Spatial property-rights fisheries with potential regime shift

Christopher Costello* Bruno Nkuiya† Nicolas Quérou‡

January 25, 2016

Abstract

We address the non-cooperative exploitation of a migratory renewable resource in the presence of possible regime shift affecting the spatial movement of the resource. At an unknown date in the future, environmental conditions may abruptly and irreversibly shift, thus altering the spatial movement patterns of the resource. We design a stochastic spatial bioeconomic model to address the effects of these types of shifts on non-cooperative harvest decisions made by decentralized owners. We find that the threat of a future shift modifies the standard golden rule and may induce larger harvest rate everywhere, irrespective of the initial stock and 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 threat. Our theoretical results are illustrated with a numerical example.

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

JEL Classification Codes: C73; H23; H73; Q22

1 Introduction

Because renewable resources such as fish, water, game, and invasive species are mobile, extraction and productivity in one location affect economic opportunities in other locations.

*Bren School, UC Santa Barbara; and NBER. E-mail:costello@bren.ucsb.edu.

†Bren School of Environmental Science & Management, University of California Santa Barbara, U.S.A. E-mail:bnkuiya@bren.ucsb.edu.

‡CNRS, UMR5474 LAMETA, F-34000 Montpellier, France. E-mail:querou@supagro.inra.fr.

The resulting spatial externality can be dealt with using a number of instruments including spatial taxes (Sanchirico and Wilen 2005), 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). 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)).

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 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 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, the state

[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.

will never return to its pre-shift state.

While regime shifts are natural world phenomena, they can fundamentally alter the constraints and incentives faced by property owners who extract mobile renewable resources. For example, one of the most commonly cited forms of regime shift concerns the spatial range or dispersal of organisms. Consider 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.[2] And recognizing the deterioration of future conditions, country B would, intuitively, increase its current extraction. But these simple and intuitive predictions 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 other? To our knowledge these, and related questions have not been addressed; we will do so here.

This paper builds on an emerging literature on fisheries 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), and Miller and Nkuiya (2015) 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. In contrast, our analysis investigates

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

cases in which regime shift will alter the distribution of resource stocks so as to create winners and losers.[3] 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.

The paper unfolds as follows. Section 2 presents the model. Section 3 focuses on the case where the occurrence of regime shift is perfectly predictable. Section 4 analyses harvesters' response to uncertainty about regime shift. Section 5 provides an illustrative example in support to analytical results obtained in Section 4. Section 6 concludes.

2 The model

A renewable resource stock is distributed heterogeneously across an ecosystem consisting of two 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 (harvest) 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

[3] 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).

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).

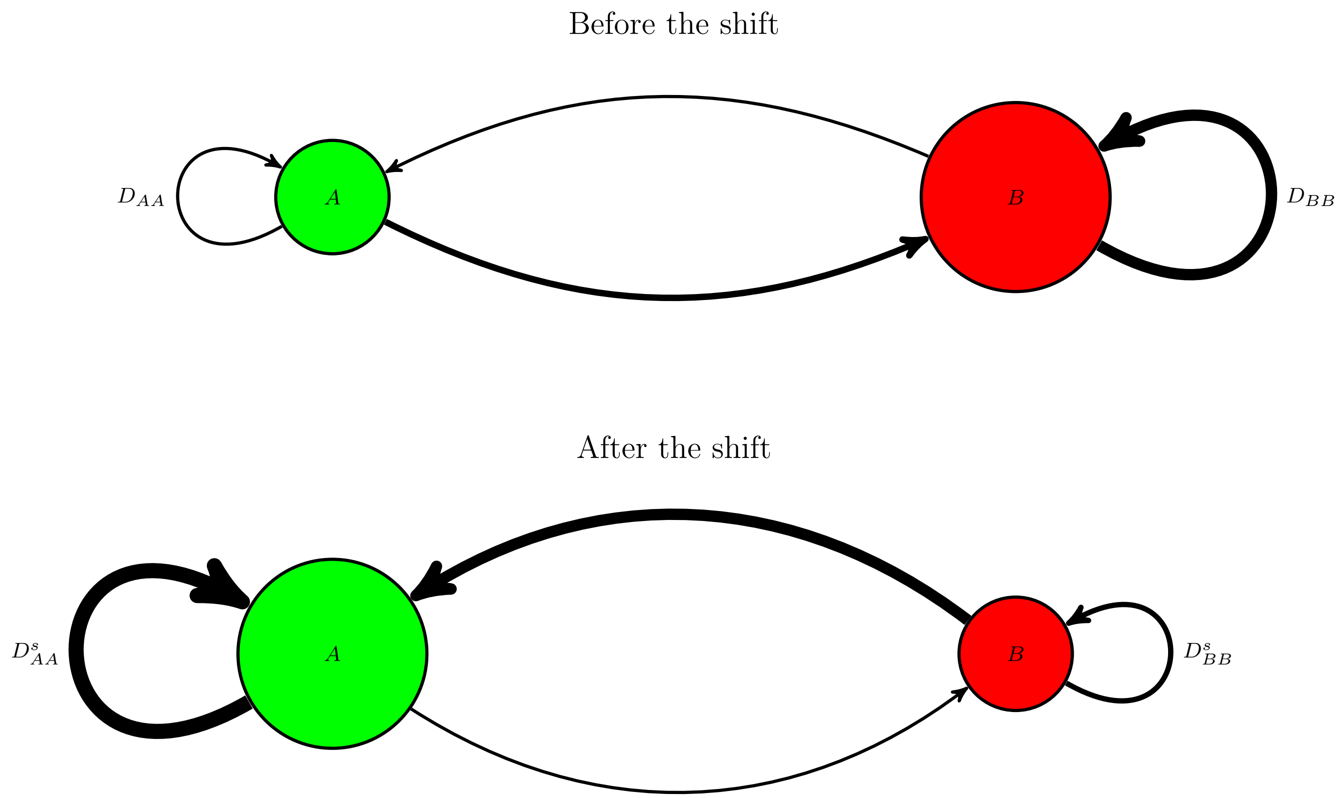

Figure 1: Effects of the shift on the migration pattern.

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 τ (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 loosely indicate the strength of connectivity. Dispersal is thus characterized as follows:

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

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 perfectly 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 3 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 residual stock (e_{jt}), which then grows ($g_j(e_{jt})$), and disperses across the system (K_{jit}).

Suppose now that each patch is owned by a single entity. For example, this could be a set of spatially-connected Territorial User Right Fisheries (TURFs), a set of farms on which bees reside, or a set of countries between which birds, game, or fish migrate. We allow for prices and costs to be patch specific, so the instantaneous profit associated with patch j is given by

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

where p_j denotes the unit price. The integral in Equation 5 represents the total cost function, which can also 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 unit 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 $c_j'(.) < 0$. To determine whether or not the marginal cost is constant is an empirical issue (see for instance, Atewamba and Nkuiya (2015), for the case of non-renewable resources). We separately examine both cases below.

At date $t = 0, 1, ..., \tau - 1$, the payoff function for player $j = A, B$ 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 player j and δ is the discount factor. We next solve the post-shift problem and use its result to derive the complete solution for the regime shift problem presented above.

3 The post-shift problem

In this section we examine the game between spatial property rights holders 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.[4] In this setting, harvester j 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, harvester j solves:

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

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 of both players 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 the two players. Player j's Bellman equation is:

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

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 harvester 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

[4] 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), **?**, Kapaun and Quaas (2013), and many papers cited therein.

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

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

(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 player j's 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. 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 ($\tilde{e}_{jt}$). 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. 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:

$$g_j'(e_j) = \frac{1}{\delta D_{jj}^s}. \tag{8}$$

(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 $D_{ij}^s > \bar{D}_{jx}^s$.

(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 $D_{ij}^s > \bar{D}_{jh}^s$, where $\bar{D}_{jx}^s$ and $\bar{D}_{jh}^s$ depend only on δ, D_{jj}^s, D_{jj} and D_{ij}, $j = A, B$ 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_{jj}^s) and the financial rate of return. This is a non-cooperative "golden rule" for spatial growth models (Kaffine and Costello 2011), where D_{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 ($i.e.$, $D_{AB}^s < D_{AB}$ and $D_{BB}^s < D_{BB}$), 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 in the pre-shift phase of the game.

4 The uncertainty case

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 players interact under the *threat* of a possible regime shift in the future. In this section, we focus on harvesters' responses to uncertainty about a possible future regime shift. Taking the escapement strategy of the other player as given, harvester $j = A, B$ chooses the escapement strategy that maximizes her expected present discounted net profits

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

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

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

subject to (4), where $x^s_{jt+1} = g_j(e_j) D^s_{jj} + g_i(e_i) D^s_{ij}$ and $x_{jt+1} = g_j(e_j) D_{jj} + g_i(e_i) D_{ij}$. 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 $\tilde{\delta}_j = \delta + \delta\lambda[W_j(x_{t+1}) - V_j(x_{t+1})]/V_j(x_{t+1})$ 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

$$p_j = c_j(e_{jt}) + \delta\lambda g_e(e_{jt}, \alpha_j) \sum_{i=A,B} \frac{\partial W_j}{\partial x_{it+1}}(x^s_{t+1})D^s_{ji} + \delta(1-\lambda)g_e(e_{jt}, \alpha_j) \sum_{i=A,B} \frac{\partial V_j}{\partial x_{it+1}}(x_{t+1})D_{ji}, \quad j = A, B.$$

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:

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

(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

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

(ii) The equilibrium escapement level in $\binom{\text{Patch } A}{\text{Patch } B}$ is $\binom{\text{increasing}}{\text{decreasing}}$ 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 $\lambda D_{jj}^s + (1-\lambda)D_{jj}$. 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, player A adjusts her harvest decisions to increase escapement (to take advantage of improved future conditions), while player 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. For instance, 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. 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_{jj}, D_{jj}^s, $j = A, B$ *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, Proposition 3i). This seems intuitive because B stands to lose from the regime shift. However, these strategic interactions may be altered from period 2 on. In the steady state, the prospect of a shift may 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 harvester B's steady-state harvest is driven by two opposite forces, captured by the two bracketed terms of the right hand side. Harvests in the patches are linked: As 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 player B's steady-state harvest rate under the threat. Term 2 represents the direct effect of the threat and is negative because function g_B is increasing and the modified golden rule defined in (13). 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* player B) will, via strategic interactions with her opponent, cause B to *decrease* her own steady state harvest. Likewise A may actually increase her harvest as a consequence of the threat, even though the future shift will advantage that player. More precisely, Result (*iii*) of Proposition 3 provides conditions on D_{AB} and D_{BA} under which such findings hold.

For ease of exposition, we have primarily focused on the linear cost case. While this is a common assumption in resource economics, 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 $c_j'(x) < 0$. Here we explore how a stock effect may alter our conclusions above. 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 player B will be disadvantaged by the regime shift, she may *increase* escapement in the pre-regime phase. More precisely, the escapement level in patch j under the threat is larger than under the no-threat case if and only if

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

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

Like the result in Proposition 4, this counterintuitive result arises as a consequence of strategic interactions, except that here, strategic interactions are being driven by the stock effect. Recall that e_j and $\tilde{e}_j$ correspond to the equilibrium escapement levels in patch j for the threat and no-threat cases, x_j and $\tilde{x}_j$ represent the steady-state resource stock obtained under the threat and no-threat cases. Moreover, x_j^s can be interpreted as tomorrow's resource stock in patch j if regime shift happens today. Hence, Proposition 4 suggests that the threat induces a larger escapement level in patch j, but only when harvester j's expected instantaneous marginal profit (properly discounted by the retention rate) is larger than the discounted marginal profit that she would obtain in the absence of the threat. When $c_j' < 0$, $e_j > \tilde{e}_j$ implies that $h_{j0} < \tilde{h}_{j0}$. In other words, in the initial period, the threat may actually induce a larger or a smaller harvest in each patch compared to the no-shift case. Numerical results presented in the next section will confirm and illustrate these findings.

5 An illustrative example

Here we present a brief numerical example to illustrate our analytical results. We consider discrete-time logistic growth functions

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

with parameters r_j and K_j.[5] Initial stocks are $x_{A0} = 0.84$ and $x_{B0} = 0.8$ and we explore a range of values for the regime shift probability, λ. Prior to the shift, we assume INLINE MATRIX D=(.7 .26 .22 .77). Following the theoretical analysis, we assume that patch B is disadvantaged by the shift, so $D^s = (.82.14.28.65)$, so D_{BA} increases and D_{BB} and D_{BA} both decrease. We use a discount factor of $\delta = .95$.

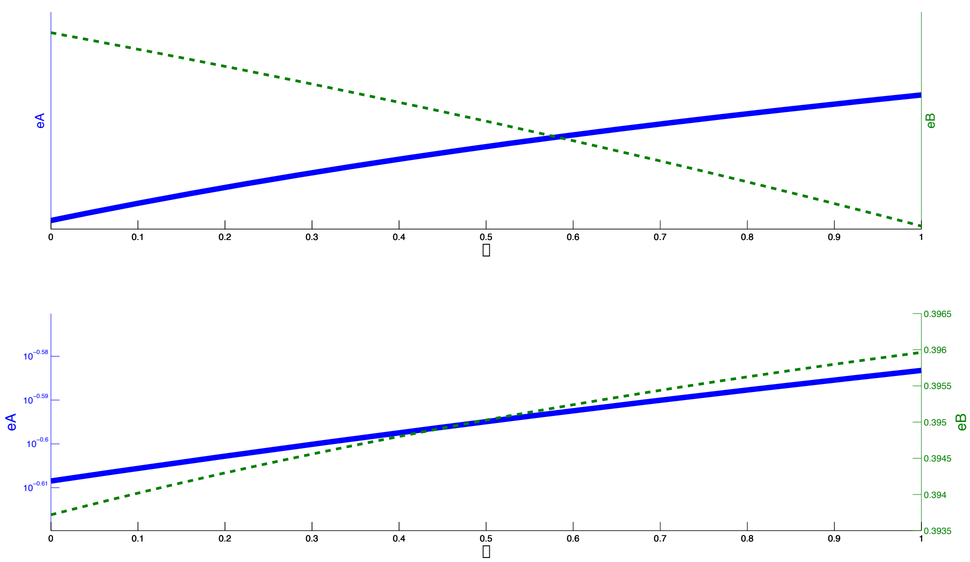

Figure 2: Effects of the threat of regime shift on equilibrium escapement levels. Top panel is for linear costs. Bottom panel is for non-linear costs.

[5] We use $K_A = 0.35$; $K_B = 3$; $r_A = 0.95$; $r_B = 0.85$.

5.1 Example with linear cost

This section focuses on the scenario where the marginal costs are constant.[6] We first examine the effects of an exogenous increase in the probability of regime shift (λ) on the equilibrium escapement levels in both patches. As illustrated in the top panel of Figure 2, an exogenous increase in λ raises the equilibrium escapement level in patch A and diminishes the equilibrium escapement level in patch B. This accords with economic intuition in advance of regime shift: As the probability of regime shift rises, Player B becomes more aggressive (so her escapement decreases) because she knows that the shift will move resource stock out of her patch, while player A becomes more conservative (she increases her escapement) because she will enjoy advantageous future conditions.

To better understand the effects of the threat of regime shift, we can also analyze the effects of λ on steady state harvests. It turns out that even though escapements move in opposite directions (with increasing λ), steady state harvests both diminish in λ (top panel of Figure 3). This result is intuitive for patch A: she increases her escapement, and so decreases her harvest, in λ. And while player B decreases her escapement, her steady state harvest is a product of both players' escapement decisions, and the decreased escapement by B is insufficient to outweigh the increased escapement by A. Thus, her steady state harvest also declines.

What do our numerical findings suggest about how a threat of spatial regime shift will affect resource stocks? Holding the probability of the shift constant (say, at $\lambda = 0.6$), the top panel of Figure 4 shows the dynamics of resource stock in patch A, patch B, and system-wide. To illustrate what happens before and after the shift, we assume the shift occurs in period $\tau = 4$.[7] Consistent with our theoretical results, the pre-shift and post-shift steady-state resource stocks in each are reached in one period, though the dynamic patterns

[6] Recall in this case that prices and costs drop out of the escapement and harvests decisions.
[7] But all pre-shift results assume $\lambda = 0.6$.

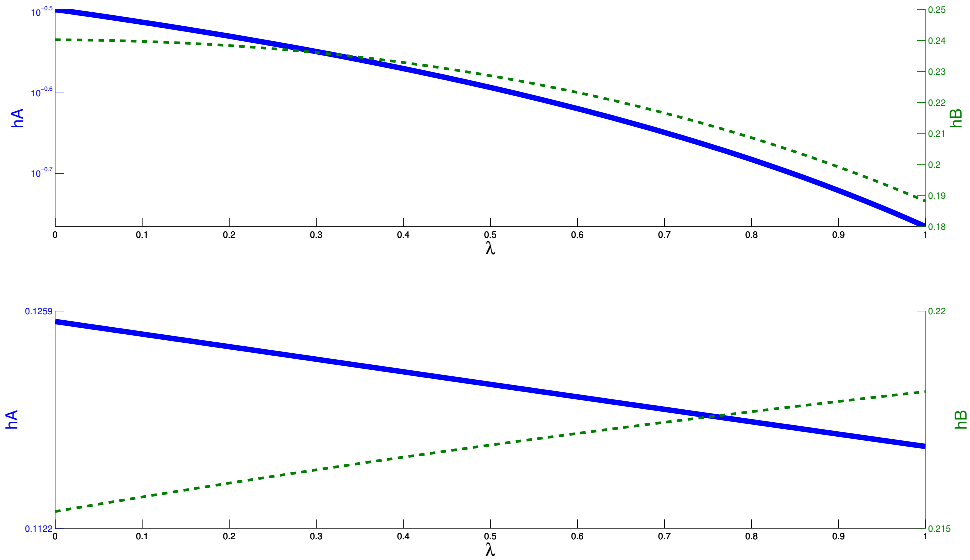

Figure 3: Effects of the threat of regime shift on steady-state harvests. Top panel is for linear costs. Bottom panel is for non-linear costs.

for the equilibrium resource stock in both patches are different. To reach their respective pre-shift steady state in period 1, the initial population in patch A declines whereas the initial stock in patch B increases. Following the shift (in period 4), the resource stock in patch A experiences a small increase to reach its post-shift steady state; stock in patch B experiences the opposite effect. Numerical findings from this section are consistent with results of Lemmas 1 and 2, and Propositions 2 and 3.

5.2 Non-linear cost functions

Since regime shift will disadvantage B and advantage A, it is intuitive that recognizing the possibility of the shift would cause B to decrease escapement and A to increase escapement. But Proposition 4 suggests that the presence of non-linear costs could actually reverse this result. Here we consider the non-linear marginal cost functions $c_j(s) = \theta/s$ for $j = A, B$, with $\theta = 0.6$ and $p_A = p_B = 3$. The other parameters are as described above.

The bottom panel of Figure 2 illustrates equilibrium escapement levels for each patch over a range of regime shift threat probabilities, λ. As the threat level increases, the equilibrium escapement levels in both patches increase. In other words, a higher threat can cause both players to increase their escapements. This numerical result is consistent with Condition 15. A clear implication of these findings is that the threat of regime shift can reduce harvest incentives in both patches at the initial date. These results contrast numerical solutions for the linear cost case (Section 5.1) and are consistent with the findings and implications of Proposition 4.

But as we have shown, an increase in escapement does not necessarily imply a decrease in steady state harvest. In contrast to the constant marginal cost case, our simulations reveal that an increase in λ reduces the steady-state harvest in patch A and increases it in patch B, as illustrated in the bottom panel of Figure 3. Hence, relative to the no-shift case, player A's steady-state harvest under the threat is lower while player B's steady-state harvest is higher. These findings suggest that the stock effect combined with the threat have profound and counterintuitive effects on the short run and long run harvest incentives.

The bottom panel of Figure 4 explores the dynamics of resource stock in the presence of non-linear costs. Comparing the top and bottom panels reveals that the stock effect on costs (i.e. the non-linear nature of costs) gives rise to qualitatively similar results as did the linear cost case, but seems to narrow the gap between the equilibrium resource stocks in each patch. Total resource stock also varies less over time in the presence of the stock effect.

A suite of further simulations covering a range of parameters corroborates our analytical findings that depending on environmental, economic and biological variables, considering linear or non-linear cost functions may yield qualitatively different responses to the threat of regime shift.

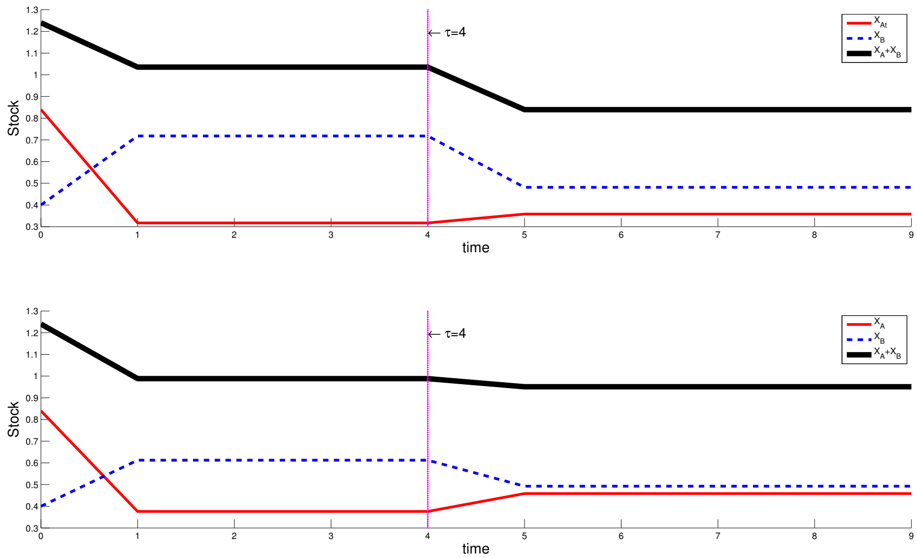

Figure 4: Evolution of the resource stocks over time. Top panel is for linear costs. Bottom panel is for non-linear costs.

6 Conclusion

One of the most widely anticipated effects of global environmental change on natural resources is the shift in the spatial distribution and migration of these stocks. While anticipated shifts range from moderate to severe, and are occasionally predictable, in most cases, the occurrence of such 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 introduce the concept of spatial regime shift where environmental conditions may suddenly and permanently shift at an unknown date in the future. We have examined harvester responses to this type of event. 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 location and a clear disadvantage to the other. Our focus is on how the players compete prior to the shift (but with common knowledge about the likelihood of the shift).

Our analysis has been agnostic about the 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. In the case where harvest costs are non-linear, each of these results can be reversed under certain biological and economic conditions that are examined in the paper.

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, even when utility is linear in harvest, we find conditions under which such a harvester is cautious in response to even a catastrophic threat.

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 likely to change as a consequence of future climate change. The results in this paper help inform predictions about the behavioral responses of countries or other jurisdictions in advance of shifts, and may reveal some counterintuitive results 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

$$W_j(x_t) = p_j(x_{jt} - e_{jt}) - \int_{e_{jt}}^{x_{jt}} c_j(v)dv + \delta W_j(x_{t+1}), \tag{16}$$

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 (16), 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 Lemma 2

Similar to the proof of Lemma 1.

Proof of Proposition 1

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

$$g_j'(e_j) = \frac{1}{\delta D_{jj}^s}, \quad g_j'(\tilde{e}_j) = \frac{1}{\delta D_{jj}}. \tag{17}$$

Since $D_{AA}^s > D_{AA}$ and $D_{BB} > D_{BB}^s$, 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.

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

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

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

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

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

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

Equation17 suggests that for $j = A, B$, e_j depends only on δ and D_{jj}^s whereas for $j = A, B$, $\tilde{e}_j$ depends only on δ and D_{jj}. As such, $\bar{D}_{jx}^s$ and $\bar{D}_{jh}^s$ depend only on δ, D_{jj}^s, D_{ij}, and D_{jj}, $j = A, B$.

B Details for Section 4

Proof of Proposition 2

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

$$g_j'(e_j) = \frac{1}{\delta(\lambda D_{jj}^s + (1-\lambda)D_{jj})}. \tag{18}$$

(ii) Using the implicit value theorem, e_j is a continuously differentiable function of λ. We then differentiate both sides of (18) with respect to λ. Rearranging the outcome yields

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

Since $g_j''(e_j) < 0, D_{BB} > D_{BB}^s$ and $D_{AA}^s > D_{AA}$, 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

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

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

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

(ii) 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

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

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

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

Notice that for $j = A, B$, $\bar{D}_j^h$ and $\bar{D}_j^x$ depend only on λ, δ, D_{jj}, and D_{jj}^s.

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 $e_j > \tilde{e}_j$.

References

Atewamba, C. and B. Nkuiya (2015). Testing the assumptions and predictions of the Hotelling model. *Environmental and Resource Economics*, 1–35.

Carson, R. T., C. Granger, J. Jackson, and W. Schlenker (2009). Fisheries management under cyclical population dynamics. *Environmental and resource economics 42*(3), 379–410.

Cheung, W. W., V. W. Lam, J. L. Sarmiento, K. Kearney, R. Watson, and D. Pauly (2009). Projecting global marine biodiversity impacts under climate change scenarios. *Fish and Fisheries 10*(3), 235–251.

Costello, C. and S. Polasky (2008). Optimal harvesting of stochastic spatial resources. *Journal of Environmental Economics and Management 56*(1), 1–18.

Costello, C., S. Polasky, and A. Solow (2001). Renewable resource management with environmental prediction. *Canadian Journal of Economics/Revue canadienne d'économique 34*(1), 196–211.

Costello, C., N. Quérou, and A. Tomini (2015). Partial enclosure of the commons. *Journal of Public Economics 121*, 69–78.

Fesselmeyer, E. and M. Santugini (2013). Strategic exploitation of a common resource under environmental risk. *Journal of Economic Dynamics and Control 37*(1), 125–136.

Gisser, M. and D. A. Sanchez (1980). Competition versus optimal control in groundwater pumping. *Water Resources Research 16*(4), 638–642.

Kaffine, D. T. and C. Costello (2011). Unitization of spatially connected renewable resources. *The BE Journal of Economic Analysis & Policy 11*(1).

Kapaun, U. and M. F. Quaas (2013). Does the optimal size of a fish stock increase with environmental uncertainties? *Environmental and Resource Economics 54*(2), 293–310.

Kennedy, C. J. and E. B. Barbier (2013). Renewable resource management with environmental prediction: the importance of structural specification. *Canadian Journal of Economics/Revue canadienne d'économique 46*(3), 1110–1122.

Miller, S. and B. Nkuiya (2015). Coalition formation in fisheries with potential regime shift. *Working Paper, University of California Santa Barbara*.

Polasky, S., A. de Zeeuw, and F. Wagener (2011). Optimal management with potential regime shifts. *Journal of Environmental Economics And Management 62*, 229–240.

Reed, W. J. (1979). Optimal escapement levels in stochastic and deterministic harvesting models. *Journal of environmental economics and management 6*(4), 350–363.

Ren, B. and S. Polasky (2014). The optimal management of renewable resources under the risk of potential regime shift. *Journal of Economic Dynamics and Control 40*, 195–212.

Sakamoto, H. (2014). Dynamic resource management under the risk of regime shifts. *Journal of Environmental Economics and Management 68*(1), 1–19.

Sanchirico, J. N. and J. E. Wilen (2005). Optimal spatial management of renewable resources: matching policy scope to ecosystem scale. *Journal of Environmental Economics and Management 50*(1), 23–46.

White, C. and C. Costello (2014). Close the high seas to fishing? *PLoS biology 12*(3), e1001826.