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Global Warming and International Fishery Management: Does Anticipation of the Temperature Change Matter?

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Global Warming and International Fishery Management: Does Anticipation of the Temperature Change Matter?

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Abstract

This paper investigates the effects of climate-induced rising of ocean temperature on the optimal fishing policies in a two players' non-cooperative game setting. We compare reactive management, under which the manager does not believe in or know about temperature trend, with proactive management where the manager considers the future temperature change in his decisions. We assume that the fish stock is initially solely owned by country one. As temperature rises, the stock starts spilling over to the zone of the other country and eventually becomes under its sole ownership. A stochastic dynamic programming model is developed to identify Nash management strategies for the two players. The main findings are that anticipation of temperature trend induces notable strategic interactions between two players. Knowing that it is gradually loosing the stock, country one is often harvesting more aggressively, whereas the country that is increasing its ownership harvests more conservatively. Compared to reactive management, proactive management benefits both parties in terms of their cumulative pay-offs; the biological stock is also larger much of the time. In most cases, the difference between two management regimes is subtle, but when the stock is slow-growing and highly schooling, proactive management may save it from collapse.

Key words: climate change, Nash game, stochastic dynamic programming, optimal fishing policy

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1 Introduction

Climate change effect on the distribution of straddling stock is receiving increasing attention in international fishery management literature (Hannesson et al. 2006, Ekerhovd 2010). Climate model projections (IPCC, 2007) indicate that during the course of 21st century the surface temperature is likely to increase by 1.1° C – 6.4 °C. The atmospheric warming has significant effects, one of which is the increase of ocean temperatures, particular in the Arctic areas. The UK climate impact program (2002) predicted that mean annual surface temperatures in the North Sea will increase 0.5–1.0 °C by 2020, 1.0–2.5 °C by 2050, and 1.5–4.0 °C by 2080. For fish rising sea temperatures have profound effects both for their distribution and abundance (Cheung et al. 2009). For example, Perry et al. (2005) showed that in the North Sea, two thirds of the studied species had shown distributional responses to warming climate.

Fish distribution shifts impose a new challenge on the management of commercial fish stocks (Hannesson 2007, Cochrane et al. 2009, Johnson and Welch 2010). Trans-boundary stocks are usually shared using the principle of 'zonal attachment' in which countries' shares of the total quota are proportional to the proportion of the stock in their Exclusive Economic Zones (EEZ). Displacement of fish will threaten the stability of existing fish stock agreements. For example, consider a fish stock that is gradually moving from the jurisdiction of country A to the jurisdiction of country B. Country A will experience a shrinking stock within its own EEZ, hence its conservation incentive may decline. On the other hand, country B may lack conservation incentive as long as he is a minor player. Ignoring such dynamics may lead to overexploitation of an important resource.

The problem of shifting zonal attachment in the climate change context was first examined by Hannesson (2007). The focal stock was assumed originally to be under sole ownership, and then over time, as temperature rises, start to 'spill' into the EEZ of another country. The two countries respond to the changes with a time lag and the management decisions are non-cooperative. Managers in the model used by Hannesson make their decisions based on their past and current knowledge: their expectation about the future stock distribution is a weighted average of the previous year's estimate and the currently observed split ratio. The optimal management decisions are based on the assumption that the current estimate of the stock distribution is representative of the future, as if there were no further change in the distribution. We define such manager as 'reactive'.

Our model builds upon Hannesson's model (2007), but our managers can also be 'proactive' decision makers. We take this to mean that the manager takes into account both the current stock distribution as well as an anticipation of future distributional change of the stock. We used dynamic programming (DP) to find the optimal harvest policies at each time step. Proactive harvest decision making in absence of a trend in the stock distribution was studied by Golubtsov and McKelvey (2007) using a DP algorithm. In contrast to their paper, our split model integrates both rising temperature trend over time and stochastic uncertainty of future environment.

Capturing this rising trend is important for our study of the problem as it is the center piece of the climate change debates. Moreover, we also consider general forms of fish stock concentration profiles in order to reveal a more complete picture of the problem. The main research questions of our study are: How will managers' belief about future temperature trend and the consequent distributional shift affect their harvest policies, and what are the implications of those decisions on the biological stock?

2 Model Specification

Solving problem of our interest requires a bio-economic model that combines both biological effects (stock dynamics in space and time) and economic effects (profit-maximizing harvest policy, constrained by the other player's actions).

2.1 The Biological Model

We use a discrete-time logistic population growth model where stock renewal and harvesting alternate. During the part of a season when fishing takes place, the stock occupies the EEZs of two countries. Renewal is determined by the total biomass.

2.1.1 Stock dynamics

The discrete-time logistic growth function with harvesting is:

$$R(s_t) = as_t(1 - s_t) + s_t \qquad (1)$$
$$s_{t+1} = p_t R(s_t)$$

where R is recruitment (i.e., the stock size before fishing), s_t is the stock size after harvest, a is the growth ratio (the greater the parameter, the faster the stock is renewed), and p_t is the harvesting strategy, here expressed as the escapement proportion. We assume that stock size is expressed relative to the carrying capacity; this parameter thus dissappears in normalization.

The fish stock we have in mind is a migratory stock that moves between spawning and fishing grounds (Figure 1). One implicit assumption of this model is that no fishing takes place during the reproductive season.

During the fishing season, the harvestable stock R may be found entirely in the EEZ of country 1 or country 2, or split among the two, depending on the ocean temperature. The share of the harvestable stock in the EEZ of country 1 is given by parameter θ_t, the split ratio; the rest spills into EEZ of country 2. Harvest takes place within the country's own EEZ; each country decides its own harvest strategy, the proportion of fish p_t^i to be left behind. As a result of harvesting, the stock size in country i is reduced to s_t^i. Both streams of fish will then unite for renewal. Next season, the stock will then increase to a new level R_{t+1} due to growth and reproduction of the fish left behind from previous season t. This so-called split stream model was first introduced by McKelvey and Golubtsov (2006).

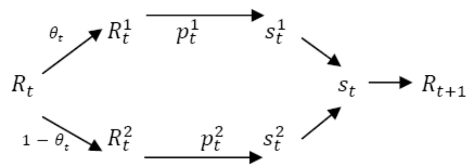

Figure 1: The split stream game

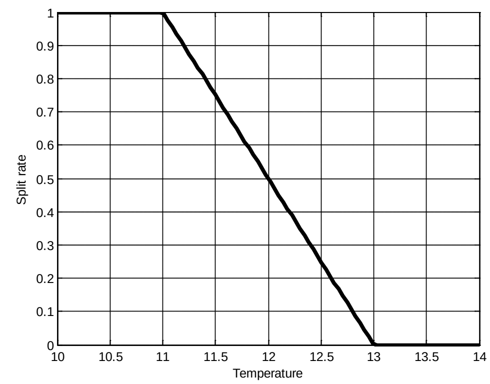

Figure 2: Temperature and split rate: two thresholds, $11°C/yr$ and $13°C/yr$

2.1.2 Stochastic split rule

We assume the split ratio θ to be a function of temperature T, defined as follows:

$$\theta(T) = \begin{cases} 1, & T < T_1 \\ \dfrac{T_2 - T}{T_2 - T_1}, & T_1 \le T \le T_2. \\ 0\,, & T > T_2 \end{cases} \qquad (2)$$

Here T_1 and T_2 are two temperature thresholds: below T_1 country 1 is the sole owner of the stock; above T_2, country 2 is the sole owner; in between, split ratio is a linear function of temperature as illustrated in Figure 2.

Temperature change is determined by a trend parameter δ, overlaid by annual stochastic fluctuations:

$$T_t = T_0 + \delta\, t + N_t(\mu, \sigma) \qquad (3-1)$$

$$T_{t+1} = T_t + \delta + N(\mu, \sigma) \qquad (3-2)$$

where T_0 is the initial sea water temperature, t is time and $N(\mu, \sigma)$ is a normally distributed random variable with mean $\mu = 0$ and standard deviation σ. In all our simulations, we have chosen $\sigma = 0.2$°C, $T_0 = 10$°C, $T_1 = 11$°C and $T_2 = 13$°C. We have applied various values of δ, ranging from 0.04 to 0.12℃/yr. Equation (3-1) and (3-2) specify two types of stochastic processes being used in our simulations. Equation (3-1) is often called white noise and equation (3-2) called colored noise, the difference of the two is whether temperature noise of this period is correlated with temperature noise of next period.

2.2 The Economic Model

In our model, two countries that share fish stock play a non-cooperative game over long time horizon. We assume that players are symmetric and omniscient: they have full knowledge about current state of the stock and temperature, and knowledge on the probability distribution of stochastic uncertainty. Managers are assumed to be *risk neutral.* The countries are engaged in a dynamic multi-period game where they, each period, try to maximize their expected current and future payoff, constrained by the actions of the other country. Thus, the chosen harvest policies are Nash strategies.

2.2.1 Revenue, cost and concentration profile

For simplicity, we assume fish price to be exogenous and normalized to 1. Cost of fishing becomes then the vital variable for economic decisions. Fish stock density is critical in determining costs of fishing: the lower the density, the more effort is needed to catch a unit of fish. To describe how fish density experienced by fishermen depends on total stock abundance, Clark (1976, 1990) introduced the concept of concentration profiles. A concentration profile describes how average maximum density of fish depends on total stock abundance and is determined by spacing behavior of fish, i.e., by the degree of their schooling behavior; this will vary from species to species.

Let us denote the effective stock density experienced by the manager i at within-season time τ, as ρ_τ^i, which is the function of instantaneous sub-stream stock size x_τ^i and split ratio θ_τ^i:

$$\rho_\tau^i = \left(\frac{x_\tau^i}{\theta_\tau^i}\right)^b, \quad i = 1{,}2 \qquad (4)$$

Given the split stream game we specified in Figure 1, the two streams of stock will meet before a new round of the split stream game takes place. Since fishes do not respect country boundaries, at the beginning of each fish season, two countries must have the same stock density. This explains why equation (4) has been corrected for split ratio θ_τ^i. Following this reasoning, two countries shall initially face same per unit cost of catching fish. Over time within the season, their sub-stream densities start diverging if players have chosen different fishing policies.

Choice of parameter b is another complexity of equation (4). If $b = 0$, density ρ becomes a stock size independent constant. This would describe a fish species which is highly schooling and when fishermen can easily find these schools. Under such circumstances, both players face same cost per unit catch throughout the fishing season, until the stock is exhausted. $b = 1$ is another special case where density is strictly proportional to the stock size; this could happen when the area of fish distribution is unchanged, but the density changes with stock size. In contrast to the former 'super-schooling' case, $b = 1$ refers to non-schooling fish that are uniformly distributed, at least from the fishermen's perspective. However, most of fish stocks behave between these extreme cases with $0 < b < 1$. Many papers in the literature assume either one or the other of the aforementioned special cases. In our model, we have used a more general form of the concentration profile to reveal a more complete picture.

Having understood implications of fish density on the unit costs, we can now derive costs at season *t* which is denoted as $cost_t$:

$$cost_t = \int_0^1 c_e \, E_\tau \, d\tau \qquad (5)$$

where c_e is a fixed value for cost per unit effort and E_τ is total fishing effort at time τ. For simplicity, seasonal discounting is ignored in equation 5. Effort E_τ is defined as function of instantaneous catch C_τ and catchability coefficient q, which tells how easy to catch that fish species:

$$E_\tau = \frac{C_\tau}{q \, \rho_\tau} \qquad (6)$$

After solving equations 4, 5, and 6, we derive the total seasonal cost each player faces as follows (for details see the Appendix):

$$cost_t^i = \begin{cases} \dfrac{\theta_t^i \, c_e}{q \ (1-b)} {R_t}^{1-b} \left(1-(p_t^i)^{1-b}\right), & 0 \le b < 1 \\ -\dfrac{\theta_t^i \, c_e}{q} \log\left(p_t^i\right), & b = 1 \end{cases} , \qquad i = 1{,}2 \quad (7)$$

Equation (7) implies that the greater the value *b*, the costlier it is to fish.

The expression for seasonal rent is straightforward:

$$rent_t^i = \theta_t^i \, R_t \left(1 - p_t^i\right) \ , i = 1{,}2 \qquad (8)$$

2.2.2 Multi-period profit maximization

The objective of a risk neutral manager is to maximize the net present value, which comprises of two terms: immediate payoff at present season t, and discounted sum of all future expected payoffs. When $0 \le b < 1$, the immediate payoff v_t^i is given by equation (9):

$$v_t^i(p_t^i, \theta_t^i, R_t) = \overbrace{\theta_t^i R_t \left(1 - p_t^i\right)}^{Seasonal\ rent\ (8)} - \overbrace{\frac{\theta_t^i \, c_e}{q \ (1-b)} \ (R_t)^{1-b} \left(1 - (p_t^i)^{1-b}\right)}^{Seasonal\ \ Cost_t\ \ (7)} \qquad (9)$$

where R_t is the total stock at time t, p_t^i is the harvest policy, subscript t denotes the fishing season, superscript i denotes the player; the equation when $b = 1$ is determined similarly. At time t, the current stock level R_t and the current temperature T_t are known and exogenously determined, hence θ_t^i is also known, and the immediate payoff is then only the function of p_t^i, the current harvest policy of player i. As for the future payoffs, when $t < t_{max}$, it is the sum of expected payoffs from $t + 1$ to terminal t_{max}, conditional on his competitor's harvest policies.

The Bellman equation of the described problem is specified in equation (10) that is subject to initial state $R_{t_0} = R_0$, a given parameter, and equation (1), the biological production function.

$$\underset{\boldsymbol{P}_t^i}{\mathbf{Max}}\ V_t^i(\mathbb{P}_t^i)|\mathbb{P}_t^{-i} = \overbrace{v_t^i(p_t^i, R_t, \theta_t^i)|_{t=t_0}}^{Current\ payoff} + \overbrace{\sum_{k=t+1}^{k=t_{max}} \frac{1}{(1+r)^{k-t}} E(v\,_k^i)|p_k^{-i}}^{All\ future\ payoffs}\ ,$$
$$i = 1,2\ ; t = t_0, t_0 + 1, \dots, t_{max} \qquad (10)$$

Here t_0 indicates the present time and r is the monetary discount rate. The manager's objective at decision point t is to choose the policy that maximizes the sum of his current payoff and all future expected payoffs, given the policy of his competitor. $\mathbb{P}_t^i = (p_t^i, \dots . p_{t_{max}^i})$, is a policy set, specifying the harvest policy player i chooses each fishing season; $\mathbb{P}_t^{-i}$ is the policy set of his competitor. When $t = t_{max}$, the future payoff is set to an arbitrary value.

In equation (10), current payoff is only the function of his own fishing policy, but the payoff at $k = t + 1$ period, is both the function of his own policy at that period as well as the sub-stream stock of the period. The stock level at period $t + 1$, R_{t+1}, is determined by two players' fishing policies at period t, and its functional form is specified in equation (1).

From equation (2) and (3), we know that θ_{t+1}, the split ratio at time $t + 1$, is a function of current temperature, the trend and temperature stochasticity, $\theta_{t+1} = f(T_t, \delta, \sigma)$. The proactive manager has full knowledge of the rising trend in temperature, and takes that into consideration in his decision making. The reactive manager does not consider future temperature change in his decision making, and he believes future split ratio to be the same as current split rate, or in other words, $\theta_{t+1} = f(T_t, \sigma)$. Notice that both the reactive and proactive managers update their information about current temperature and thus split ratio of the stock. Their decision making diverges in the way they evaluate the expected future payoff, but not the current payoff.

2.3 Dynamic Programming

We apply dynamic programming (DP) in our model. The DP determines a Markov perfect equilibrium for dynamic recursive games. The simulations are divided into two parts: backward induction and forward induction. The backward induction is to search sub-game perfect Nash equilibrium for all combinations of stock, temperature and period, based on the manager's belief about future change. Its temperature uncertainty follows white noise process (see equation 3-1). The forward induction simulates the assumed "real" temperature change in which temperature uncertainty follows random walk process (see equation 3-2). We also consider situations where the actual trend is stronger or weaker than the trend assumed by the managers in question.

In addition to calendar time both players in the game condition their strategies on other variables such as stock level, the split ratios and competitor's strategies, therefore the equilibrium we deal with is close-loop Nash equilibrium (Fudenberg and Tirole, 1991, p510).

A grid-based search algorithm on a 20 × 20 grid is used in identifying Nash equilibrium. While in most cases a unique, globally stable Nash solution can be found, in some cases no-Nash does occur under certain circumstances. This gives interesting dynamics of the problem. More elaborations will be provided in a forthcoming paper.

2.4 Simulations

In all simulations, we assume two managers/countries in question are identical in terms their management regimes (reactive or proactive) and in the economic parameters (price of fish, cost of fishing effort, and discount rate). All figures presented below are mean trends of 500 replicate forward runs. All the results are based on a setting where the fish stock is first under the sole ownership of country 1, then starts gradually spilling into the jurisdiction of country 2, until at some point it enters the sole ownership of country 2. With our standard parameters, spilling occurs with probability 50% or higher from year 10 to year 42; the stock is on average equally shared at year 26.

3 Results and discussion

To set the stage, we first describe the results under reactive management, before moving on to comparisons with proactive management, the main focus of this paper.

3.1 Reactive management

Under reactive management, the transition from the sole ownership of country 1 to the sole ownership of country 2 is marked by a U-shaped "notch" pattern in the abundance trajectory of the biological stock (figure 3). Before the stock starts spilling to partial ownership of country 2, the sole owner, player 1, fishes the stock to the optimal level that maximizes his expected net returns, without anticipation of changes in the ownership. Amid the transition the stock is exploited to a low level because of the non-cooperative harvest. Most of the time, the minor owner harvests more aggressively than the major owner who has more incentive to maintain the stock at a productive level; the minor owner can free-ride the major owner's conservation effort. The low-point of the stock abundance is reached in the middle of transition when neither player is the major owner. The stock starts gradually recovering when player 2 gains a major share of the stock; ex-post the transition, single-owner optimum is again reached. These findings echo the conclusions of Hannesson (2007).

The trajectory of stock decline and recovery is almost symmetric under reactive management: decisions that country 1 makes as the majority player are similar to those that country 2 does in the same position; some differences do exist, however, because the asymmetry in stock dynamics: stock size can decline arbitrarily fast, whereas it can only increase in abundance at a finite rate.

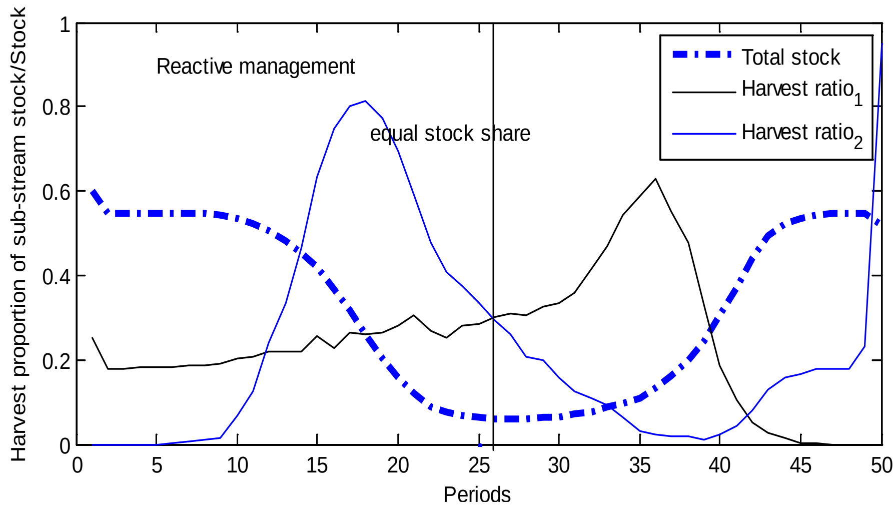

Figure 3: *Mean trends (500 runs) of total stock level and harvest policies under reactive management. Parameters: a=0.4, b=0.5, r=6%, trend=0.08 °C/yr , sigma=0.2°C/yr nbins=20 sbins=20, tbins=30; R0=0.6,T0=10°C/yr*

3.2 Reactive vs. proactive management

Based on our definition of these two management regimes, we can anticipate that under proactive management, the dominant player will realize in advance that the stock is slipping out of his territory, therefore reacting faster. Similarly the minor player will know in advance that he is taking over the stock. For proactive management, under which future temperature change is allowed to influence current harvest policy, the knowledge about the future makes the roles of country 1 and country 2 inherently different.

3.2.1 Implication on stock and payoff

Figure 4 shows two representative examples of the development of total stock over time under reactive and proactive management regimes. The right panel illustrates the more typical case: there is no qualitative difference between the two management regimes. The stock ex-ante and ex-post transition is at the same level regardless of which management regime applies. Some divergence appears during the ownership transition. We can notice some characteristic features. First, in the beginning of the transition, the stock declines earlier, but it also starts to recover earlier amid the transition. Second, when compared to reactive management, the stock trajectory under proactive management becomes more conspicuously asymmetric, largely because the stock recovers faster.

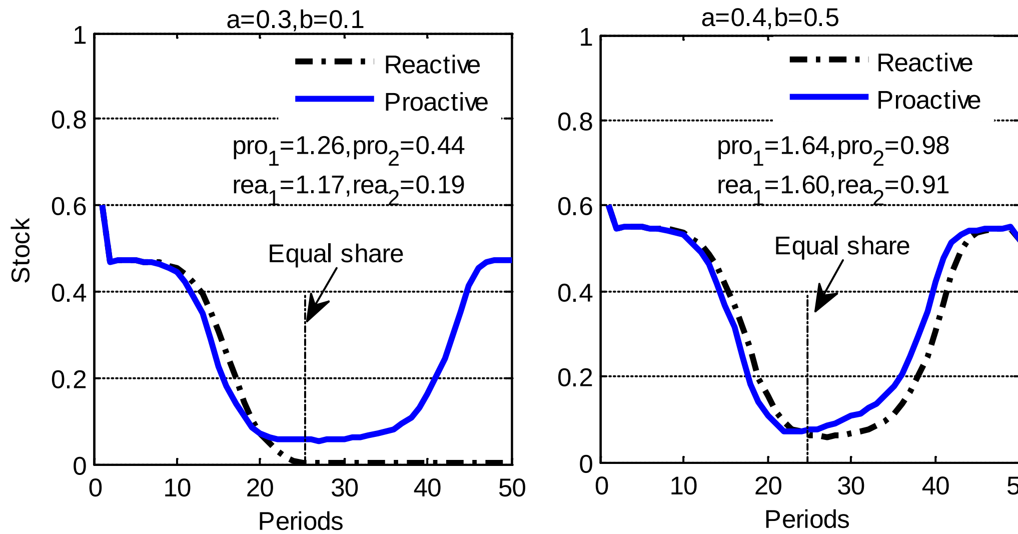

Figure 4: *Total stock level under proactive and reactive management: mean trends (500 runs) r=6%, trend=0.08°C/yr, Initial stock R0=0.6, initial temperature T0=10°C/yr, pro_i and rea_i are the profit flows summing from period 2 to 49 respectively under proactive and reactive management .*

The left panel shows the less typical case where reactive and proactive management yield qualitatively different outcomes. This can happen when the stock in question has a slow growth and high schooling tendency (here $a = 0.3$ and $b = 0.1$). As Figure 4 shows the reactive management results in a stock collapse, while the proactive management under the same conditions is able to avoid such tragedy. This does not imply proactive management is risk-free, but it does show that reactive management is more vulnerable to the negative consequences of non-cooperative exploitation.

In terms of the flow of immediate payoff (Figure 4), the proactive management brings slightly higher cumulative payoffs (excluding the first and the last period) for both players than the reactive management; the difference becomes large only when the stock collapses under reactive management. We see that it is country 1 that gains higher payoffs (because he benefits more from fishing the stock down), but that country 2 benefits more from the proactive management.

3.2.2 Strategic interactions

A comparison of the two players' optimal policies under the alternative management regimes (figure 5) helps to understand the mechanisms behind the observed differences in stock trajectories. As the stock starts to spill to the jurisdiction of country 2, we observe that proactive management induces strategic interactions between two players. Summarizing figure 5, we can distinguish four phases characterized by different interactions:

During the first phase, country 1 harvests a higher proportion of his stock under proactive regime compared to reactive regime. This is understandable because country 1 is gradually losing the stock, hence he has less incentive to conserve it for the future. In contrast, there is no discernible policy change for country 2. This happens because during the early stage of the transition, country 2's policy is entirely governed by maximizing current payoffs: country 2's conservation efforts would primarily benefit the major owner, and the time of gaining the major ownership is still far away. Country 2 is essentially a free-rider, and predicting the future correctly has no bearing for its policy (Figure 5). The stock responds to the increased total harvest under proactive management by declining earlier compared to reactive management.

During phase two, lasting until about the middle of the transition, country 2 starts to harvest more conservatively under proactive management compared to reactive management. This happens because its policy choices start to reflect also the future value of the stock: country 2's policy starts impacting the total stock significantly and he can expect to become the major benefactor of his own conservation efforts when he eventually is becoming the major stock owner. Nevertheless, country 2 is still free-riding on country 1's conservation efforts, albeit less so than before. Country 1's policy during this period is more varied. Most of the time he is harvesting similarly or less under the proactive compared to reactive management. Reduced harvest can occur because the stock is smaller and because country 2's increased conservation incentive allows reaching a Nash equilibrium characterized by less intensive competition. The net effect of reduced harvest by country 2 and possibly by country 1 too is that the stock decline is halted and it may even start to recover slowly.

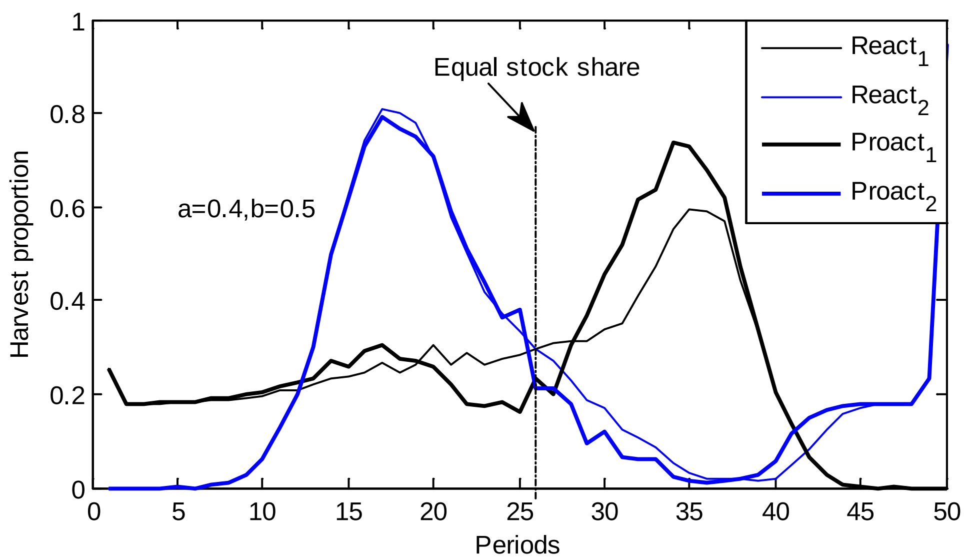

Figure 5: *Proactive vs. reactive management: policy dynamics (mean trends of 500 runs): a=0.4, b=0.5, r=6%, trend=0.08°C/yr, sigma=0.2°C/yr nbins=20, sbins=20, tbins=30; initial stock R0=0.6; initial temperature T0=10°C.*

Phase three is characterized by consistent differences between proactive and reactive management. Country 1 becomes the minor stock owner and increases his harvest ratio as he no longer would be the main benefactor of his conservation efforts; also, saving stock for the future pays off less and less as his stakes are diminishing. In contrast, country 2 maintains his more conservative policy: it is in his interest to allow the stock to gradually rebuild towards more productive levels. This may even involve no fishing at all for a period, echoing Clark's finding (1990) that the single owner's optimal strategy is to reach the optimal stock level at the quickest possible pace. Consequently, the stock is recovering quickly.

Finally, during the last phase, in the end of transition, the minor owner's policy is shaped by immediate profit maximization and becomes indistinguishable between proactive and reactive management. Country 2 is approaching sole ownership and can take advantage of the rebuilding of the stock, consequently, it can often harvest more intensively under proactive than under reactive management.

3.2.3 Effect of stock growth, concentration profile and discount rate

Figure 6 summarizes the influence of two biological key parameters in the model, growth ratio (a) and concentration profile (b). The minimum stock level during the ownership transition ends up higher if the value of *a* and/or *b* is greater. The greater a is, the faster stock can recover from overexploitation. The mechanism behind the effect of *b* is different: a high value of *b* implies the stock is a low-schooling one and costly to fish if stock level is low, it is then the high exploitation costs that has prevented stock from being over exploited.

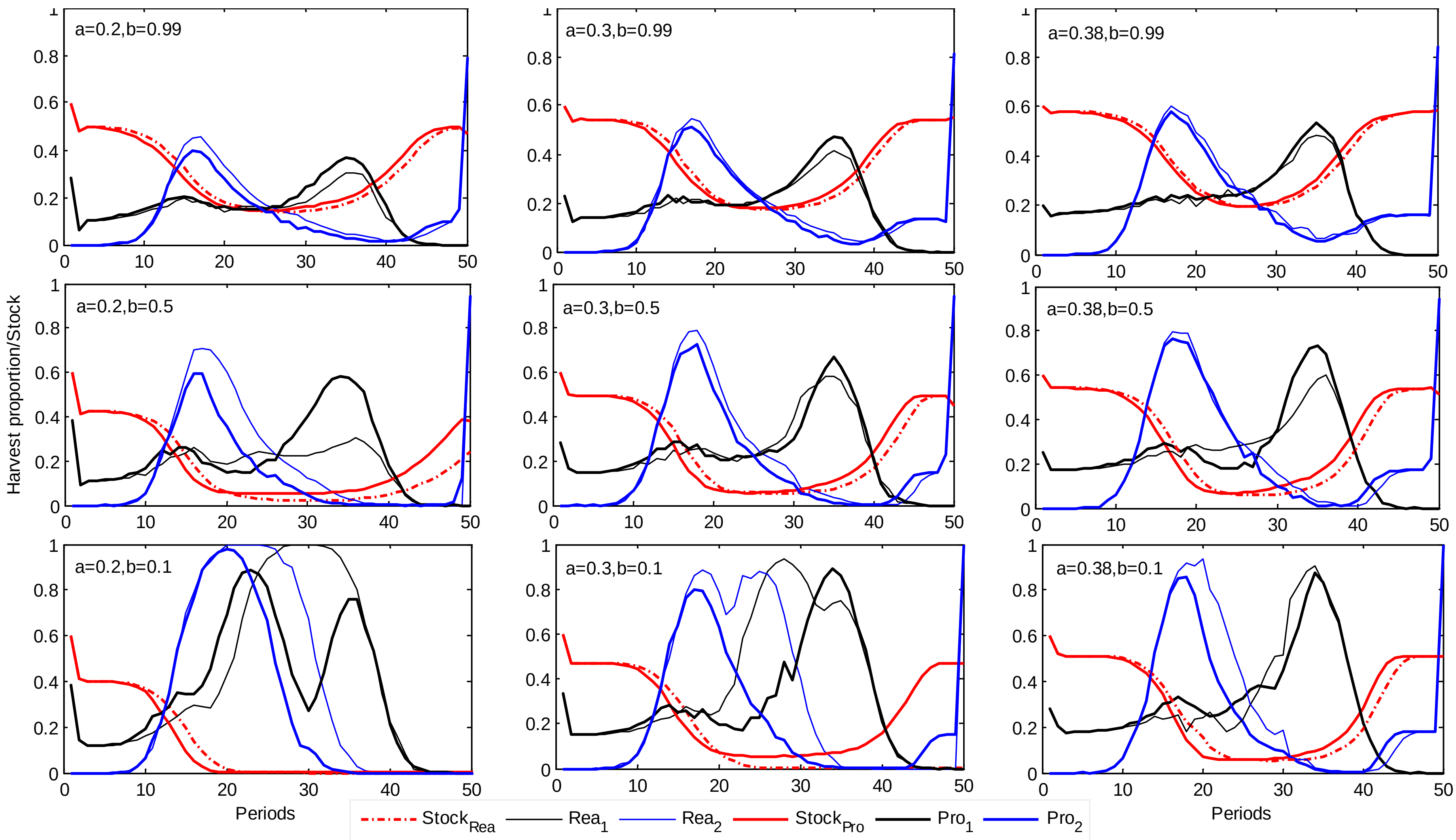

Figure 6: *Proactive management: sensitivity tests: trend=0.08 ° C/yr, nbins=20 sbins=20, tbins=30; R0=0.6 ,T0=10 ° C/yr. In the legend, pro=proactive,rea=reactive.*

The described four-phase strategic interactions (section 3.2.2) resulting from correct prediction of temperature trend persists across our simulations, though with some variations. However, increase in *b* has tendency of diminishing player 1's conservation incentive during phase 2. This result is intuitive because if fishing down a small stock gets harder and costlier, player 1's conservation efforts during phase 2 will not be paid off during phase 3. Actually, the more player 1 conserves at phase 2 (and when he is still the main owner) affects remarkably the asymmetry of proactive stock trajectory, as well as the level of stock divergence between two management regimes.

As discussed in section 3.2.1, proactive management can reduce, but not eliminate, risk of stock collapse (figure 6). This happens primarily because country 2 has increased incentive to conserve the stock under proactive management.

The effect of discount rate (r) is trivial in our simulation. A low *r* implies that the manager value future payoff, hence he tends to spread his harvest more over time. Correspondingly, we observe that the stock level is higher throughout when discount rate is lower, other things being equal.

3.3 Prediction of correct temperature trend

Until now, we have assumed that the proactive managers have accurate knowledge about the future temperature trend (this issue does not arise under reactive management). This is clearly unrealistic as there are great uncertainties in predictions for future temperature increase. Therefore we need to evaluate what is the influence of using an incorrect estimate of temperature change.

With proactive management, predicting correct trend matters but in a subtle way: predicting a slower trend than the real one($trend_{bwd} = 0.04°C/yr, trend_{fwd} = 0.08°C/yr$) leads to a harvest policy lagging behind the optimal one; while an over-prediction of temperature trend ($trend_{bwd} = 0.12°C/yr, trend_{fwd} = 0.08°C/yr$) will lead to a harvest policy that is ahead of the optimal one (figure 7). In the former case, underestimation of future gain makes player 2 less motivated to conserve stock when he is the minor owner; similarly, underestimating future stock loss, player 1 catches less fish than he in the optimal case could do after becoming minor player. It is worth noting that trend parameter does not affect equilibrium stock level ex-ante and ex-post transition, as it does to the minimum stock level.

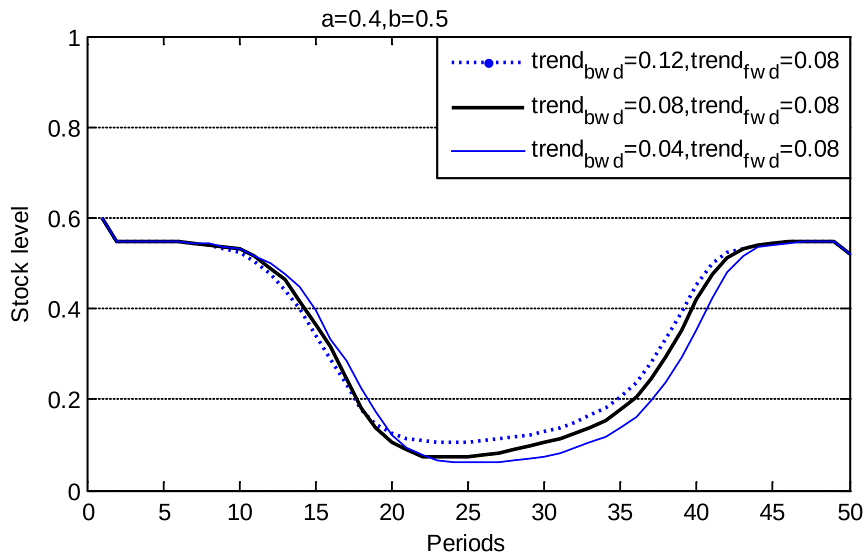

Figure 7: Prediction of correct trend*: mean trends (500 runs) of total stock level under proactive management: discount rate r=6%, trend unit is °C/yr , initial stock R0=0.; initial temperature T0=10°C*

4 Conclusions

Our model has attempted to simulate how climate warming induced stock displacement affects international fishery management based on annually updated harvest policies. The presented split stream model certainly is a simplified version of the reality, but it does capture some essential characteristics of some migratory stocks.

Warming induces fish stock spilling from one country to another, and this may challenge existing management agreements. For example, mackerel was earlier an occasional visitor to Icelandic waters, but it has in recent years become abundant enough to support a sizeable commercial fishery (ICES 2010). This is problematic in the international context because Iceland is not a coastal state for mackerel, not part of the agreed management plan, and its fishery is not accounted for in the quota regulation.

Responding to climate-induced gradual shift of stock ownership, reactive and proactive management trigger different policy dynamics:

- With reactive management, the main owner has a stronger conservation incentive than the minor owner who can free-ride the main owner's conservation efforts; consequently, the main owner harvests a lower proportion of his stock than the minor owner. In this case, two countries behave symmetrically.
- With proactive management, the roles of two countries become inherently asymmetric. When country 1 is the major owner but anticipates loosing the stock, it harvests more intensively than when it has no information about diminishing stock share. When country 2 is the major owner, and even for some time before, it knows that the future

will be even more in his favor, and it is in his best interests to recover the stock as quick as possible becomes his dominant strategy. At this stage, country 1 may become very aggressive because he knows that the stock is disappearing from his territory for good and he is enjoying the last chances to exploit the stock.

In comparison to the noticeable changes in harvest policies caused by shift of management regime from reactive to proactive, the impact of regime shift on total stock level and cash flows is more subtle. Short decision cycle and slow temperature trend only explain part of the story. More importantly, strategic responses of two countries under proactive management to a certain degree compensate each other, helping to mitigate the effects on stock and payoff. Worth noting is that anticipation of the change in ownership does not change the most prominent feature of the harvest policies of a shared stock: the main owner conserves more than the minor one, and the minor owner tends to free ride the main owner's conservation efforts. Nevertheless, proactive management benefits the stock and both of the players. These benefits mostly originate from the former minor owner's anticipation of increasing stakes in the stock, and hence, increased incentives for less competitive and more sustainable harvest. This benefits the stock and also the player who is losing the stock.

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Appendix 1: ***fishing costs and concentration profile***

Let C_t^i be the catch rate of country i at time t. The expression can be written as following:

$$C_t^i = \frac{\theta_t^i R_t - s_t^i}{\Delta t}$$

where θ_t^i is the split ratio at season t for country i, R_t is total stock before harvesting at season t, s_i is the stock size in country i after harvesting. Δt is the time span, equal to 1 in the model. We assume that a uniform catch rate is maintained within a season.

Total catch during season t then becomes:

$$catch_t^i = \int_0^1 C_\tau^i \, d\tau = \theta_t^i R_t - s_t^i \qquad (1)$$

The stock (x) change over time *t* in a country can be written as following:

$$x_\tau^i = \theta_t^i R_t - \tau * C_t^i \qquad (2)$$

The concentration profile ρ is the function of biomass or stock x:

$$\rho(x_\tau^i) = \left(\frac{x_\tau^i}{\theta_t^i}\right)^b, \quad i = 1,2 \qquad (3)$$

where b is a non-negative parameter, x_t^i is sub-stream stock size(or biomass) in country i. If *b=1*, it indicates stock is uniformly distributed and reducing the stock will not affect fish distribution area but the density; If b=0, it shows stock density is constant, representing stock of super schooling type. In our model, we look at a more general case with $0 < b < 1$.

Total effort by country i at period t is E_t^i:

$$E_t^i = \frac{C_t^i}{q\rho(x_t^i)} \qquad (4)$$

where q is the catch-ability, a parameter indicating how easy to catch certain fish species.

p_t^i is the escapement proportion, a decision variable, indicating what proportion of fish in his stream that the manager of country i decides to leave behind at season *t*:

$$p_t^i = \frac{s_t^i}{\theta_t^i R_t} \qquad (5)$$

Now we can derive the function for total costs in season t:

$$cost_t^i = \int_0^1 c_e E_\tau^i d\tau = \frac{c_e}{q}\int_0^1 \frac{C_\tau^i}{\rho\,(x_\tau^i)} d\tau = \frac{{\theta_t^i}^b c_e(\theta_t^i \boldsymbol{R_t} - s_t^i)}{q\,\Delta t}\int_0^1 (x_t^i)^{-b} dt \qquad (6)$$

Where c_e is the cost per unit of effort, assuming a constant parameter and same for both countries in game.

We know that:

$$\int_0^1 (x_\tau^i)^{-b} d\tau = \frac{\left(\theta_t^i R_t\right)^{1-b} - {s_t^i}^{1-b}}{C_t^i\ (1-b)} = \frac{\left(\theta_t^i R_t\right)^{1-b}(1-{p_t^i}^{1-b})}{C_t^i\ (1-b)} \quad (7)$$

Plug equation (5) and (7) into equation (6), we obtain total seasonal cost function for country i :

$$\boldsymbol{cost_t^i = \frac{\theta_t^i\, c_e\, {R_t}^{1-b}(1-{p_t^i}^{1-b})}{q\ (1-b)}} \quad \mathbf{0} < b < 1\ , \mathbf{i} = \mathbf{1}, \mathbf{2} \qquad (\mathbf{8})$$