\beta(1-q)}{1-\alpha\beta q}\right)^{T-\tau}\right)$. In the beginning, however, k^A_τ will be close to the steady-state value of (Eq. 15), $\frac{1}{1-\alpha\beta}$, especially when T is large. It is easy to see that $k^A_\tau > k^A_{\tau+1}$: The term in the first bracket is smaller than one (as both $\alpha\beta < 1$ and $q < 1$ and therefore $\alpha\beta - \alpha\beta q < 1 - \alpha\beta q$), and the first term will therefore decrease as the exponent gets larger. In contrast, k^B_τ is constant: Player B is the sole-owner of the resource in the last stage $\tau = T$. This implies that $k^B_T = k^* = \frac{1}{1-\alpha\beta}$ and thus $k^B_\tau = \frac{1}{1-\alpha\beta} = k^B$ for all τ.

Note that this simplifies the expression player B's best-reply dramatically:

$$b_\tau = \min\{1 - s_\tau\ ;\ (1-a_\tau)(1-\alpha\beta)\} \quad \text{(Eq. 13')}$$

The best-reply function of player A does not simplify. However, to remove it from clutter as well, we define two auxiliary parameters:[e]

$$\varphi^i_\tau \equiv qk^i_\tau + (1-q)k^i_{\tau+1} \quad \text{(Eq. 16)}$$

$$\gamma^i_\tau \equiv \frac{1}{1+\alpha\beta\varphi^i_\tau} \quad \text{(Eq. 17)}$$

Although the linear coefficients K^A_τ and K^B_τ do not matter for the choice of the harvesting rate, we do not to spell them out in order to fully describe the value functions. The general recursive structure for K^A_τ and K^B_τ can be solved as:

$$K^A_\tau = \frac{1}{1-\beta q}\left[\ln a_\tau + \beta\left((1-q)K^A_{\tau+1} + \varphi^A_\tau(\ln M + \alpha\ln(1-d_\tau))\right)\right] \quad \text{(Eq. 18)}$$

$$K^B_\tau = \frac{1}{1-\beta q}\left[\ln b_\tau + \beta\left((1-q)K^B_{\tau+1} + \varphi^B(\ln M + \alpha\ln(1-d_\tau))\right)\right] \quad \text{(Eq. 19)}$$

In contrast to (Eq. 14), we here have a difference equation where the first coefficients are not constant, nor the same for both players. Therefore we do not solve these difference equations because writing them down is not instructive. Nevertheless, we have the necessary building blocks in hand to describe the general pattern of the equilibrium.

General pattern of the equilibrium

Recall that the game is stationary within each stage. However the extraction rates differ from stage to stage as summarized in the following claim.

Claim 1. *The extraction pattern is characterized by at most three phases:*

I. *In the first phase, player B's extraction rate is constrained by the share of the resource available to him, while player A's rate is not. Total extraction rate d_τ is increasing with τ in Phase I. The individual extraction rates are given by:*

$$a_\tau = s_\tau \gamma^A_\tau \qquad\qquad b_\tau = 1 - s_\tau \tag{Eq. 20}$$

The first phase ends when $s_\tau \leq \frac{\alpha\beta}{1-(1-\alpha\beta)\gamma^A_\tau}$.

II. *In the second phase, neither player's extraction rate is constrained. A's rate is increasing and B's rate is decreasing with τ. The total extraction rate is increasing.*

$$a_\tau = \frac{\gamma^A_\tau(1-\gamma^B)}{1-\gamma^A_\tau\gamma^B} \qquad\qquad b_\tau = \frac{\gamma^B(1-\gamma^A_\tau)}{1-\gamma^A_\tau\gamma^B} \tag{Eq. 21}$$

The second phase ends when $s_\tau \leq \frac{\alpha\beta\gamma^A_\tau}{1-(1-\alpha\beta)\gamma^A_\tau}$.

III. *In the third phase, the extraction rate of player A, but not player B is constrained by the available share of the resource. Total extraction rate is decreasing with τ.*

$$a_\tau = s_\tau \qquad\qquad b_\tau = (1-s_\tau)\gamma^B \tag{Eq. 22}$$

It follows immediately from Claim 1 that the harvest rate reaches its highest value at the last stage of Phase II or at first stage of Phase III. However, it is not possible to obtain a closed-form expression for the maximal harvest rate: The condition for the onset of Phase III, can be simplified[f] to $qk^A_\tau + (1-q)k^A_{\tau+1} \geq \frac{\tau}{T-\tau}$. One cannot solve for the critical τ at which equality holds because τ – taken to be a continuous variable for the moment – enters exponentially in k^A_τ but linearly in the right-hand side.

Fig. 1 illustrates the extraction rates (upper panel) and the player's value functions (where player A is red and player B is green). We plot three scenarios with the same expected length of the transition ($Z = 10$), but different values of q and T. Note that the first and last stage are the situations where player A or player B are the sole-owner, respectively. Consequently, the harvest rate and the value function of the respective opponent are zero for these stages.

Considering the upper panel of the harvest rates first, with an abrupt change in ownership ($T = 2$), each phase consists of one stage (the phases are indicated by the dashed vertical lines). When the change in ownership is smoother ($T = 5$ and $T = 9$), the duration of the phases expands and the relative changes in the individual harvest rates become visible. In particular in Phase II, when neither player is constrained by the share that is accessible to him, player B's extraction rate is decreasing in anticipation that he will eventually become the sole-owner of the resource. However, player A's extraction rate is increasing so strongly that the total extraction rate is increasing, too. Note that Fig. 1 nicely illustrates that the maximal harvest rate could be at the end of phase II (as in the two left panels) or at the beginning of phase III (as in the rightmost panel). In phase III, the harvest rate and the value function of player B approach the sole-owner benchmark.

Turning to the value function (lower panel), we see that player A's value function is monotonously declining and player B's value function is increasing. Note that player A's value function when she is a sole-owner in stage 1 is already heavily depressed by the shadow of the future loss. The changes in q and T have no effect on the overall shape of the trajectories of the value function, in particular player A's initial Net-Present Value of the fishery is the same. The reason is that Z has been kept constant in these plots and it is only the passing of time t that matters for the Net-Present Value, no matter over how many stages τ the shift in stock ownership occurs.

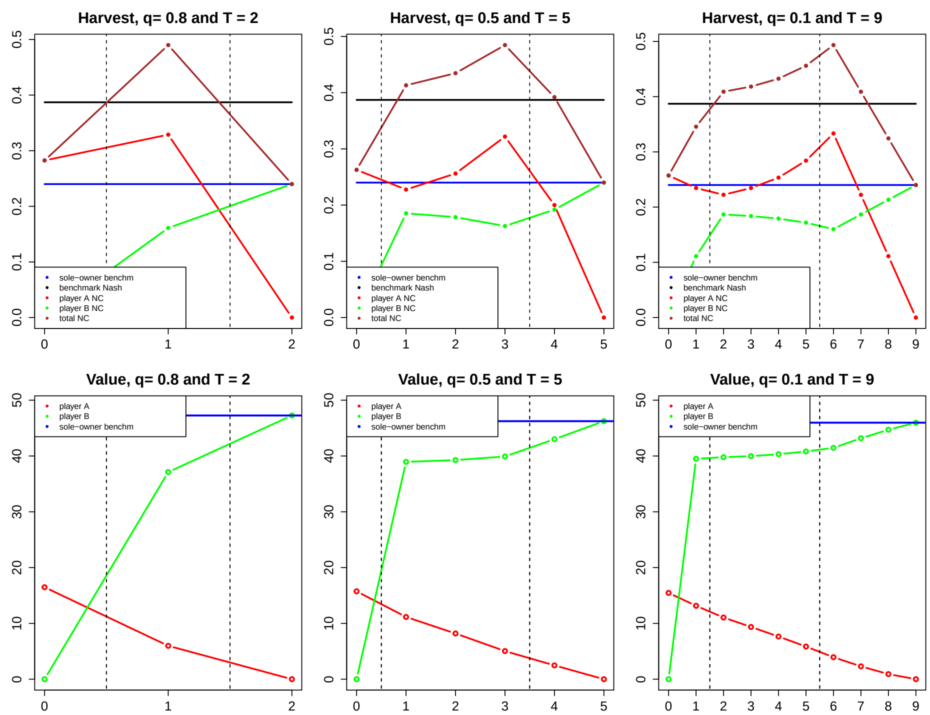

Fig. 1: Illustration of extraction rates and value functions ($\alpha = 0.8, \beta = 0.95, M = 3$)

Next we consider how the changes in a biological growth parameter α and a discount factor β affect the non-cooperative extraction rates, as well as describe how the extraction rates depend on the probability q and the number of stages T, *i.e.* the transition parameters which affect the expected length of the transition period Z.

Effects of the bioeconomic and transition parameters

Claim 2. *An increase in the bioeconomic parameters* α *and* β *leads to a lower total extraction rate in all phases.*

These results are intuitive. An increase in α means the natural regrowth potential of the resource becomes weaker, inducing the players to harvest less aggressively. By comparing (Eq. 20)-(Eq. 22) it becomes clear, that this effect is strongest in the third phase, when player A's harvesting is already constrained by the available share of the resource, and weakest in the second phase when neither player's harvesting is constrained.

An increase in the discount factor, β, means that the players place a higher value on the future harvesting opportunities. Therefore, a higher discount factor naturally leads to a decreased extraction rate. Again, this effect is at weakest in the second phase.

Claim 3. *An increase in q or T decreases, directly or indirectly, the total extraction rate in all phases. Moreover, an increase in q or T may extend the absolute duration of Phase III.*

In other words, the higher the probability the system stays in the current stage and the more stages there are, the lower the total extraction rate. The intuitive reason is that player A owns more of the stock for a longer time and therefore has higher conservation incentives. In contrast, when a shift in stock-ownership is expected to occur in the near term, and the more severe the consequences of such a shift for player A, the more she would want to extract while she still can. As we know from Claim 1 above, player B's effort to counteract the over-harvesting from player A is not sufficiently strong to reduce total extraction.

SELF-ENFORCING COOPERATIVE AGREEMENTS

In this section, we explore whether the players can agree on sharing the gains from maximizing the joint surplus of resource exploitation. We require that each player's participation constraint – which is given by his payoff in absence of cooperation – is satisfied. In other words, we analyze whether there exists some share λ so that player A prefers obtaining that share of the socially optimal harvest rather than harvesting non-cooperatively, and whether player B would at the same time prefer obtaining a share $(1-\lambda)$ rather than harvesting non-cooperatively.[g] Such an agreement is self-enforcing in the sense that player A has no incentive to harvest non-cooperatively, given that player B harvests cooperatively, and vice-versa.

It is well known that self-enforcing cooperative agreements of more than a few players are very difficult to form [14, 16]. Here we show that even two players may not be able to coordinate on the first-best if the stock shifts from one player to the other. This is especially remarkable because two players can always form a self-enforcing agreement in the baseline case of no stock shift.[h]

To clearly distinguish the different continuation values, we denote the player's value function in the non-cooperative Nash equilibrium at stage τ by $V_\tau^{nc,A}(x_t)$ and $V_\tau^{nc,B}(x_t)$, respectively. In contrast, $V_\tau^{coop,i}(\lambda,x_t)$ describes the value of cooperation for player i, given the share λ and the current resource stock x_t. The function $V_{\tau+1}^{i}(x_{t+1})$ is generic value of the game in the next stage (where it is a priori not known whether cooperative or non-cooperative play will dominate). Below, we show that the game remains stationary within each stage. As a consequence, non-cooperation in one stage does not necessarily imply non-cooperation in an earlier stage.

Recalling that d^* denotes the socially optimal harvest rate, we have:

$$V_\tau^{coop,A}(\lambda,x_t) = \ln(\lambda d^* x_t) + \beta\left(qV_\tau^{coop,A}(\lambda,x_{t+1}) + (1-q)V_\tau^{A}(x_{t+1})\right)$$

$$V_\tau^{coop,B}(\lambda,x_t) = \ln((1-\lambda) d^* x_t) + \beta\left(qV_\tau^{coop,B}(\lambda,x_{t+1}) + (1-q)V_\tau^{B}(x_{t+1})\right)$$

A cooperative agreement can be reached if condition (Eq. 23) holds.

$$V_\tau^{coop,A}(\lambda,x_t) \geq V_\tau^{nc,A}(x_t) \qquad \text{and} \qquad V_\tau^{coop,B}(\lambda,x_t) \geq V_\tau^{nc,B}(x_t) \tag{Eq. 23}$$

This setting effectively allows financial side-payments (to the extent that it makes sense to talk of financial side-payments in the Levhari and Mirman model) as the players' constraints on the share that they can actually harvest are not taken into account in this setup. However, we show below that constraining the players' instantaneous payoffs to what they can maximally harvest does not curtail the scope for cooperation.[i]

Clearly, $V_\tau^{coop,A}(\lambda,x_t)$ is increasing in λ and $V_\tau^{coop,B}(\lambda,x_t)$ is decreasing in λ. Let therefore $\lambda_{min}^{A} \in (0,1]$ be the minimum share of the optimal harvest that player A would be willing to accept in order to approve cooperative management. Similarly, let $\lambda_{max}^{B} \in (0,1]$ the maximum share that player B would be willing to give to player A and still harvest cooperatively. Accordingly, we can define the scope for cooperation by:

$$\Gamma \equiv \left\{\lambda_{max}^{B} - \lambda_{min}^{A}; 0\right\} \tag{Eq. 24}$$

Claim 4. *The scope for cooperation vanishes as* $\alpha\beta \to 1$. *But if* $\Gamma > 0$, λ_{min}^{A} *and* λ_{max}^{B} *are given by* (Eq. 25) *and* (Eq. 26)*, respectively, and cooperation possibilities are not constrained by the available harvest shares.*

$$\lambda^{A}_{min} = \frac{a_\tau}{1-\alpha\beta}\left(\frac{1-a_\tau-b_\tau}{\alpha\beta}\right)^{\alpha\beta\varphi^{A}_{\tau}} \qquad \text{(Eq. 25)}$$

$$\lambda^{B}_{max} = 1-\frac{b_\tau}{1-\alpha\beta}\left(\frac{1-a_\tau-b_\tau}{\alpha\beta}\right)^{\alpha\beta\varphi^{B}} \qquad \text{(Eq. 26)}$$

As it is clear from equation (Eq. 25) and (Eq. 26), the scope for cooperation depends in a complicated way on the parameters α and β. In Fig. 2, we therefore illustrate how the scope for collaboration depends on these parameters and on q and T. We plot a grid of 100x100 combinations of $\alpha\beta$ between 0.5 and 0.9 (on the x-axis) and q between 0.5 and 0.9 (on the y-axis) and check for each combination whether $\Gamma > 0$ in all stages. If yes, we color that box green, if not, we color it red. We do so for three different values of T. The pattern that emerges is that the scope for cooperation is a little larger when $T = 5$ rather than $T = 15$, but these changes are small compared to the detrimental impact of increasing the bionomic parameters $\alpha\beta$ or increasing q (the latter result again showing that a more gradual change is conducive to cooperation).

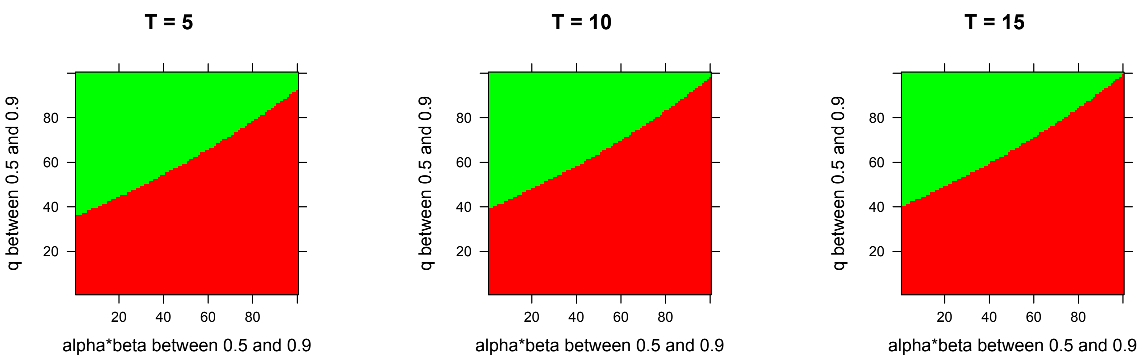

Fig. 2: Parameter values for which it is possible to have cooperation in all stages

Now Fig. 2 only considers whether there was any stage in which there would be no scope for collaboration. In Fig. 3 we then shows how the bargaining set changes over the different stages of the game. In particular, it becomes obvious how the scope for collaboration is compressed at the end and the beginning of the transition phase. This is not surprising, as it is here that both players have the strongest bargaining positions. Towards the end, for example, player A has nothing left to loose, but also player B has little incentive to give him much as player A's harvest share is constrained anyway. Furthermore, Fig. 3 illustrates how player A's bargaining strength is declining over the different stages, though not in a monotonic fashion. Indeed, the changes from one stage to the next can be quite large, especially in the beginning or the end.

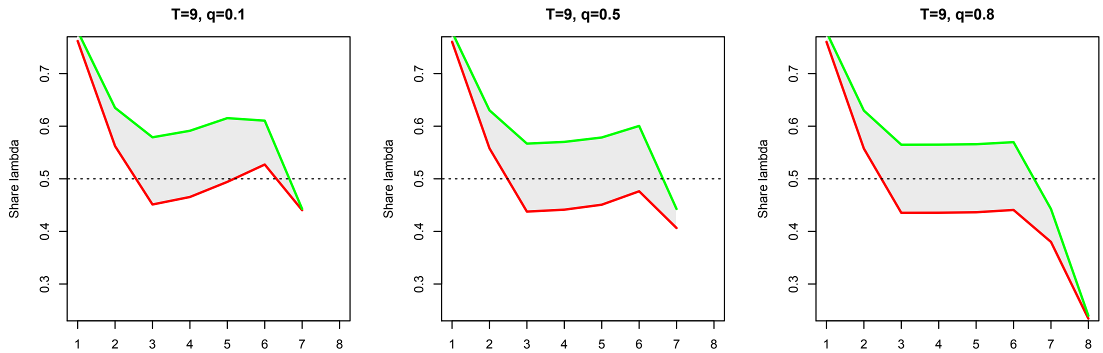

Fig. 3: Illustration of bargaining set at different stages ($\alpha = 0.6, \beta = 0.95$)

CONCLUSION

We have studied by an analytic model how two players exploit a fish stock if it shifts from one player to another with different paces, and under which conditions it is possible to obtain a self-enforcing agreement. We found that a longer expected time of the shift, an increase in the player's valuation of the future and a decrease in the renewability of the stock imply less intensive exploitation of the resource. Furthermore, two players may not be able to coordinate on the first-best agreement, whereas they can always form a self-enforcing agreement in a case without a shift. In general, the slower the shift is, the larger the scope for cooperation. More sudden shift implies higher intensity of non-cooperative exploitation, but increases the chances of obtaining a cooperative solution. The cooperative incentives vanish when the regrowth potential of the resource is low simultaneously with a high discount factor.

REFERENCES

[1] Kathleen A. Miller, Gordon R. Munro, U. Rashid Sumaila, and William W. L. Cheung. Governing marine fisheries in a changing climate: A game-theoretic perspective. *Canadian Journal of Agricultural Economics*, 61(2):309–334, 2013.

[2] Megan Bailey, U. Rashid Sumaila, and Marko Lindroos. Application of game theory to fisheries over three decades. *Fisheries Research*, 102(1-2):1–8, February 2010. ISSN 0165-7836. URL `http://www.sciencedirect.com/science/article/B6T6N-4XRYT2D-1/2/0a1bdfd3b267a02fbb89d85fd0652496`.

[3] Rognvaldur Hannesson. Game theory and fisheries. *Annual Review of Resource Economics*, 3(1):181–202, September 2011. ISSN 1941-1340. URL `http://dx.doi.org/10.1146/annurev-resource-083110-120107`.

[4] David Levhari and Leonard J. Mirman. The Great Fish War: An Example Using a Dynamic Cournot-Nash Solution. *The Bell Journal of Economics*, 11(1):322–334, Spring 1980. ISSN 0361915x.

[5] J.-C. Pereau, A. Cisse, F. Blanchard, and Luc Doyen. Cooperative and non-cooperative harvesting in a multi-species fish war model. In *European Association of Environmental and Resource Economists, 20th Annual Conference, 26-29 June 2013, Toulouse, France.*, 2013.

[6] Elena Antoniadou, Christos Koulovatianos, and Leonard J. Mirman. Strategic exploitation of a common-property resource under uncertainty. *Journal of Environmental Economics and Management*, 65(1):28–39, January 2013. ISSN 0095-0696. URL `http://www.sciencedirect.com/science/article/pii/S0095069612000599`.

[7] R. McKelvey, K. Miller, and P Golubtsov. Fish wars revisited: a stochastic incomplete-information harvesting game. In Justus Wesseler, Hans-Peter Weikard, and Robert D. Weaver, editors, *Risk and Uncertainty in Environmental and Natural Resource Economics*, pages 93–112. Edward Elgar, 2003.

[8] Xiaozi Liu, Marko Lindroos, and Leif Sandal. Sharing a fish stock with density-dependent distribution and unit harvest costs. In *14th International BIOECON Conference*, Cambridge, UK, 2012.

[9] Xiaozi Liu and Mikko Heino. Comparing proactive and reactive management: Managing a transboundary fish stock under changing environment. *Natural Resource Modeling*, forthcoming:no–no, 2013. ISSN 1939-7445. doi: 10.1111/nrm.12009. URL `http://dx.doi.org/10.1111/nrm.12009`.

[10] Rognvaldur Hannesson. Global warming and fish migration. *Natural Resource Modeling*, 20(2):301–319, 2007. ISSN 1939-7445. URL `http://dx.doi.org/10.1111/j.1939-7445.2007.tb00209.x`.

[11] Rögnvaldur Hannesson. Sharing the Northeast Arctic Cod: Possible Effects of Climate Change. *Natural Resource Modelling*, 19(4):633–654, 2006.

[12] Rögnvaldur Hannesson. Sharing a migrating fish stock. *Marine Resource Economics*, 28(1):1–17, March 2013. ISSN 0738-1360. doi: 10.5950/0738-1360-28.1.1. URL http://www.bioone.org/doi/abs/10.5950/0738-1360-28.1.1.

[13] Hans Ellefsen. The stability of fishing agreements with entry: The northeast atlantic mackerel. *Strategic Behavior and the Environment*, 3(1–2):67–95, 2013.

[14] Oh Sang Kwon. Partial international coordination in the great fish war. *Environmental and Resource Economics*, 33(4):463–483, 2006. ISSN 0924-6460. doi: 10.1007/s10640-005-4994-x. URL http://dx.doi.org/10.1007/s10640-005-4994-x.

[15] Michèle Breton and Michel Y. Keoula. Farsightedness in a coalitional great fish war. *Environmental and Resource Economics*, 51(2):297–315, 2012. ISSN 0924-6460. URL http://dx.doi.org/10.1007/s10640-011-9501-y.

[16] Michle Breton and Michel Y. Keoula. A great fish war model with asymmetric players. *Ecological Economics*, 97:209–223, 2014.

[17] Scott Barrett. Self-enforcing international environmental agreements. *Oxford Economic Papers*, 46(0):878–94, 1994. URL http://EconPapers.repec.org/RePEc:oup:oxecpp:v:46:y:1994:i:0:p:878-94.

[18] Marita Laukkanen. Cooperative and non-cooperative harvesting in a stochastic sequential fishery. *Journal of Environmental Economics and Management*, 45(2, Supplement):454 – 473, 2003. ISSN 0095-0696. doi: http://dx.doi.org/10.1016/S0095-0696(02)00020-7. URL http://www.sciencedirect.com/science/article/pii/S0095069602000207.

[19] Marita Laukkanen. Cooperation in a stochastic transboundary fishery: The effects of implementation uncertainty versus recruitment uncertainty. *Environmental and Resource Economics*, 32(3):389–405, 2005. ISSN 0924-6460. doi: 10.1007/s10640-005-6542-0. URL http://dx.doi.org/10.1007/s10640-005-6542-0.

[20] Gordon R. Munro. The Optimal Management of Transboundary Renewable Resources. *The Canadian Journal of Economics / Revue canadienne d'Economique*, 12(3):355–376, Aug. 1979. ISSN 00084085. URL http://links.jstor.org/sici?sici=0008-4085%28197908%2912%3A3%3C355%3ATOMOTR%3E2.0.CO%3B2-N.

[21] Larry Karp and Leo Simon. Participation games and international environmental agreements: A non-parametric model. *Journal of Environmental Economics and Management*, 65(2):326–344, 2013. URL http://ideas.repec.org/a/eee/jeeman/v65y2013i2p326-344.html.

[22] Aart de Zeeuw. Dynamic effects on the stability of international environmental agreements. *Journal of Environmental Economics and Management*, 55(2):163–174, March 2008. ISSN 0095-0696. doi: 10.1016/j.jeem.2007.06.003. URL http://www.sciencedirect.com/science/article/pii/S0095069607001052.

[23] Knut Sydsæter, Peter Hammond, Atle Seierstad, and Arne Strøm. *Further Mathematics for Economic Analysis*. Prentice Hall, Harlow, 2005.

ENDNOTES

[a]Less pessimistic results are sometimes obtained under alternative model structures [21] or the use of "farsighted" instead of Nash conjectures [22, 16].

[b]Let i_{min} be the lowest extraction rate of player i and let d_{max} be the largest equilibrium total extraction rate. Then a condition that guarantees non-negative objective function values is $i_{min}M\left((1-d_{max})M\right)^{\frac{\alpha}{1-\alpha}} \geq 1$ for $i = A, B$.

[c]This assumption does ease the exposition considerably, but one could always introduce a non-linearity in the transition dynamics by replacing $s_\tau = \frac{T-\tau}{T}$ with the requirement that $s_0 = 1; s_\tau \geq s_{\tau+1}$ and $s_T = 0$ (which is strictly speaking all we need for our proofs), or by making q depend on the specific stage (so that q_τ is not necessarily the same as $q_{\tau+1}$).

[d]We refer to a standard mathematic textbook for economists e.g. Sydsæter et al. [23, p.391]. To see the solution more clearly, it is useful to change variables so that we start counting from the terminal stage T. That is, we introduce a new variable $n = 0, 1, 2, ...$ so that $n = 0 \equiv \tau = T$. This means that equation (Eq. 14) is written as: $k^i_{n+1} = l + mk^i_n$ which can be solved to get $k^i_n = m^n k_0 + l(\sum(m^n))$. As we have a geometric series in the brackets, the solution of the equation can be rewritten as: $k^i_n = \frac{l(1-m^n)}{1-m} + mk_0 \Leftrightarrow k^i_n = m^n[k_0 - \frac{l}{1-m}] + \frac{l}{1-m}$, where $\frac{l}{1-m} = \frac{1}{1-\alpha\beta q}\frac{1}{1-\frac{\alpha\beta(1-q)}{1-\alpha\beta q}} = \frac{1}{1-\alpha\beta q}\frac{1}{\frac{(1-\alpha\beta q)-\alpha\beta(1-q)}{1-\alpha\beta q}} = \frac{1}{1-\alpha\beta q-\alpha\beta+\alpha\beta q} = \frac{1}{1-\alpha\beta}$.

[e]Direct insertion shows that for $i = B$ we have $\gamma^B = 1 - \alpha\beta$. In the Appendix, we give an overview over all fundamental and derived parameters and how the latter change with changes in the former.

[f]
$$s_\tau \leq \frac{\alpha\beta\gamma^A_\tau}{1-(1-\alpha\beta)\gamma^A_\tau} \quad \Leftrightarrow \quad \left(1-(1-\alpha\beta)\gamma^A_\tau\right)\frac{T-\tau}{T} \leq \alpha\beta\gamma^A_\tau$$
$$\Leftrightarrow \quad \frac{T-\tau}{\gamma^A_\tau} - (T-\tau)(1-\alpha\beta) \leq \alpha\beta T \quad \Leftrightarrow \quad (T-\tau)(1+\alpha\beta\varphi^A_\tau) - T + \tau - \alpha\beta\tau \leq 0 \quad \Leftrightarrow \quad \varphi^A_\tau \leq \frac{\tau}{T-\tau}$$

[g]That is, we assume that at any time t, the players perceive the Nash equilibrium described in section as the only alternative to a cooperative agreement for that stage. In essence, the players follow a grim trigger strategy within each stage. We do not require that the threat of non-cooperative play is renegotiation-proof.

[h]Consider K^* from equation (Eq. 5) and K^{nc} from equation (Eq. 8). A cooperative agreement is self-enforcing if $K^* - K^{nc} = \frac{\ln(2-\alpha\beta)}{1-\alpha\beta} - \ln 2 > 0$, which is true for all $\alpha\beta \in (0,1)$.

[i]This stands in interesting contrast to the classical work from Munro [20] on cooperative agreements for transboundary stocks. But again, we are quick to point out that the distinction between quota-swaps and financial side-payments does not have an obvious counterpart in the utility-based model of Levhari and Mirman [4].