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Extracting spatial resources under possible regime shift

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Abstract

How will countries harvesting mobile renewable resource react to the threat of climate change? We address the non-cooperative exploitation of a migratory renewable resource in the presence of possible regime shift that affects its movement. Motivated by the anticipated effects of climate change, we model a regime shift that will alter the spatial movement patterns of the resource at some point in the future. We develop a stochastic spatial bioeconomic model to address the effects of this class of regime shift on non-cooperative harvest decisions made by decentralized owners such as countries exploiting a migratory fish or other natural resource stock. We find that the threat of a future shift modifies the standard golden rule and may induce more aggressive harvest everywhere, irrespective of whether the owner will be advantaged or disadvantaged by the shift. We also identify conditions under which the threat of regime shift induces owners to reduce harvest rates in advance of the shift. Our analysis suggests that different property rights structures (single ownership vs common property) or heterogenous growth can give rise to previously unexplored incentives and can even reverse conventional wisdom about how countries will react to the threat of environmental change.

Keywords: Regime shift; spatial management; renewable resources; property rights

JEL Classification Codes: C73; H23; H73; Q22

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1 Introduction

Because renewable resources such as fish, water, game, and infectious diseases are mobile, extraction and productivity in one location affect economic opportunities in other locations. The resulting spatial externality can be dealt with by a central planner using a number of instruments including spatial taxes, limits of extractive effort, or other means. But in practice, many spatially connected renewable resources are managed via private property rights where autonomous entities (such as countries, villages, cooperatives or individual property right owners) choose their own extraction rates, taking as given the mobility of the resource and the extraction of their competitors. Indeed spatial property rights are implicitly the default approach for managing many renewable resources,[1] despite their potential for inducing spatial externalities driven by resource mobility. This general problem has become a canonical model in spatial resource economics. The main finding from that literature is that non-cooperative extraction will necessarily entail over-extraction (relative to a social optimum) because no single owner is incentivized to account for the effects of her extraction on others (Kaffine and Costello 2011; Fenichel et al. 2014). The aggregate effects of this non-cooperation can range from extremely deleterious (see White and Costello (2014)) to practically insignificant (see Gisser and Sanchez (1980)).[2]

This interesting and growing literature has evolved in a deterministic setting in which productivity and dispersal functions are common knowledge and fixed over time. Rather, a growing scientific literature suggests that global change may induce regime shifts that affect resource dynamics, and thus may alter future economic incentives and returns. While there are many types of documented (and speculated) regime shifts, they generally share three common features. First, regime shifts tend to be abrupt - over a relatively short period

[1]For example, migratory waterfowl and fish are managed by the multiple countries whose boundaries they traverse, groundwater is managed by overlying landowners, game is often managed by private wildlife management areas or hunting clubs, and invasive species are controlled by adjacent landowners.

[2]See Stavins (2011) for empirical evidence on tragedies of the commons.

of time they can shift the state of the world from one state to another state. Second, the occurrence date of a regime shift is probabilistic - while scientists might have a sense of the likelihood of a regime shift occurring, we do not know with certainty when it will occur. Third, many regime shifts are thought to be irreversible - once the shift occurs, due to hysteresis, it may be difficult to return to its pre-shift state (Scheffer et al. 2001).[3]

Facing this type of regime shift fundamentally alters the constraints and incentives faced by property owners who extract mobile renewable resources. Yet the effects of spatial regime shift on non-cooperative extractive behavior have not been completely analyzed. As a prominent example of the kind of regime shift we tackle, consider effects of climate change on the spatial range or dispersal of a migratory fish species such as tuna. Under pre-shift parameters, suppose tuna tend to migrate equally between countries A and B. But if a regime shift were to occur, the migratory pattern may shift to favor country A. If that kind of shift were predictable, it would clearly alter the incentives of countries A and B: Recognizing the improvement in future conditions, country A might be willing to forego harvest today to build resource stocks and capitalize on improved future conditions.[4] And recognizing the deterioration of future conditions, country B would, intuitively, increase its current extraction. These intuitive predictions of countries' behaviors are consistent with results in Hannesson (2007) and Diekert and Nieminen (2015), but they turn out to be vulnerable to strategic interactions across players. This stylized example illustrates our key inquiry: How will the presence of a possible future regime shift alter strategic interactions of private property owners who extract a mobile natural resource? Will the threat of regime shift always entail a loss of precaution by one agent and an increase in precaution by the

[3] Issues of uncertainty and irreversibility have been analyzed in the context of the timing of environmental policy adoption (see Ulph and Ulph (1997) for an early contribution). They also matter significantly for problems of voluntary contributions to global public goods (see Elsayyad and Morath (2016) for issues raised by technology transfers, or Nordhaus (2015) and Harstad (2016) for discussions on the design of a climate treaty).

[4] See Costello et al. (2001) and Carson et al. (2009) for aspatial models of resource management with environmental predictions.

other? We address these and related questions in this paper.

This paper builds on an emerging literature on natural resource management that addresses related questions, but in a context where the random occurrence of a regime shift inflicts a permanent loss to all harvesters. Polasky et al. (2011) and Ren and Polasky (2014) focus on the optimal management whereas Fesselmeyer and Santugini (2013), Sakamoto (2014), Miller and Nkuiya (2016), and Diekert (2017) analyze the strategic management of a common pool resource. These contributions consider only scenarios in which all harvesters are identical and do not explicitly take into account the spatial movement of the resource. But since we are primarily interested in strategic interactions, our analysis investigates cases in which regime shift will alter the distribution of resource stocks so as to create winners and losers.[5] We thus explicitly take into account the spatial movement of the resource and consider heterogenous harvesters subject to different, but connected, economic, environmental, and biological conditions.

Our analysis contributes to an interesting class of economic papers addressing renewable resource management under the prospect of regime shift in the resource distribution, which advantages one patch and disadvantages it in the other patch. To gain traction on this challenging problem, existing papers rely on fairly extreme assumptions: among others, each patch is owned by a single agent and economic and biological conditions are identical across patches.[6] Prominent contributions include Diekert and Nieminen (2015) and Liu and Heino (2013) that concentrate on deterministic regime shift processes with finite transitional periods, and find that the harvester gaining the stock conserves it, whereas the one losing the stock acts aggressively. Hannesson (2007) considers a random regime shift process and exogenously assumes that escapement is constant within each environmental regime. He

[5]For example, climate change may irreversibly trigger local scarcity or extinction in the sub-polar regions and invasion in the arctic for many species of fish (Cheung et al. 2009).

[6]In reality, habitat, salinity, water currents, nutrients, oxygen concentration and extraction costs may vary across patches leading to heterogenous biological, economic, and environmental conditions.

finds that the stock cannot go extinct whenever the intrinsic growth parameter is not too low (and smaller than one) and the shares of the stock are sufficiently heterogenous. In this paper, we consider the strategic interactions across agents and adopt a feedback approach such that in a given period, escapement endogenously depends on environmental conditions and the resource stock. To the best of our knowledge, this setting is novel and delivers new harvest incentives relative to the existing literature.

The simplest case is when marginal harvesting costs are constant. In that setting, analytical findings reveal that harvesters in the advantaged patch conserve the resource stock in the initial period whereas those in the disadvantaged patch increase initial harvest in response to the possible future shift in the resource distribution. In the steady state, we identify two opposing mechanisms through which uncertainty about the shift affects harvest decisions. The first is a direct effect of the shift that tends to enhance harvest in the disadvantaged patch (relative to the no-shift case). The second mechanism is the strategic effect that tends to reduce harvest incentives in the disadvantaged patch because harvesters in the advantaged patch conserve the resource stock in the short run. Surprisingly, we find that each of these mechanisms can dominate the other depending on environmental, biological, and economic conditions. To better understand the effects of uncertainty about the shift, we also investigate the case in which harvesting costs decline as the resource stock increases. We find that a stock effect plays a pivotal role in extraction incentives. When the stock effect is sufficiently strong, we find that the conventional wisdom is weakened or even reversed.

The paper unfolds as follows. Section 2 presents the model. Section 3 focuses on behavior following the regime shift. Section 4 analyses harvesters' incentives in anticipation of a future regime shift. Section 5 extends the analysis to the case where each patch is itself common property. Section 6 concludes.

2 The model

A renewable resource stock is distributed heterogeneously across an ecosystem consisting of two areas or "patches," A and B. Patches may differ in shape, size, environmental, and economic characteristics; for example, patches may be countries, private lands, or communal harvesting areas. The time index is denoted by $t = 1, 2, 3, ...$ and h_{jt} represents the extraction in patch j during period t. The resource stock at the beginning of period t in a given patch j is denoted by x_{jt} while the remaining residual stock (or "escapement") e_{jt} is defined as $e_{jt} \equiv x_{jt} - h_{jt}$, which is the post-harvest stock at the end of period t. As such, when there is no harvest, say, in patch j, the current escapement is equal to the current resource stock: $e_{jt} = x_{jt}$.

Resource mobility will induce a spatial connection across patches. In period t, a fraction K_{ijt} of patch i's resource stock moves to patch j, $i \neq j$ while the fraction K_{iit} stays within patch i. Therefore, $K_{ijt} + K_{iit} \leq 1$ for $i, j \in \{A, B\}$ with $i \neq j$. In the case where this inequality is not binding, a fraction of the resource population living in patch i moves out of the system at date t. The current resource distribution across patches is determined by the 2×2 dispersal matrix K_t, whose element K_{ijt} is a binomial random variable that either takes the value D_{ij} (before the shift), or D^s_{ij} (after the shift).

At the beginning of the initial period, dispersal is in its pre-shift form, so $K_{ij0} = D_{ij}$. Regime shift occurs at an unknown future date denoted by $\tau > 0$ (that may be infinite), and dispersal irreversibly shifts to regime s, characterized by a dispersal matrix with terms D^s_{ij}. We assume that the shift will give a bio-physical advantage to region A and a disadvantage to region B, so $D^s_{BA} > D_{BA} \geq 0$, $D_{BB} > D^s_{BB} \geq 0$, $D_{AB} > D^s_{AB} \geq 0$, and $D^s_{AA} > D_{AA} \geq 0$. Figure 1 illustrates the pre-shift (top panel) and post-shift (bottom panel) migration patterns where the arrow thickness and size of the patches indicate the strength of connectivity. Dispersal is thus characterized as follows:

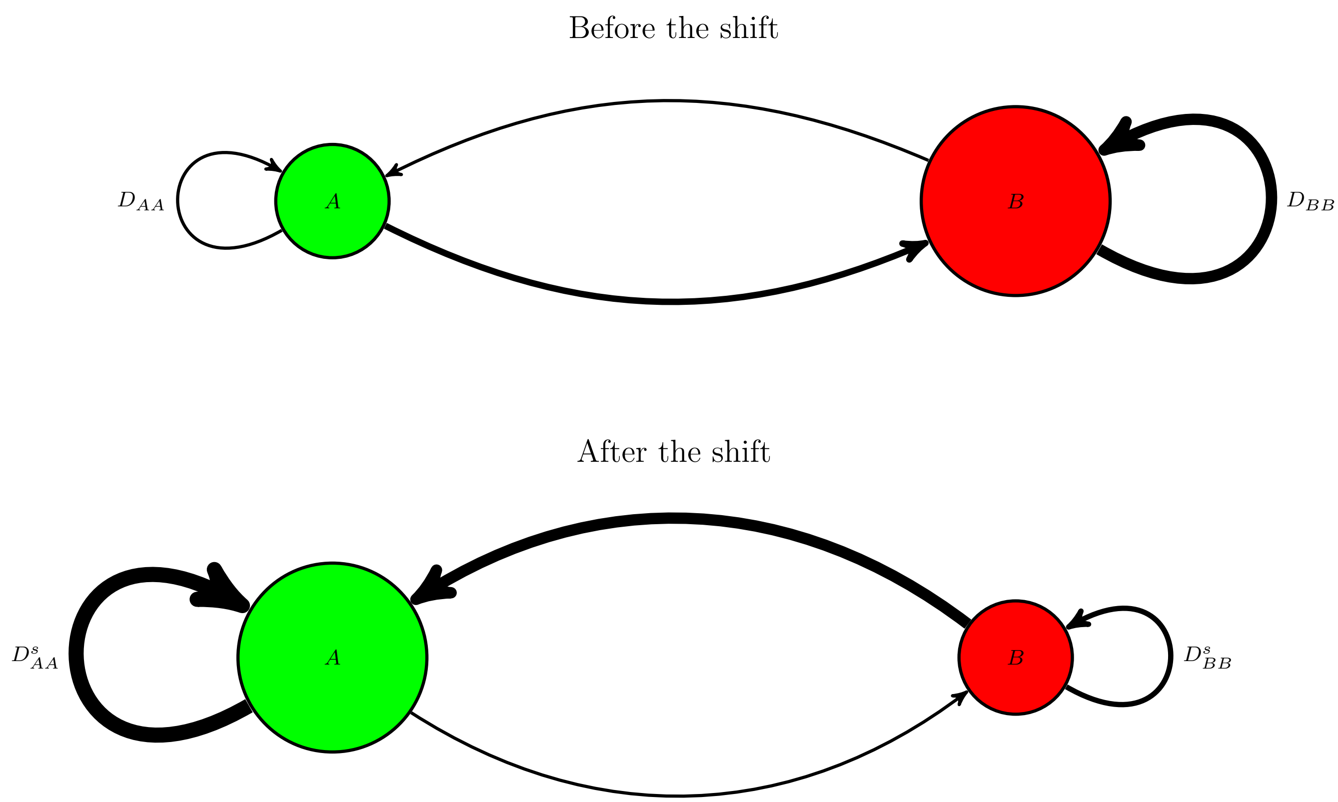

Figure 1: Effects of the shift on the migration pattern.

$$K_{ijt} = \begin{cases} D_{ij} & \text{for} \quad t < \tau, \\ D^s_{ij} & \text{for} \quad t \geq \tau \quad \text{for} \quad i, j = A, B. \end{cases}$$

The regime shift process described above can be represented by the stochastic process ℓ_t that may either take the values I (for "initial") or S (for "shift") with transition probabilities

$$P(\ell_{t+1} = S | \ell_t = S) = 1; \quad P(\ell_{t+1} = S | \ell_t = I) = \lambda, \tag{1}$$

$$P(\ell_{t+1} = I | \ell_t = I) = 1 - \lambda. \tag{2}$$

At the outset of the initial period, the resource stocks x_{A0} and x_{B0} in patches A and B are known. In the absence of harvest, the resource stock grows according to the growth and dispersal equation

$$x_{jt+1} = \sum_{i=A,B} g_i(x_{it})K_{ijt}, \quad j = A, B, \tag{3}$$

where $g_i(.)$ represents patch i's growth function that satisfies standard conditions. It is increasing, concave and twice continuously differentiable.

In the presence of harvest, growth depends on escapement, so the law of motion becomes

$$x_{jt+1} = \sum_{i=A,B} g_i(e_{it})K_{ijt}, \quad j = A, B. \tag{4}$$

The evolution of the resource population is stochastically determined by harvest, growth, and environmental conditions K_{ijt}. The timing is thus: the present period stock (x_{jt}) is observed and then harvested (h_{jt}) giving escapement (e_{jt}), which then grows ($g_j(e_{jt})$), and disperses to itself (K_{jjt}) and to the other patch (K_{jit}).

Suppose now that each patch is owned by a single entity. For example, this could be a Territorial User Right Fishery (TURF), a farm on which bees reside, or a country hosting migratory fish, game, or waterfowl. We allow for, but do not require, prices and costs to be patch specific. Denote by p_j the unit price associated with patch j; costs may depend on the stock size and are treated later in this section.

The harvester's period-t harvest is $(x_{jt} - e_{jt})$ so, in the absence of harvesting costs, her period-t profit is $p_j(x_{jt} - e_{jt})$. In the presence of harvesting costs, the period-t profit for harvester j is simply the integral of profit flows over the entire extractive period and can be written as follows

$$\pi_{jt} = \int_{e_{jt}}^{x_{jt}} [p_j - c_j(v)]dv. \tag{5}$$

Here, the term $c_j(v)$ is the marginal harvesting cost when the available stock is v. The integral $\int_{e_{jt}}^{x_{jt}} c_j(v)dv$ in Equation 5 represents the total cost of harvest during period-t, which may be patch specific. We assume that $c_j'(v) \leq 0$, that is, the marginal cost decreases in the resource stock level. The rationale is that at a given date, a larger resource stock entails a smaller marginal harvest cost. In the case where $c_j'(.) = 0$, the profit in patch j is linear in harvest; profit is strictly concave in harvest as long as $c_j'(.) < 0$ (i.e. a *stock effect* is present). To determine whether or not the marginal cost is constant is an empirical issue (see for instance, Atewamba and Nkuiya (2017), for the case of non-renewable resources). We will show that a sufficiently strong stock effect can fundamentally alter harvest incentives, particularly in the presence of regime shift. We separately examine both cases below.

Prior to the shift, i.e. for any date $t < \tau$, the present value payoff function in patch $j = A, B$ is given by

$$\sum_{k=t}^{\tau-1} \delta^{(k-t)} \left[p_j(x_{jk} - e_{jk}) - \int_{e_{jk}}^{x_{jk}} c_j(v)dv \right] + \delta^{\tau-t} W_j(x(\tau)),$$

where $W_j(x(\tau))$ represents the period-τ continuation value of the problem for that harvester and δ is the discount factor. We next solve the post-shift problem and use its result to derive the complete solution for the uncertain regime shift problem presented above.

3 The post-shift problem

In this section we examine the game between harvesters that will occur *following* the regime shift. We follow the growing literature, starting with the seminal paper of Reed (1979), that uses escapement as the control variable.[7] In this setting, the patch-j harvester chooses an escapement strategy to maximize her present discounted profits taking as given the escapement strategy of her rival. Thus, immediately following the regime shift, the owner of

[7] This is a benign assumption because harvest and escapement are linked by the identity $h_t \equiv x_t - e_t$. This approach has subsequently been adopted by numerous authors including Costello and Polasky (2008), Costello et al. (2015), Kapaun and Quaas (2013), and many papers cited therein.

patch j solves:

$$W_j(x_\tau) = \max_{e_{jt}, t \geq \tau} \sum_{k=\tau}^{+\infty} \delta^{(k-\tau)}[p_j(x_{jk} - e_{jk}) - \int_{e_{jk}}^{x_{jk}} c_j(v)dv],$$

subject to (4) with $x_\tau \equiv (x_{A\tau}, x_{B\tau})$ given.

We seek a Markov Perfect Nash Equilibrium (MPNE), which will define the equilibrium harvest decisions $(e_A(x_A, x_B), e_B(x_A, x_B))$ following the regime shift. The escapement decision rule $(e_A(x_A, x_B), e_B(x_A, x_B))$ is a MPNE if, given the resource stock at the outset of period τ ($x_\tau \equiv (x_{A\tau}, x_{B\tau})$), at any date $t \geq \tau$, $\{e_j(x_{As}, x_{Bs}), s \geq t\}$ is a solution to the optimization problem above. The feedback Nash equilibrium is a MPNE and can be found by specifying and manipulating the Bellman Equations for both players. The Bellman equation for the harvester operating in patch j can be written as:

$$W_j(x_t) = \max_{e_{jt}} \left\{ p_j(x_{jt} - e_{jt}) - \int_{e_{jt}}^{x_{jt}} c_j(v)dv + \delta W_j(x_{t+1}) \right\},$$

which is subject to (4) with the initial resource stock $x_\tau \equiv (x_{A\tau}, x_{B\tau})$ given.

The first-order conditions require

$$p_j = c_j(e_{jt}) + \delta \sum_{i=A,B} \frac{\partial W_j}{\partial x_{it+1}}(x_{t+1}) g_j'(e_{jt}) D_{ji}^s, \quad j = A, B. \tag{6}$$

This equation states that patch J chooses her escapement level to equate the resource price with its augmented marginal cost, which is the marginal cost, augmented by the value forgone by harvesting today rather than keeping the resource for future harvests. The challenge is that the form of the value function $W_j(x)$ is unknown. However, its properties can be derived given the structure of this problem. These derivations allow us to characterize the equilibrium over the post regime shift phase, summarized as follows:

Lemma 1. *Over the post regime shift phase, the following results hold.*

(i) Patch j is harvested down to the escapement level e_j, which is stock independent and is solution to

$$p_j - c_j(e_j) = \delta D^s_{jj}[p_j - c_j\left(g_j(e_j)D^s_{jj} + g_i(e_i)D^s_{ij}\right)]g'_j(e_j), \quad i = A, B \quad \text{and} \quad i \neq j. \tag{7}$$

(ii) Each patch's equilibrium resource stock reaches its steady state in one period, and is thereafter time-independent.

Proof. All proofs reside in the appendix. □

Equation 7 implicitly defines harvester j's best response function, $e_j(e_i)$, and suggests that her actions depend on the flow of the resource to her own patch (D^s_{ij}), but that $e_j(e_i)$ does not depend on D^s_{ji} nor $D^s_{ii}, i \neq j$, which are terms defining the resource flow to the other patch. This is the case because harvester j does not ascribe any value to additional resource stock located out of its boundaries (*i.e.* $\frac{\partial W_j}{\partial x_{it}}(x_t) = 0$ for $i \neq j$) because she knows that the best response of her rival would be to harvest any additional stock that arrives. Importantly, this is a result of the analysis, not an assumption. The equilibrium escapement level corresponds to the intersection of best response functions $e_A(e_B)$ and $e_B(e_A)$. We can also employ this analysis to identify the equilibrium escapement level of the no-shift case, in which the resource distribution is deterministic and never shifts. We denote the no-shift variables by a tilde (e.g. $\tilde{e}_{jt}$). They can be retrieved from Condition 7 by replacing (for $i, j = A, B$) D^s_{ij} by D_{ij} and $(x_{A\tau}, x_{B\tau})$ by (x_{A0}, x_{B0}). Because the no-shift case takes the same form as the post shift case (albeit with different parameter values), the equilibrium escapement level of the no-shift case is also time and stock independent (see Lemma 1). The equilibrium resource stock outcome of the no-shift case converges to its steady state in the second period of the game.

To better understand the effects of the shift, we next compare the outcomes of the post regime shift case and the no-shift case.

Proposition 1. *Assume that marginal costs are constant (i.e., $c'_j(x) = 0$ for all x, $j = A, B$). Over the post regime shift phase, the following results hold.*

(i) For $j = A, B$, e_j is implicitly defined by:

$$g'_j(e_j) = \frac{1}{\delta D^s_{jj}}. \tag{8}$$

(ii) Relative to the no-shift case, the equilibrium escapement level in the post regime shift problem is larger in patch A and smaller in patch B: $e_{Bt} \leq \tilde{e}_{Bt}$ and $e_{At} \geq \tilde{e}_{At}$ for all $t \geq \tau$.

(iii) At any date $t \geq \tau + 1$, the equilibrium resource stock (x_{jt}) in patch j is greater relative to the no-shift case ($\tilde{x}_{jt}$) if and only if $D^s_{ij} > \bar{D}^s_{jx}$.

(iv) At any date $t \geq \tau + 1$, the equilibrium harvest rate (h_{jt}) in patch j is larger relative to the no-shift case ($\tilde{h}_{jt}$) if and only if $D^s_{ij} > \bar{D}^s_{jh}$, where $\bar{D}^s_{jx}$ and $\bar{D}^s_{jh}$ depend only on δ, D^s_{jj}, D_{AA}, D_{BB} and D_{ij}, $i = A, B$, $i \neq j$, and are given in the appendix.

Result (i) of Proposition 1 suggests that harvester $j = A, B$ chooses her escapement level to equate the biological return of the resource discounted by the patch retention rate (D^s_{jj}) and the financial rate of return. This is a non-cooperative "golden rule" for spatial growth models (Kaffine and Costello 2011), where D^s_{jj} acts like an additional discount factor. Result (ii) of Proposition 1 is driven by the facts that (a) in each patch, the equilibrium escapement level and the patch retention rate are positively related; (b) patch B's retention rate decreases with the shift whereas this result is reversed for patch A. Results (iii) and (iv) of Proposition 1 lead to an unexpected outcome. Despite the fact that the shift inflicts biophysical damages to patch B (*i.e.*, $D^s_{AB} < D_{AB}$ and $D^s_{BB} < D_{BB}$), the resource stock in patch B may be larger depending on the resource growth and spatial characteristics. In addition, harvester B may have incentives to increase her harvest compared to the no-shift case.

We have so far addressed the cases where the shift has already occurred and where the shift will never occur. We next use these results to completely characterize the equilibrium behavior prior to the shift.

4 Non-cooperative behavior in advance of a regime shift

We have focused on analyzing the deterministic spatial game induced either following an irreversible regime shift or in the complete absence of regime shift. But our central research question asks how harvesters interact under the *threat of a possible regime shift in the future.* In this section, we focus on harvesters' responses to the prospect of a future regime shift. Taking the escapement strategy of the other harvester as given, harvester $j = A, B$ chooses the escapement strategy that maximizes her expected present discounted net profits

$$V_j(x_t) = \max_{e_{js}, s \geq t} \mathbb{E} \sum_{k=t}^{+\infty} \delta^{(k-t)} [p_j(x_{jk} - e_{jk}) - \int_{e_{jk}}^{x_{jk}} c_j(v) dv], \tag{9}$$

which is subject to (4). We are interested in identifying a MPNE that we next derive using the feedback Nash equilibrium approach. Harvester j's value function given in (9) satisfies:

$$V_j(x_t) = \max_{e_{jt}} [p_j(x_{jt} - e_{jt}) - \int_{e_{jt}}^{x_{jt}} c_j(v) dv + \delta(1 - \lambda) V_j(x_{t+1}) + \delta \lambda W_j(x_{t+1}^s)], \tag{10}$$

subject to (4), where $x_{jt+1}^s = g_j(e_{jt}) D_{jj}^s + g_i(e_{it}) D_{ij}^s$ and $x_{jt+1} = g_j(e_{jt}) D_{jj} + g_i(e_{it}) D_{ij}$. The first two terms on the right hand side of Equation 10 are just contemporaneous revenue and cost from harvesting the resource in patch j. The third term is the discounted expected value in the case where the regime shift does not occur at the end of period t (this occurs with probability $(1 - \lambda)$). The final term is the discounted expected value in the case where regime shift does occur at the end of period t, in which case we invoke the value functions from the post regime shift problem derived in Section 3 (this occurs with probability λ).

To interpret Equation 10, it is instructive to rewrite it as follows:

$$V_j(x_t) = \max_{e_{jt}}[p_j(x_{jt} - e_{jt}) - \int_{e_{jt}}^{x_{jt}} c_j(v)dv + \tilde{\delta}_j V_j(x_{t+1})], \tag{11}$$

where $\tilde{\delta}_j = \delta + \delta\lambda[W_j(x^s_{t+1}) - V_j(x_{t+1})]/V_j(x_{t+1})$ can be thought of as a risk-adjusted discount factor. Equation 11 can be interpreted as the Bellman equation associated with a deterministic model in which the discount rate endogenously accounts for the possibility of regime shift.

The first-order condition for this maximization problem can be written as

$$p_j = c_j(e_{jt}) + \delta\lambda g'_j(e_{jt}) \sum_{i=A,B} \frac{\partial W_j}{\partial x_{it+1}}(x^s_{t+1}) D^s_{ji} + \delta(1-\lambda) g'_j(e_{jt}) \sum_{i=A,B} \frac{\partial V_j}{\partial x_{it+1}}(x_{t+1}) D_{ji}, \quad j = A, B.$$

Since x_{At+1}, x_{Bt+1}, x^s_{At+1} and x^s_{Bt+1} depend on e_{At}, e_{Bt} and do not explicitly depend on x_{At} and x_{Bt}, this optimality condition suggests that e_{At} and e_{Bt} are time and stock independent. This intuition is verified in the following lemma.

Lemma 2. *Prior to the spatial regime shift, the following results hold:*

(i) The pair (e_A, e_B) constitutes a MPNE, where e_j is implicitly defined as follows:

$$\begin{aligned} p_j - c_j(e_j) = {} & \delta\lambda D^s_{jj}[p_j - c_j\left(g_j(e_j)D^s_{jj} + g_i(e_i)D^s_{ij}\right)]g'_j(e_j) \\ & + \delta(1-\lambda)D_{jj}[p_j - c_j\left(g_j(e_j)D_{jj} + g_i(e_i)D_{ij}\right)]g'_j(e_j), \quad i \neq j. \end{aligned} \tag{12}$$

(ii) e_j is stock and time independent.

(iii) A given patch equilibrium resource stock is time dependent and reaches its steady state in the second period.

Lemma 2 suggests that the MPNE in escapement has a simple structure that depends on spatial characteristics, but is state independent. As such, the equilibrium escapement level in patch j is simply e_j as defined in (12). In contrast to results obtained in Lemma 1, Equation 12 suggests that the escapement level in a patch depends on the probability of regime shift, the patch's self retention rate before and after the shift. Moreover, in (12), terms multiplying λ capture harvester j's strategic responses to the threat of regime shift. Interestingly, for the particular case where $\lambda = 0$, (12) characterizes the equilibrium escapement levels for the no-shift case. The outcome of Lemma 2 allows us to derive the following results.

Proposition 2. *Assume that marginal costs are constant (i.e., $c_j'(x) = 0$ for all x, $j = A, B$). Over the pre-regime shift phase, the following results hold:*

(i) The equilibrium escapement level in patch $j = A, B$, satisfies

$$g_j'(e_j) = \frac{1}{\delta(\lambda D^s_{jj} + (1-\lambda)D_{jj})}. \tag{13}$$

(ii) The equilibrium escapement level in $\left(\begin{smallmatrix} \text{Patch } A \\ \text{Patch } B \end{smallmatrix}\right)$ is $\left(\begin{smallmatrix} \text{increasing} \\ \text{decreasing} \end{smallmatrix}\right)$ in the likelihood of the shift:

$$\frac{\partial e_A}{\partial \lambda} > 0 \quad \textit{and} \quad \frac{\partial e_B}{\partial \lambda} < 0. \tag{14}$$

Result (i) reveals that harvester j chooses her escapement to equate the financial rate of return with the expected biological return, which is biological growth $g_j'(e_j)$, discounted by patch j's expected retention rate, $\lambda D^s_{jj} + (1-\lambda)D_{jj}$. In other words, the non-cooperative golden rule (13) obtained in the certainty case is modified in response to the threat of future spatial regime shift. As the probability of the shift is raised, anticipating the shift, harvester A adjusts her harvest decisions to increase escapement (to take advantage of improved future conditions), while harvester B reduces her escapement in response to the threat (to extract the resource before it shifts migration out of her region). Since the no-shift outcome is the special case where $\lambda = 0$, result (ii) of Proposition 2 implies that over the pre-regime shift phase, the equilibrium escapement level is lower in patch B and larger in patch A, compared to the no-shift levels.

These results provide a new perspective on the literature using escapement strategies as control variable to address the management of a renewable resource. The seminal paper by Reed (1979) established the optimality of constant escapement in a stochastic fishery model. Extending that model, for example, Costello et al. (2015) examine the implications of partial enclosure of a renewable common resource in a deterministic setting where the resource distribution regime never shifts; and Costello and Polasky (2008) focus on the effects of environmental variability on optimal spatial harvest responses. These papers find that the optimal escapement level is time and state independent (and are thus constant). The above results suggest that regime shift creates a discontinuity in the equilibrium escapement levels, so optimal escapements shift in response to the regime shift. This is consistent with previous analyses of optimal resource management of a single, a-spatial stock under cyclical population dynamics (Carson et al. 2009) or with environmental predictions (Costello et al. 2001; Kennedy and Barbier 2013).

We have focused on the implications of spatial regime shift on escapement decisions. But we can also analyze the effects of regime shift on harvest and resource stock. We summarize these results as follows:

Proposition 3. *Assume that marginal costs are constant (i.e., $c_j'(x) = 0$ for all x, $j = A, B$). Over the phase prior to the shift, the following results hold.*

(i) $h_{B0} > \tilde{h}_{B0}$ *and* $h_{A0} < \tilde{h}_{A0}$.

(ii) At any date $t \geq 1$, $x_{Bt} > \tilde{x}_{Bt}$ *if and only if* $D_{AB} > \bar{D}_B^x$ *and* $x_{At} > \tilde{x}_{At}$ *if and only if* $D_{BA} < \bar{D}_A^x$.

(iii) At any date $t \geq 1$, $h_{Bt} > \tilde{h}_{Bt}$ *if and only if* $D_{AB} > \bar{D}_B^h$ *and* $h_{At} > \tilde{h}_{At}$ *if and only if* $D_{BA} < \bar{D}_A^h$, *where* $\bar{D}_j^x$ *and* $\bar{D}_j^h$ *depend only on* λ, δ, D_{kk}, D_{kk}^s, $k = A, B$ *and are given in the Appendix.*

At the initial date, anticipating that a shift may occur in the future, harvester B is more aggressive (harvests more than she would in the no-shift case) while harvester A adopts precautionary behavior (reduces her harvest compared to the no-shift case), see Proposition 3*i*. This seems intuitive because harvester B stands to lose from the regime shift. In the steady state, however, these strategic interactions may be altered to induce a larger or a smaller harvest rate in each patch depending on the values of the spatial characteristics.

To better understand the intuition underpinning this result, it is instructive to decompose the difference between the steady-state harvest rate for harvester B under the threat and no-threat cases as follows:

$$h_{Bt} - \tilde{h}_{Bt} = \underbrace{[g_A(e_A) - g_A(\tilde{e}_A)]D_{AB}}_{\text{Term 1>0}} + \underbrace{[(D_{BB}g_B(e_B) - e_B) - (D_{BB}g_B(\tilde{e}_B) - \tilde{e}_B)]}_{\text{Term 2<0}}.$$

This condition shows that the effect of the threat of regime shift on harvest B's steady-state harvest is driven by two opposite forces, captured by the two underbraced terms of the right hand side. Harvests in the patches are linked: As harvester A reduces her initial harvest, a larger stock will end up in patch B. Term 1 represents the strategic effect on resource growth; it is positive by Proposition 2 and the fact that function g_A is increasing. This force tends to raise harvester B's steady-state harvest rate under the threat. Term 2 represents the direct effect of the threat and is negative because the function g_B is increasing and due to the modified golden rule defined in (13).[8]

As D_{AB} is reduced, the former force becomes weaker and the latter force becomes stronger. Thus, it is entirely possible that the prospect of a future shift (that will *disadvantage* harvester B) will cause harvester B to *decrease* her own steady state harvest in advance of the shift. Likewise, harvester A may actually increase her harvest as a consequence of the threat, even though the future shift will advantage that harvester. More precisely, Result (*iii*) of Proposition 3 provides conditions on D_{AB} and D_{BA} under which these interesting

[8]To formally see why Term 2 is negative, it can be shown by using (13) that $D_{BB}g'_B(e_B) - 1 > 0$. For the special case where $\lambda = 0$, we thus have $D_{BB}g'_B(\tilde{e}_B) - 1 > 0$. Combining this result with the facts that $\tilde{e}_B > e_B$ and the function $D_{BB}g_B(x) - x$ is concave, we conclude that $D_{BB}g_B(e_B) - e_B < D_{BB}g_B(\tilde{e}_B) - \tilde{e}_B$.

results will hold.

For ease of exposition, we have primarily focused on the linear cost case. While this is a common assumption in resource economics, and delivers intuitive results, it fails to capture the stock effect under which the harvest cost increases as the resource stock tends to decline. Such a stock effect is present whenever $c_j'(x) < 0$. It turns out that the presence of a stock effect can fundamentally alter strategic behavior across patches. We find here that these altered strategic incentives can be sufficiently strong to reverse the conventional wisdom about how harvesters will react to the threat of regime shift. The results are summarized in the following proposition.

Proposition 4. *In the case where the cost functions are non-linear, it is possible that* $e_A < \tilde{e}_A$ *and* $e_B > \tilde{e}_B$.

This result suggests that despite the fact that the typical harvester in B will be disadvantaged by the regime shift, she may *increase* escapement in the pre-regime phase.[9] More precisely, the escapement level in patch j under the threat is larger than under the no-threat case if and only if

$$\begin{aligned} \lambda D^s_{jj}[p_j - c_j(x^s_j)]g_j'(e_j) + (1-\lambda)D_{jj}[p_j - c_j(x_j)]g_j'(e_j) \\ > D_{jj}[p_j - c_j(\tilde{x}_j)]g_j'(\tilde{e}_j), \end{aligned} \tag{15}$$

where $x^s_j = g_j(e_j)D^s_{jj} + g_i(e_i)D^s_{ij}$, $x_j = g_j(e_j)D_{jj} + g_i(e_i)D_{ij}$, and $\tilde{x}_j = g_j(\tilde{e}_j)D_{jj} + g_i(\tilde{e}_i)D_{ij}$.

Like the result in Proposition 2, this counterintuitive finding arises as a consequence of strategic interactions, except that here, strategic interactions are being driven by the stock effect. It is illustrative to consider the case of two countries harvesting a mobile fish stock.

[9] Using the growth functions defined in (18) along with the marginal costs $c_j(v) = \theta_j/v$, $j = A, B$ and the set of parameters $\delta = 0.95$, $x_{A0} = 0.84, x_{B0} = 0.8$, $D_{AA} = 0.7$, $D_{BB} = 0.77$, $D_{AB} = 0.26$, $D_{BA} = 0.22$, $D^s_{AA} = 0.82$, $D^s_{BB} = 0.65$, $D^s_{AB} = 0.14$, $D^s_{BA} = 0.28$, $K_A = 0.45$, $K_B = 3$, $N_A = 2 = N_B$, $r_A = 3.55$, $r_B = 3.45$, we find numerically that e_A and e_B are both increasing in λ.

When the stock effect is absent (so $c' = 0$), there is no strategic feedback across countries. In other words, while the countries' *harvest* choices are inextricably linked, the *escapement* choices are not; when $c' = 0$, the escapement choice of country B has no impact on the escapement choice of country A. In that setting, a country that stands to lose its stock in the future is incentivized to leave fewer fish in the water and a country that stands to gain its stock is incentivized to leave more fish in the water.

But when a stock effect is present ($c' < 0$), the optimal escapement level of country B does depend on the escapement level in country A. When country A leaves more fish in the water, some of them swim to country B, so the stock of fish in B is larger. This lowers the cost of fishing, and it turns out that this always leads country B to leave more fish in the water. So, under the threat of regime shift such as climate change, there are two important effects on country B. First, country B knows it will be disadvantaged by climate change, so it tends to want to leave *fewer* fish in the water. But, because country A tends to leave more fish in the water (for precisely the same reason), spatial movement means it is possible that the stock of fish in country B will be larger, which tends to make country B want to leave *more* fish in the water. Which effect dominates will depend on the relative magnitudes of the two effects. Thus, it is quite possible that the country that will be disadvantaged by climate change may leave *more* fish in the water than under the no-threat case.

5 An extension to common property

While patches act non-cooperatively over harvest, we have assumed that each individual patch is harvested by a single owner. But in some settings, it is more realistic for patch j to be common property, and is itself harvested by several non-cooperative agents. For example, if patches are the exclusive economic zones of countries, then harvesters would be individual fishing vessels within those territorial waters. The incentives engendered by this common property feature of non-cooperative spatial patches have not been analyzed previously. In this section we explore the role of common property in determining harvest and conservation incentives in anticipation of a regime shift.

To capture the common property feature, we generalize the previous model such that patch j is now harvested by $N_j \geq 1$ harvesters acting non-cooperatively in all periods. Harvesters are identical within each patch, but we maintain the assumption that incentives may differ across patches with respect to economic, environmental, and biological conditions.

As we assumed previously, we denote by p_j and c_j the unit price and marginal harvesting cost function associated with patch j. Each of the N_j harvesters in patch j have access to an equal fraction of the stock, $\frac{x_{jt}}{N_j}$. This available stock will be extracted by harvester k down to escapement level $\xi_{jt}^{(k)}$. Since harvesters are identical within each patch, the harvester's period-t harvest is $(\frac{x_{jt}}{N_j} - \xi_{jt}^{(k)})$ so, in the absence of harvesting costs, her period-t profit is $p_j(\frac{x_{jt}}{N_j} - \xi_{jt}^{(k)})$. In the presence of harvesting costs, the period-t profit for harvester $k = 1, 2, ..., N_j$ associated with patch j can thus be written as

$$\pi_{jt}^{(k)} = \int_{\xi_{jt}^{(k)}}^{\frac{x_{jt}}{N_j}} [p_j - c_j(v)]dv. \tag{16}$$

Recall that we are interested in a Markov Perfect Nash Equilibrium (MPNE), which determines the equilibrium escapement decision rules for all harvesters as functions of (x_A, x_B): $(\xi_A^{(1)}(x_A, x_B), \xi_A^{(2)}(x_A, x_B), ..., \xi_A^{(N_A)}(x_A, x_B), \xi_B^{(1)}(x_A, x_B), ..., \xi_B^{(N_B)}(x_A, x_B))$. Since we are in a two-patch setting and harvesters operating in a given patch are identical, from now on, we concentrate on symmetric equilibria within each patch: $\xi_A(.) = \xi_A^{(k)}(.)$ and $\xi_B(.) = \xi_B^{(\ell)}(.)$ for all k, ℓ. Therefore, it suffices to find a pair of escapement strategies $(e_A(.), e_B(.))$ with $e_A(.) = N_A \xi_A(.)$ and $e_B(.) = N_B \xi_B(.)$.

Lemma 3. *Prior to the spatial regime shift, the following results hold:*

The pair (e_A, e_B) constitutes a MPNE, where e_j is implicitly defined as follows:

$$p_j - c_j(\frac{e_j}{N_j}) = \delta\lambda D^s_{jj}[p_j - c_j\left(g_j(e_j)\frac{D^s_{jj}}{N_j} + g_i(e_i)\frac{D^s_{ij}}{N_j}\right)]\frac{g'_j(e_j)}{N_j} \tag{17}$$
$$+ \delta(1-\lambda)D_{jj}[p_j - c_j\left(g_j(e_j)\frac{D_{jj}}{N_j} + g_i(e_i)\frac{D_{ij}}{N_j}\right)]\frac{g'_j(e_j)}{N_j}, \quad i \neq j.$$

This proposition provides an interesting characterization of the equilibrium strategic behaviors. In particular, it reveals that the equilibrium escapement levels prior to the shift depend on the biological return, N_j, economic and environmental conditions as well as the probability of spatial regime shift. Because the common property case considered in this section generalizes the model from Section 2 to N_j harvesters, a natural question is how the number of harvesters affects strategic responses to the possible occurrence of the shift. We formally address this and related questions below. For the sake of tractability, we restrict our attention to the standard logistic growth function case, which can be written as follows

$$g_j(e_j) = e_j + r_j e_j(1 - \frac{e_j}{K_j}) \quad \text{for} \quad j = A, B, \tag{18}$$

where K_j represents the carrying capacity and r_j the intrinsic growth rate for patch j.

We first examine the effects on harvest decisions prior to the shift.

Proposition 5. *Adopting g_j as defined in* (18) *and provided marginal harvesting costs are constant:*

(i) Patch j's equilibrium escapement, e_j, is decreasing in N_j and satisfies

$$g'_j(e_j) = \frac{N_j}{\delta(\lambda D^s_{jj} + (1-\lambda)D_{jj})}. \tag{19}$$

(ii) Relative to the no-shift case, the threat of a shift increases the steady-state harvest rate in patch A, but only if N_A satisfies $\delta(1 + r_A)D_{AA} > N_A > \hat{N}_A$.

(iii) Relative to the no-shift case, the threat of a shift reduces the steady-state harvest rate in patch B, but only if N_B satisfies $\delta(1+r_B)D^s_{BB} > N_B > \hat{N}_B$, where $\hat{N}_A$ and $\hat{N}_B$ are positive numbers that depend on spatial characteristics and are given in the appendix.

In the above results, conditions $\delta(1+r_A)D_{AA} > N_A$ and $\delta(1+r_B)D^s_{BB} > N_B$ respectively ensure that resource stock in patch A (resp. B) is not harvested to extinction. These results highlight the implications of having more than one harvester in a patch. For example, relative to the no-shift case, Result (ii) of Proposition 5 reveals in the single harvester case that the harvest rate in patch A is lower in the steady-state whenever $\min(\hat{N}_A, \delta(1+r_A)D_{AA}) > 1$. This result, however, is reversed when $N_A \geq 2$ and $\delta(1+r_A)D_{AA} > N_A > \hat{N}_A$. Moreover, Result (iii) of Proposition 5 highlights in the single harvester case that the steady-state harvest rate in patch B is larger whenever $\min(\hat{N}_B, \delta(1+r_B)D_{BB}) > 1$. This latter finding, however, is reversed as long as $N_B \geq 2$ and $\delta(1+r_B)D_{BB} > N_B > \hat{N}_B$. These findings show the importance of the group size asymmetry (*i.e.*, $N_A \neq N_B$). Whether N_A or N_B is small or large, these findings reveal the existence of harvest responses to the threat that cannot be captured by a model in which the number of players in both patches is identical (e.g., standard models in which there is a single agent in each patch).

It is also possible to derive the implications of considering common property vs. sole ownership and heterogenous growth on conservation. Our findings are summarized in the following proposition.

Proposition 6. *Provided that $c'_j(.) = 0$ and $g_j(.)$ is defined in* (18).
(i) Patch j is harvested down to extinction, but only if $N_j \geq \delta(1+r_j)(\lambda D^s_{jj} + (1-\lambda)D_{jj})$.
(ii) In the case where $r_j \leq 1$, patch j is harvested down to extinction whenever $N_j \geq 2$.
(iii) There is no stock extinction in patch j when $N_j = 1$, $\lambda D^s_{jj} + (1-\lambda)D_{jj}) > 1/\delta(1+r_j)$, and $r_j \leq 1$.

Our motivation for these extended results is that the related literature has focused only on the cases in which (i) the growth functions are logistic and identical with the intrinsic growth rate smaller than one; (ii) each patch is owned by a single harvester. Relaxing each of those assumptions yields novel equilibria. For example, Proposition 6 suggests that different property rights structures may lead to different equilibrium states: extinction vs no extinction. More precisely, patch j is harvested to extinction when $r_j \leq 1$, $c_j'(.) = 0$, and $N_j \geq 2$. However, when the other patch is owned by a single agent and its expected self-retention rate is large, Result (iii) shows that strategic harvest decisions do not drive the resource stock extinct.

Moreover, we find that when patches have different growth functions, equilibria arise that cannot be captured by models with identical growth functions. For instance, when $N_j = 1$ and $c_j = 0$, extinction is the equilibrium outcome in both patches when $r_A = r_B$ and

$$\delta(1 + r_j) \times \min(\lambda D^s_{AA} + (1 - \lambda)D_{AA}), \lambda D^s_{BB} + (1 - \lambda)D_{BB}) < 1.$$

However, only patch B is harvested to extinction when $r_A \neq r_B$, $N_j = 1$, $c_j = 0$, and the following conditions hold:

$$\delta(1 + r_A) \times [\lambda D^s_{AA} + (1 - \lambda)D_{AA})] > 1 \quad \text{and} \quad \delta(1 + r_B) \times [\lambda D^s_{BB} + (1 - \lambda)D_{BB}] \leq 1.$$

These findings illustrate potential biases that may arise when heterogeneity in property rights structure or biological return exist, but are not taken into account.

Simultaneously accounting for common property and a stock effect on harvesting costs quickly becomes analytically intractable. But one way to get traction in the case where $c_j' < 0$ is as follows. Let $c_i' = 0$ and other model parameters be such that the optimal aggregate residual stock level e_i does not depend on N_j and is characterized by

$$g_i'(e_i) = \frac{N_i}{\delta\left(\lambda D_{ii}^s + (1-\lambda)D_{ii}\right)}$$

Assume that the other patch is such that $c_j' < 0$ and initial model parameters (in particular the size of the user group, denoted N_j^0) are such that the optimal aggregate residual stock level e_j is characterized by Condition 17. Assume moreover that $p_j - c_j(0) > 0$ and $g_j'(.)$ is bounded from above. Then we have:

Proposition 7. *There exists $\tilde{N}_j > N_j^0$ such that the resource will be driven extinct in patch j for any size of user group greater than or equal to $\tilde{N}_j$.*

This result reinforces the general intuition from above: Adding common property to the regime shift game induces an extinction threat that could jeopardize the very existence of the renewable resource.

6 Conclusion

One of the most widely anticipated effects of global environmental change is the shift in the spatial distribution and migration of natural resource stocks. While effects will range from moderate to severe, and are occasionally predictable, in most cases, the occurrence of these shifts is uncertain. We have examined the effects of the threat of future spatial regime shift on strategic interactions between spatial property rights owners harvesting a mobile natural resource. Because our model allows for different economic returns, heterogenous growth, stock effects on costs, and spatial migration of the resource, we have been able to extract a number of novel and interesting results about how strategic behavior interacts with the threat of spatial regime shift. Our main contribution is to examine how the prospect of a spatial regime shift will affect non-cooperative incentives and equilibrium behavior across heterogeneous property owners. We considered as a baseline the no-shift case in which the resource distribution is deterministic and never shifts; this amounts to a non-cooperative spatial game in a deterministic environment. Then, introducing the possibility of a future regime shift, we examined the non-cooperative behavior of competing spatial property rights holders across a range of shift magnitudes. We modeled spatial regime shift as an abrupt change in the biophysical conditions that govern dispersal of the resource. The shift confers a clear advantage to one harvester and a clear disadvantage to the other. Our focus is on how the harvesters compete prior to the shift (but with common knowledge about the likelihood of the shift).

Our analysis allows for an arbitrary degree of regime shift. In the extreme, the shift could irreversibly drive the entire resource population out of one of the patches and into the other. In keeping with the literature, we call this the "complete shift" case, where $D^s_{BB} = D^s_{AB} = 0$ and $D^s_{BA} = 1$. Using methods similar to those in Propositions 3 and 4, our analysis yields qualitatively similar results as for the partial regime shift case.

Whatever its magnitude, the threat of regime shift always increases initial harvest in the disadvantaged patch when harvest costs are linear. But we also found that strategic interactions can induce that patch to harvest *less* in steady state under the threat of regime shift. Indeed, this finding can maintain even under the threat of complete shift. The equilibrium escapement level in a patch depends on the resource price, marginal harvesting costs, but only when a patch is common property. We find that strategic interactions can even lead to complete extinction, provided the common property feature is sufficiently strong relative to the growth of the resource. In the case where harvest costs are non-linear, new strategic incentives arise; this effect can even reverse the conventional wisdom, so a patch that will be advantaged by the regime shift may act more aggressively in advance of the shift.

Our results may shed some light on an interesting economic literature examining renewable resource management under the threat of a doomsday event (see for instance, Polasky et al. 2011). When the probability of regime shift is exogenous and utility is linear in harvest, the wisdom so far is that aggressive behavior always prevails prior to the shift. In this paper, the probability of regime shift is exogenous and a harvester makes her harvest decisions under the threat of the shift. In contrast to the aforementioned literature, we find conditions under which such harvesters may be cautious in response to disadvantageous regime shifts.

These results also relate to an interesting emerging policy debate. Many resource stocks such as marine fish, waterfowl, and some economically-significant game species migrate across national or other jurisdictions. At the same time, these migratory patterns are expected to change as a consequence of future climate change (Molinos et al. 2016). The results in this paper help inform predictions about the behavioral responses of countries or other jurisdictions in advance of shifts, and unveil some counterintuitive predictions arising from strategic interactions to capture the resource. While informative in their own right, these results could be leveraged to inform policy responses for managing transboundary resources subject to possible future regime shift.

Appendix

A Details for Section 3

Proof of Lemma 1

(i) The equilibrium value function can be written as

$$W_j(x_t) = p_j(x_{jt} - e_{jt}) - \int_{e_{jt}}^{x_{jt}} c_j(v)dv + \delta W_j(x_{t+1}), \tag{20}$$

Since in (4), x_{t+1} depends only on e_i and e_j, Condition 6 implies that e_i and e_j are stock independent. Therefore,

$$\frac{\partial W_j}{\partial x_{it}}(x_{t+1}) = 0, \quad \text{for all} \quad i, j \in \{A, B\}, \quad i \neq j.$$

Combining this result along with (20), it follows that

$$\frac{\partial W_j}{\partial x_{kt}}(x_t) = \begin{cases} p_j - c_j(x_{jt}) & \text{if } k = j, \\ 0 & \text{if } k \neq j. \end{cases}$$

Substituting this equation into (6), we conclude that stock independency holds.

(ii) This is a simple consequence of the fact that e_i and e_j are time and state independent.

Proof of Proposition 1

(i) In the case where $c_j'(x) = 0$ for all x, $j = A, B$, Equation 7 yields

$$g_j'(e_j) = \frac{1}{\delta D_{jj}^s}, \quad g_j'(\tilde{e}_j) = \frac{1}{\delta D_{jj}}. \tag{21}$$

(ii) Since $D^s_{AA} > D_{AA}$ and $D_{BB} > D^s_{BB}$, it follows that $g'_A(e_A) < g'_A(\tilde{e}_A)$ and $g'_B(e_B) > g'_B(\tilde{e}_B)$. Hence, $\tilde{e}_A < e_A$ and $\tilde{e}_B > e_B$. This is the case because functions $g_j(.), j = A, B$ are concave such that functions $g'_j(.), j = A, B$ are decreasing.

(iii) For $t \geq \tau + 1$:

$x_{jt} \equiv g_j(e_j)D^s_{jj} + g_i(e_i)D^s_{ij} > g_j(\tilde{e}_j)D_{jj} + g_i(\tilde{e}_i)D_{ij} \equiv \tilde{x}_{jt}$ if and only if

$$D^s_{ij} > \bar{D}^s_{jx} \equiv \frac{g_j(\tilde{e}_j)D_{jj} + g_i(\tilde{e}_i)D_{ij} - g_j(e_j)D^s_{jj}}{g_i(e_i)}.$$

(iv) For $t \geq \tau + 1$, the relation

$h_{jt} \equiv x_{jt} - e_{jt} = g_j(e_j)D^s_{jj} + g_i(e_i)D^s_{ij} - e_{jt} > g_j(\tilde{e}_j)D_{jj} + g_i(\tilde{e}_i)D_{ij} - \tilde{e}_{jt} = \tilde{x}_{jt} - \tilde{e}_{jt} \equiv \tilde{h}_{jt}$ holds if and only if

$$D^s_{ij} > \bar{D}^s_{jh} \equiv \frac{g_j(\tilde{e}_j)D_{jj} + g_i(\tilde{e}_i)D_{ij} - g_j(e_j)D^s_{jj} + (e_j - \tilde{e}_j)}{g_i(e_i)}.$$

Equation21 suggests that for $j = A, B$, e_j depends only on δ and D^s_{jj} whereas for $j = A, B$, $\tilde{e}_j$ depends only on δ and D_{jj}. As such, $\bar{D}^s_{jx}$ and $\bar{D}^s_{jh}$ depend only on δ, D^s_{jj}, D_{AA}, D_{BB}, and D_{ij}, $i = A, B$ and $i \neq j$.

Proof of Lemma 2

Similar to the proof of Lemma 1.

B Details for Section 4

Proof of Proposition 2

(i) In the case where $c'_j(.) = 0$, Equation 7 simplifies to

$$g'_j(e_j) = \frac{1}{\delta(\lambda D^s_{jj} + (1-\lambda)D_{jj})}. \tag{22}$$

(ii) Using the implicit value theorem, e_j is a continuously differentiable function of λ. We then differentiate both sides of (22) with respect to λ. Rearranging the outcome yields

$$\frac{\partial e_j}{\partial \lambda} = \frac{D_{jj} - D^s_{jj}}{g''_j(e_j)[\lambda D^s_{jj} + (1-\lambda)D_{jj})]^2}, \quad \text{for} \quad j = A, B.$$

Since $g''_j(e_j) < 0, D_{BB} > D^s_{BB}$ and $D^s_{AA} > D_{AA}$, the result follows.

Proof of Proposition 3

(i) Since $e_{A0} \equiv x_{A0} - h_{A0} > \tilde{e}_A \equiv x_{A0} - \tilde{h}_{A0}$, we necessarily have $\tilde{h}_{A0} > h_{A0}$. Moreover, since $e_{B0} \equiv x_{B0} - h_{B0} < \tilde{e}_B \equiv x_{B0} - \tilde{h}_{B0}$, we necessarily have $\tilde{h}_{B0} < h_{B0}$.

(ii) Using the facts that $x_{jt} \equiv g_j(e_j)D_{jj} + g_i(e_i)D_{ij}$, $\tilde{x}_{jt} = g_j(\tilde{e}_j)D_{jj} + g_i(\tilde{e}_i)D_{ij}$, $g_A(e_A) > g_A(\tilde{e}_A)$, and $g_B(e_B) < g_B(\tilde{e}_B)$, we get $x_{Bt} > \tilde{x}_{Bt}$ if and only if

$$D_{AB} > \bar{D}^x_B \equiv D_{BB}\frac{g_B(\tilde{e}_B) - g_B(e_B)}{g_A(e_A) - g_A(\tilde{e}_A)}.$$

Using a similar reasoning, we find that $x_{At} > \tilde{x}_{At}$ if and only if

$$D_{BA} < \bar{D}^x_A \equiv D_{AA}\frac{g_A(e_A) - g_A(\tilde{e}_A)}{g_B(\tilde{e}_B) - g_B(e_B)}.$$

(iii) Using a similar method as for the proof of result (ii) along with the fact that

$h_j = x_j - e_j$, $j = A, B$, we get

- $h_{Bt} > \tilde{h}_{Bt}$ if and only if

$$D_{AB} > \bar{D}^h_B \equiv \frac{D_{BB}(g_B(\tilde{e}_B) - g_B(e_B)) - (\tilde{e}_B - e_B)}{g_A(e_A) - g_A(\tilde{e}_A)}.$$

- $h_{At} > \tilde{h}_{At}$ if and only if

$$D_{BA} < \bar{D}^h_A \equiv \frac{D_{AA}(g_A(e_A) - g_A(\tilde{e}_A)) - (e_A - \tilde{e}_A)}{g_B(\tilde{e}_B) - g_B(e_B)}.$$

Notice that for $j = A, B$, $\bar{D}^h_j$ and $\bar{D}^x_j$ depend only on λ, δ, D_{kk}, and D^s_{kk}, $k = A, B$.

Proof of Proposition 4

Recall that for $j = A, B$, e_j satisfies Equation 12. Hence, the left-hand side of Condition 15 is equal to $p_j - c_j(e_j)$ while the right-hand side corresponds to $p_j - c_j(\tilde{e}_j)$. So Condition 15 can be rewritten $p_j - c_j(e_j) > p_j - c_j(\tilde{e}_j)$. Since function $\ell_j(x) = p_j - c_j(x)$ is increasing, we conclude that Condition 15 holds if and only if $e_j > \tilde{e}_j$.

Proof of Lemma 3

Similar to the proof of Lemma 2.

Proof of Proposition 5

(i) In the case where $c'_j = 0$, Condition (17) simplifies to (19). Using the fact that g_j is concave and partially differentiating both sides of (19) and rearranging, it can be shown that e_j is decreasing in N_j.

Using (19) and (18), we derive

$$e_j = \frac{K_j}{2r_j}[1 + r_j - \frac{N_j}{\delta(\lambda D^s_{jj} + (1-\lambda)D_{jj})}]. \tag{23}$$

Notice that $e_A > 0$ if and only if $\delta(1 + r_A)D_{AA} > N_A$. Likewise, we have $e_B > 0$, but only when $\delta(1 + r_B)D^s_{BB} > N_B$.

(ii) Denote by h^s_A, the steady-state total harvest for patch A. According to (4), we have $h^s_A = g_A(e_A)D_{AA} + g_B(e_B)D_{BA} - e_A$. Combining this result with (18) and (23), we derive

$$h^s_A - h^s_A|_{\lambda=0} = \eta_A(\lambda D^s_{AA} + (2-\lambda)D_{AA})N^2_A - 2\eta_A\delta(\lambda D^s_{AA} + (1-\lambda)D_{AA})N_A + \xi_A, \tag{24}$$

where,

$$\xi_A = \lambda D_{BA}K_B N^2_B \frac{(D^s_{BB} - D_{BB})(\lambda D^s_{BB} + (2-\lambda)D_{BB})}{r_B\delta^2 D^2_{BB}(\lambda D^s_{BB} + (1-\lambda)D_{BB})^2} < 0; \eta_A = \frac{\lambda K_A(D^s_{AA} - D_{AA})}{\delta^2 D_{AA} r_A(\lambda D^s_{AA} + (1-\lambda)D_{AA})^2} > 0.$$

Denote by $\hat{N}_A$ the unique positive root of (24). Clearly, $h^s_A > h^s_A|_{\lambda=0}$ whenever $N_A > \hat{N}_A$.

(ii) A similar reasoning as for the proof of Result (ii) suggests that $h^s_B|_{\lambda=0} > h^s_B$ whenever $N_B > \hat{N}_B$, where $\hat{N}_B$ is the unique positive root of the second degree polynomial:

$$-\eta_B(\lambda D^s_{BB} + (2-\lambda)D_{BB})N^2_B + 2\eta_B\delta(\lambda D^s_{BB} + (1-\lambda)D_{BB})N_B + \xi_B = 0,$$

where,

$$\xi_B = D_{AB}K_A N^2_A \frac{(D^s_{AA} - D_{AA})(\lambda D^s_{AA} + (2-\lambda)D_{AA})}{r_A\delta^2 D^2_{AA}(\lambda D^s_{AA} + (1-\lambda)D_{AA})^2} > 0; \eta_B = \frac{K_B(D_{BB} - D^s_{BB})}{\delta^2 D_{BB} r_B(\lambda D^s_{BB} + (1-\lambda)D_{BB})^2} > 0.$$

Proof of Proposition 6

Using (19) and (18), it can be shown that if escapement for patch j is strictly positive, it is necessarily given by (23).

(i) Using (23), we derive $e_j \leq 0$ iff $N_j \geq (1+r_j)(\lambda D^s_{jj} + (1-\lambda)D_{jj})$. The result then follows.

(ii) Assume that $N_j \geq 2$ and $r_j \leq 1$. These assumptions imply $N_j \geq (1+r_j)(\lambda D^s_{jj} + (1-\lambda)D_{jj})$ such that by Result (i), patch j is harvested down to extinction.

(iii) In the case where $N_j = 1$, we can verify that e_j defined in (23) is strictly positive as long as $r_j \leq 1$ and $[\lambda D^s_{jj} + (1-\lambda)D_{jj})] > 1/\delta(1+r_j)$. The result then follows.

Proof of Proposition 7

It suffices to show that e_j cannot be positive for N^0_j arbitrarily large. By Condition (17), if $e_j > 0$ we know that the following inequality holds:

$$\begin{aligned} p_j - c_j(\frac{e_j}{N^0_j}) = {}& \delta\lambda D^s_{jj}[p_j - c_j\left(g_j(e_j)\frac{D^s_{jj}}{N^0_j} + g_i(e_i)\frac{D^s_{ij}}{N^0_j}\right)]\frac{g'_j(e_j)}{N^0_j} \\ & + \delta(1-\lambda)D_{jj}[p_j - c_j\left(g_j(e_j)\frac{D_{jj}}{N^0_j} + g_i(e_i)\frac{D_{ij}}{N^0_j}\right)]\frac{g'_j(e_j)}{N^0_j}, \quad i \neq j. \end{aligned} \tag{25}$$

Since $D^s_{ij}\frac{g_i(e_i)}{N^0_j} \to 0$ and $\frac{g'_j(e_j)}{N^0_j} \to 0$ as N^0_j gets arbitrarily large, the left hand side term of equation (25) goes to zero. However, its right hand side term remains positive (as N^0_j gets arbitrarily large) because $p_j > c_j(0)$ and c_j is decreasing. Therefore, as N^0_j becomes arbitrary large, condition (25) (that characterizes interior solutions in escapement) cannot hold. Hence, there exists $\tilde{N}_j$ such that patch j is driven to extinction as long as $N_j \geq \tilde{N}_j$.

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