

# Spatial bioeconomics under uncertainty

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## Abstract

The combination of a randomly fluctuating environment and dispersal of biological organisms calls into question the adequacy of traditional bioeconomic models, the vast majority of which are both deterministic and aspatial. Perhaps for this reason, economists have been largely silent on recent policy debates surrounding fisheries management in a complex environment. In particular, much of the scientific community recommends marine protected areas - spatial harvest closures - to mitigate the problems associated with institutional failure in such stochastic spatial systems. Yet this recommendation does not immediately accord with economic intuition. We analyze the economic problem of optimal spatial harvest in a dynamic stochastic environment and derive an analytical solution. The theory has direct implications for spatial resource management, including informing under what biological and economic circumstances, harvest closures are optimal.

## 1 Introduction

This paper addresses the optimal exploitation of renewable resources in the presence of spatial interconnections in a randomly fluctuating environment. Existing bioeconomic theory implicitly assumes that spatial relationships and stochasticity can be ignored. Emerging biological evidence, when combined with realistic economic behavior, suggest otherwise. The theory is presented from the point of view of the sole owner, who can optimize over spatial harvest of this complex bioeconomic system.

Fifty years ago, scientists were beginning to recognize that many of world's fisheries, once plentiful and seemingly limitless, were in trouble; fish stocks were declining and increasing amounts of fishing effort were required to maintain harvest levels. At the time, biologists played the leading role in policy design and analysis for fishery management. Only later would economists engage in this discussion and convincingly articulate the role economic behavior played in the problem, and the potential role economic institutions could play in the solution (Gordon 1954; Scott 1955). As H.S. Gordon explained:

Owing to the lack of theoretical economic research, biologists have been forced to extend the scope of their own thought into the economic sphere and in some cases have penetrated quite deeply, despite the lack of the analytical tools of economic theory. Many others, who have paid no specific attention to the economic aspects of the problem have nevertheless recognized that the ultimate question is not the ecology of life in the sea as such, but man's use of these resources for his own (economic) purposes (Gordon 1954).

The seminal works of Gordon (1954) and Scott (1955) spawned an immense economics literature more or less devoted to examining the institutional failures inherent in a competitive fishery. Gordon (1954) illuminated the externality of one harvester on others, while Scott (1955) was the first to note the dynamic nature of the problem - current harvest had an effect on future stocks. When

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combined with a reasonable depiction of economic harvesting behavior, these observations pointed out the “tragedy of open access”. In the absence of certain kinds of institutions, rents would be completely dissipated and the value of the fishery driven to zero. Subsequent works by Crutchfield and Zellner (1962), Smith (1968), Smith (1969), Clark and Munro (1975), and others examined this dynamic interplay in detail, and outlined a number of possible institutional corrections, which, it was thought, could help secure rents in perpetuity. The subsequent literature on bioeconomics examined a number of extensions to the basic model including rational expectations (Berck and Perloff 1984), environmental variability (Reed 1979), overcapitalization (Grafton et al. 1996), political economy (Johnson and Libecap 1982), and others.<sup>1</sup>

Five decades hence, despite countless subsequent contributions by economists, most fisheries are by any performance measure patently worse-off than they were in the 1950’s (Myers and Worm 2003; Jackson et al. 2001). And just as Gordon observed in 1954, biologists are playing policy analysts, and are, in fact, leading scientific inquiry into how emerging scientific insights will change the way we think about the policy and the design of institutions for managing these systems. As before, most of the analysis by biologists on this issue takes little account of economic behavior, incentives, and objectives.

Spatial connectivity of the bioeconomic environment – driven by the interplay between environmental, biological, and economic conditions – imposes an important spatial externality that remains largely ignored in economic analysis but is perhaps as significant a cause of misallocation of resources as the dynamic externality identified five decades ago. This spatial externality derives from the fact that most commercially important fish species distribute themselves across vast areas. Economic exploitation takes place by individual fishermen in particular locations. When combined, these bioeconomic conditions imply a spatial externality of harvest - one fisherman’s exploitation in a particular location affects larval production, and therefore harvest opportunities, for fishermen in other locations in subsequent periods. While Scott almost surely did *not* have the spatial externality of dispersal in mind, his insights about the role of property rights to effectively solve the fishery problem clearly apply: “...the property must be allocated on a scale sufficient to insure that one management has complete control of the asset” (p. 116). Because the bioeconomic system is connected in a complex spatial web in which actions in one location affect available opportunities in others, it is possible that the harvesting strategies (and indeed institutions) that were conceived under an assumption of an aspatial environment, are insufficient in the presence of spatial externalities.

Would accounting for these complex dynamical and often stochastic spatial linkages appreciably change, in a qualitative way, the way we think about bioeconomic analysis? That is the focus of this paper.

## 1.1 Spatial connections beget spatial policies

As early as the 1990’s biologists had substantiated that the marine environment was more complicated than aspatial deterministic bioeconomic models appreciated. In fact most harvested fish species were a part of a spatially-connected biological environment where “the vast majority of marine species possess a pelagic larval dispersal phase” (Roberts 1997), which means that after marine fish spawn the larvae are subject to the whim of ocean currents and are sometimes transported thousands of kilometers. While the general tendencies of ocean currents are known, this process is highly random, as is the survival and ultimate productivity of the fish. When combined, the spatial nature of larval dispersal and the uncertainty and variability in the biological system might help explain why institutions, which were derived under the assumption of an aspatial environment, had failed. A new set of institutions, it is argued, are required for fishery management to be successful.

What emerged out of these basic scientific insights is perhaps the most intensively researched and debated marine policy issue in history - marine protected areas (MPAs), which are areas of ocean that are closed to all harvest activity. Once proposed, biologists were quick to weigh-in on the policy debate despite the surprising lack of data or formal analysis. An influential early paper on the subject states “It is time to trust the insights of ecologists for once, press for the establishment

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<sup>1</sup>Wilens (2000) provides an informative and thorough history of the contributions of economists to institutional policy design.

of marine reserves and place fisheries management and marine conservation on a sound basis at last” (Roberts 1997). The subsequent scientific literature is immense - and growing. The *de facto* objective of this literature is to prove, that marine reserves are “good” for fisheries.

Despite the economic nature of this question, the approach has, almost categorically, ignored even basic insights from economics. For example an influential analytical paper on the benefits of marine reserves for fisheries assumes away fishing costs, yet requires that all fish outside the reserve are harvested (Hastings and Botsford 1999). In that case, and under other special biological assumptions, the authors show that marine reserves could produce the same (though not greater) *yield* as a quota-managed fishery.

To our knowledge the first substantive attempt to link spatial relationships in a true bioeconomic model is in Clark (1990), which explores both open access and optimized harvest in a model where spatial connections are driven by diffusion. An extension of this approach is provided by Neubert (2003). Our analysis differs from those papers in two important ways. First, we incorporate a randomly fluctuating environment, which we find plays an important qualitative role in the sole owner’s optimized harvest over space. A more important difference is the treatment of spatial connections. By assuming diffusion along a line, the linkages across patches are highly stylized. This simplification significantly limits the scope of economic questions that can be answered. We attempt to expand this analysis by allowing a patchy environment in which spatial connections are more meaningful. A small literature exists on game theoretic interactions between multiple parties who jointly harvest a highly migratory fish stocks and straddling fish stocks (see, e.g. Bjorndal et al. (2004) and Naito and Polasky (1997)). Ours differs from that literature in that we consider sessile organisms (those that do not move appreciably in their adult life-stage) and treat space explicitly, rather than implicitly.

A series of papers by James Sanchirico and James Wilen represent the most comprehensive investigation of the bioeconomics of spatially connected marine resources and realistic economic activity to date. Sanchirico and Wilen (1999) is the first paper to outline a model of spatial exploitation in a discrete patchy environment. The focus of Sanchirico and Wilen (2001) was to examine the consequences of establishing a reserve in the absence of any regulation in the harvest region. Open access outside the reserve drives rents to zero, so the authors examine the consequences of reserve creation on total harvest. A similar analysis in which larvae are mobile, adults are sessile, assuming open access conditions prevail, is provided by Pezzey et al. (2000).

But given our interest in *optimal* spatial exploitation, this small economics literature that focuses on open access conditions provides little guidance. We are aware of only one paper that examines optimal spatial exploitation in a patchy environment. Sanchirico and Wilen (2005) analyze the question by examining the case of “regulated open access” in which the fishery manager can choose spatially heterogeneous landings and effort taxes in a deterministic environment. In that model the objective is linear in these control variables and so a bang-bang solution is obtained. Focus is devoted to the singular control that obtains in the equilibrium. The focus of that paper is on interior solutions which leaves largely unanswered the question of whether harvest closures are optimal.

## 2 Problem statement

Taking emerging biological evidence as given, we derive an optimal spatial harvest strategy for a sole-owner in an uncertain environment. Focusing on the optimal spatio-temporal exploitation by the sole owner will inform the design of appropriate property rights institutions for correcting the spatial externality. Our focal resource is a renewable resource (most appropriately a fishery) for which breeding adults are sessile but young are dispersed across space. Examples of such resources include sea urchin, abalone, and rockfish from the marine environment, and plants from the terrestrial environment. The spatial externality is captured as follows: optimal harvest within patch  $i$  will depend not only on the bioeconomic features within that patch, but on the growth potential, stock size, and indeed harvest choices, in all patches to which larvae spawned in patch  $i$  might disperse. Motivated by biological models that identify multiple sources of uncertainty and variability in such systems, we incorporate spatial heterogeneity among an arbitrary number of patches, stochastic

dispersal of young (e.g. due to wind or ocean currents), and random shocks to the production function into an integrated bioeconomic framework. The objective is to identify a spatially-explicit optimal feedback control rule to maximize the expected net present value of the resource.

We analyze a model that incorporates the spatial heterogeneity, stochasticity, and dynamic optimization components listed above. The model is solved analytically, using stochastic dynamic programming, for an optimal feedback control rule which identifies the optimal harvest in every patch as a function of the state of the system. The result is interpreted and explored with a simple intuition-building exercise.

Among other novel features, this framework facilitates exploring the consequences of spatially heterogeneous management strategies such as marine protected areas (MPAs). But instead of asking whether harvest or profits can benefit from MPAs, we identify the conditions under which reserves *emerge* as an optimal solution to the spatial harvesting problem. Put simply, if the optimal harvest in a patch is zero, then that patch should be a reserve; reserves can be either temporary or permanent. The analytical framework allows us to explore a wide array of novel policy relevant questions relating to spatial resource exploitation under uncertainty. In the analysis we specifically address the following questions:

1. What is the optimal spatial harvest strategy for a solely-owned resource subject to spatial heterogeneity (in biology and economics)?
2. How does this strategy differ from the aspatial case? And what are the consequences of ignoring space?
3. How does the optimal harvest strategy depend on variability and uncertainty?
4. Are permanent reserves (MPAs) *ever* optimal? Under what conditions? How should they be designed?
5. Are temporary reserves ever optimal? If so, when?
6. How does the imposition of an MPA affect optimal exploitation outside the reserve?

Despite the complex ecological and economic dynamics of this problem, we are able to derive analytical results to answer these questions. Among other interesting results, we find that variability and stochasticity change, in non-trivial ways, the way we should think about spatial management of renewable resources. And in general optimal management involves heterogeneous harvest effort across space. However, we also identify a necessary and sufficient condition under which the dispersal dynamics across patches can be ignored in an optimal spatial harvest strategy. In that case, the optimal harvest will still be spatially-heterogeneous, but will depend only on the features of the production site, so is identical to the result that would have been obtained under the assumption that each patch was its own, unconnected, fishery. But in general we find that spatial interconnections cannot be ignored in optimal management. Further, when sites are sufficiently heterogeneous, permanent reserves may indeed be optimal. Even without significant productivity heterogeneity, stochastic growth and larval dispersal can lead to optimal temporary closures to let stocks rebuild.

Of further relevance to the design and implementation of harvest closures, we explore in detail how implementing a spatial fishing closure should affect optimal management outside the reserve. Contrary to much of the existing literature (only a small fraction of which examines optimal strategies), we find that if a permanent reserve is optimally placed, harvest outside the reserve should decrease, relative to the no-reserve case. This surprising result obtains because reserves are optimal only when (roughly speaking) the marginal productivity in a patch is high. This increases the incentive to allow larval dispersal from other patches to the reserve. On the other hand, if a reserve is arbitrarily placed (in a sub-optimal location), then harvest outside that reserve should increase, for the same reason as identified above.

### 3 Spatial bioeconomic model under uncertainty

We introduce a spatially-explicit bioeconomic model where both space and time are measured in discrete units. There are  $I$  geographically non-overlapping patches indexed by  $i$  and  $T$  (possibly infinite) time periods indexed by  $t$ . The sole owner’s objective is to determine the feedback control rule that maximizes the expected value of the resource over the  $T$  period horizon. This rule will, in general, be a patch and time-specific harvest function that depends on the population of harvestable individuals in every patch. Certain aspects of the bioeconomic environment are stochastic and are uncertain from the perspective of the manager. We denote random variables by capital letters and realizations of random variables by lower-case letters. We begin with a description of the biological environment and then focus attention on the spatial economic environment. Management controls can be made optimal only by combining these features into an integrated spatio-temporal optimization framework.

#### 3.1 Spatial fish biology

While ill-equipped to address questions about optimal resource exploitation, biologists are used to analyzing spatially-explicit resource dynamics. We focus attention on biological resources for which adults are sessile, and progeny are mobile. This is a realistic assumption for species such as lobster, urchin, rockfish, trees, and plants. It is unrealistic for highly migratory or mobile species such as tuna, wildebeest, and whales. The stock of adults in patch  $i$  at time  $t$  is  $x_{it}$  which is known at time  $t$ . Harvest  $h_{it}$  takes place in patch  $i$ , yielding a known period- $t$  stock of reproducing adults:  $e_{it} = x_{it} - h_{it}$ . For fish,  $e_{it}$  is known as “escapement”; the stock of fish that “escape” the fishery. The dynamics of this biological population depend critically on the spatial distribution of escapement,  $e_{it}$ , and on the subsequent reproductive success in each patch, measured by the number of “young” ( $Y_{it}$ ) produced in each patch. For marine species, this is larval production. For terrestrial plant species, this is seed production. The number of young produced depends in the usual way on a spatially distinct average growth function  $f_i(e)$ , where  $f'_i(e) > 0$   $f''_i(e) < 0$ . But because reproductive success has been shown to be influenced by stochastic processes (e.g. wind, nutrient availability, rainfall) we build in a spatially distinct period- $t$  multiplicative random shock to growth,  $Z_{it}^f$ , as follows:

$$Y_{it} = Z_{it}^f f_i(e_{it}) \tag{1}$$

Where the statistical distribution of  $Z_{it}^f$  is known and such distributions are time-independent. Equation 1 is a spatial version of the stochastic fishery problem considered by Reed (1979), Costello et al. (2001), and others.

The young produced in patch  $i$  disperse across space and settle in random locations. The stock of young that successfully settle in patch  $i$  in period  $t$  will depend, in general, on production in all patches and on the propensity to drift to, and settle in, patch  $i$ . For example, recent biological evidence suggests that oceanographic currents, combined with bathometric features of the seafloor may funnel a large percentage of larvae to a particular patch. This connectivity between patches is well-studied in biology. Biologists use the term “dispersal kernel” to denote the proportion of total production in a patch that settles in each of the  $I$  patches. In the conventional biological literature, the dispersal kernel is a deterministic concept. More recently biologists have recognized that large random fluctuations in the environment may render the dispersal kernel itself random. The nature of this stochasticity will depend both on the number of release events from patch  $i$  at time  $t$ , and on the correlation in settling location for young that are released in the same event. Denote by  $D_{ji}$  a random variable indicating the percentage of young that originate in patch  $j$  and settle in patch  $i$  (so  $\sum_i D_{ji} = 1$ ), total settlement to patch  $i$  is:<sup>2</sup>

$$S_{it} = \sum_{j=1}^I Y_{jt} D_{ji} \tag{2}$$

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<sup>2</sup>Note that the the number of independent larval releases from this distribution will determine the variability in  $D$ . As the number of such releases approaches  $\infty$ ,  $D$  simply reverts to the deterministic dispersion kernel itself. In that case,  $D$  is deterministic.

Following settlement, individuals are sessile and some reach adulthood. Survival to adulthood in patch  $i$  may depend on ocean conditions and on the stock of settlers in that patch. Survival can be written:  $Z_{it}^S \sigma_i(S_{it})$ , where  $Z_{it}^S$  is a spatially distinct random shock to larval survival and the spatially distinct function  $\sigma_i(S_{it})$  describes the average survival to adulthood in patch  $i$ . Again, we assume that the statistical distribution of  $Z_{it}^S$  is known and is independent across periods.

Finally, some adults survive from period to period, where adult survival may depend on the density of adults. Adult survival is given by  $Z_{it}^\mu \mu_i(e_{it})$ , where  $Z_{it}^\mu$  is a spatially distinct random shock to survival, and the spatially distinct function  $\mu_i(e_{it})$  describes average survival as a function of the number of adults.

This description of the spatial biological relationships embeds four sources of stochasticity. To summarize, these sources of stochasticity are:

- $Z_{it}^f$ : shock to production of young (e.g. wind affects pollination for terrestrial plants)
- $D_{ji}$ : stochastic spatial dispersal (e.g. ocean currents dictate larval drift)
- $Z_{it}^\mu$ : shock to survival of adults (e.g. upwelling influences nutrient availability in marine systems)
- $Z_{it}^S$ : shock to survival of settlers (e.g. temperature impacts suitability of settlement location)

We assume that the distributions of each of these random variables is known, the expected value of all multiplicative shocks is 1, the support is bounded below by 0, and that the random variables are independent of each other and of calendar time. From the perspective of the sole owner in time period  $t$ , the number of adults in patch  $i$  in time period  $t + 1$  is a random variable given by:

$$X_{it+1} = Z_{it}^\mu \mu_i(e_{it}) + Z_{it}^S \sigma_i(S_{it}) \quad (3)$$

$$= Z_{it}^\mu \mu_i(e_{it}) + Z_{it}^S \sigma_i \left( \sum_{j=1}^I Z_{jt}^f f_j(e_{jt}) D_{ji} \right) \quad (4)$$

The first term on the right hand side of equation 4 gives the (stochastic) adult survival from the previous period. The second term on the right hand side gives the (stochastic) contribution of reproduction and settlement from all other patches. Importantly, the stock size in any patch  $k$  in time period  $t + 1$  will depend on escapement in all  $I$  patches,  $e_{it}$ ,  $i = 1, \dots, I$ , and on the random variables in all  $I$  patches,  $Z_{it}^f$ ,  $D_{ik}$ ,  $Z_{it}^\mu$ , and  $Z_{it}^S$ ,  $i = 1, \dots, I$ .

### 3.2 Spatial economics

The bioeconomic objective is to maximize the expected net present value of the resource over a  $T$ -period (possibly infinite) horizon. Following Reed (1979), Clark and Kirkwood (1986), and others, we assume an elastic demand at price,  $p$  per unit harvest, and that the marginal cost of harvest  $c_i(s)$  is a non-increasing function of the current stock,  $c'_i(s) \leq 0$ . By indexing  $c_i(\cdot)$  by  $i$  we allow for the possibility that harvest costs may be location specific. For example marginal harvest costs in fishing may increase with depth or distance to port. Then the patch- $i$  period- $t$  payoff from harvest  $h_{it}$  starting with a population of  $x_{it}$  and ending with a population of  $e_{it}$  is:  $ph_{it} - \int_{e_{it}}^{x_{it}} c(s) ds$ .

The sole owner's objective is to maximize expected discounted profit across all  $I$  patches over all  $T$  time periods, as follows:

$$\max_{\{h_{it}\}} E \sum_{t=1}^T \delta^t \sum_{i=1}^I \left[ ph_{it} - \int_{e_{it}}^{x_{it}} c(s) ds \right] \quad (5)$$

where  $E$  is the expectation operator and  $\delta$  is the discount factor. The maximization problem is subject to the the growth equation, 4. The objective is to identify a feedback control rule  $\mathbf{h}_t^*(\mathbf{x}_t)$ , that is an  $I$ -vector function of state-dependent controls, that yields the optimal patch-specific harvest as a function of the patch-specific stock in any given period,  $t$ .

## 4 The spatial bioeconomic problem

In this section we derive an analytic solution to the spatial bioeconomic harvest problem under uncertainty. We first derive the interior solution and the conditions required for its existence. Focus is then shifted to the bioeconomically relevant and interesting case when these conditions are violated, so the solution is at a corner and it is optimal to close an area to harvesting, either temporarily (to let stock rebuild) or permanently (because the patch's system-wide contribution to growth always exceeds the marginal value of harvest). A question central to this analysis is if, and under what biological or economic conditions, such closures are optimal. Our approach - of solving for the optimal spatial harvest by the sole owner and observing whether reserves emerge as a solution - will further allow us to determine the optimal spatial and temporal design of such closures, taking into account the spatial externalities resulting from biological connectivity and economic heterogeneity across space.

It is convenient to represent the spatial bioeconomic problem under uncertainty as a stochastic dynamic programming problem with  $\mathbf{x}_t$  as the period- $t$  state vector of stocks and  $\mathbf{e}_t$  as the period- $t$  control vector, as follows:

$$V_t(\mathbf{x}_t) = \max_{\mathbf{e}_t} \sum_{i=1}^I \left[ p(x_{it} - e_{it}) - \int_{e_{it}}^{x_{it}} c(s) ds \right] + \delta E_t \{V_{t+1}(\mathbf{X}_{t+1})\}. \quad (6)$$

which is subject to spatial state transitions given by equation 4. The continuation value is a function of the vector of subsequent stocks,  $\mathbf{X}_{t+1} \equiv [X_{1t+1} X_{2t+1} \dots X_{It+1}]$ , where from the perspective of period- $t$ , period  $t+1$  stocks are random variables. It is convenient to define a function that gives the single-period profits in the case of unregulated resource extraction. Let  $\check{x}_i$  be the stock level to which a purely myopic harvester would extract the resource. Therefore,  $\check{x}_i$  is either zero or the level of stock at which marginal profit is zero, whichever is larger. The patch- $i$  period- $t$  profit from harvesting down to  $\check{x}_i$  is given by the following function:

$$Q_i(x_{it}) \equiv p(x_{it} - \check{x}_i) - \int_{\check{x}_i}^{x_{it}} c_i(s) ds \quad (7)$$

Using this function, we can re-write the dynamic programming equation 6 as follows:

$$V_t(\mathbf{x}_t) = \max_{\mathbf{e}_t} \sum_{i=1}^I [Q_i(x_{it}) - Q_i(e_{it})] + \delta E_t \{V_{t+1}(\mathbf{X}_{t+1})\}. \quad (8)$$

which is subject to biological state transitions given in 4. Before proceeding, we note that we will represent optimal solutions by  $\mathbf{e}_t^*(\mathbf{x}_t)$ .

### 4.0.1 An interior solution to the spatial bioeconomic problem under uncertainty

In this section we derive the interior solution to the dynamic programming problem 8. To do so we will require the following definition.

**Definition 1** *An optimization problem is **state separable** if the first order conditions are independent of the state vector.*

State separability is a technical property that will be employed in the following analysis.

**Lemma 1** *Provided that an interior solution exists, the period  $t$  dynamic program given in equation 8 is state separable.*

**Proof.** The dynamic programming problem is:

$$V_t(\mathbf{x}_t) = \max_{\mathbf{e}_t} \underbrace{\sum_{i=1}^I [Q_i(x_{it}) - Q_i(e_{it})]}_{\text{Current Payoff}} + \underbrace{\delta E_t \{V_{t+1}(\mathbf{X}_{t+1})\}}_{\text{Future Payoff}}. \quad (9)$$

The first order condition is:

$$-Q'_i(e_{it}) + \delta E_t \left\{ \sum_{j=1}^I \frac{\partial V_{t+1}(X_{t+1})}{\partial X_{jt+1}} \frac{\partial X_{jt+1}}{\partial e_{it}} \right\} = 0 \quad (10)$$

To show state separability, we must show that all terms in this expression are independent of  $x_{it}$ . The first term, which reflects the marginal contribution of escapement to the myopic payoff, is independent of  $x_{it}$  by inspection. The term inside the expectation operator is the product of the partial derivative of the value function with respect to  $X_{jt+1}$  and the partial derivative of  $X_{jt+1}$  with respect to  $e_{it}$ . Note that in an interior solution  $e_{it} < x_{it}$ . Therefore  $X_{t+1}$  is a function of  $e_t$  but not of  $x_t$ . Since the value function is a function of only stocks in period  $t + 1$ , its derivative is independent of period  $t$  stocks. Inspecting equation 4, and invoking the interior solution assumption for this Lemma,  $\frac{\partial X_{jt+1}}{\partial e_{it}}$  is also independent of  $x_{it}$ . Since all terms in 10 are independent of  $x_{it}$ , the period  $t$  problem is state separable. ■

This discussion leads us to our first result, which characterizes the interior solution to this problem.

**Proposition 1** *If an interior solution to the dynamic programming equation exists, the optimal feedback control rule will, in general, vary across space, but will be both time and state independent.*

**Proof.** The necessary condition for an interior optimal solution to the dynamic programming equation (equation 8) for patch  $i$  at time  $t$  is given by equation 10. Note that  $e_{it}^*$  is independent of  $x_{it}$  by Lemma 1. Therefore, a change in stock in the next period affects the value function in  $t + 1$  only through terms  $Q_j(x_{jt+1})$ , for  $j = 1, \dots, I$ . Using this fact along with the state transition equations (equation 4), we can rewrite the necessary condition for patch  $i$  at time  $t$  as follows:

$$-Q'_i(e_{it}^*) + \delta E_t \left\{ Q'_i(x_{it+1}) Z_{it}^\mu \mu'_i(e_{it}^*) + \sum_{j=1}^I Q'_j(x_{jt+1}) Z_{jt}^S \sigma'_j(\cdot) Z_{it}^f f'_i(e_{it}^*) D_{ij} \right\} = 0 \quad (11)$$

Since the distribution of shocks is independent of time, as is biological growth, dispersal and economic returns, the optimal choice,  $e_{it}^*$ , is independent of time. However, since biological growth, dispersal and economic returns can vary across patches, the optimal choice can, in general, vary across space. ■

Proposition 1 states that the optimal policy is to identify a patch-specific escapement level, and to harvest down to that level every period. Optimal escapements may vary across space for three important reasons. First, spatial heterogeneity in the economic environment (captured here by different harvest costs) drives spatial incentives for harvest. Second, spatial heterogeneity in the biological environment (captured by differences in biological productivity across patches) will influence exploitation. Finally, and perhaps most importantly, patterns of dispersal of young can affect harvest. In general, this spatial configuration plays an important role in the sole owner's optimal harvest strategy.

Next we examine the role of spatial externalities in the sole owner's solution. In particular we identify a bioeconomically meaningful sufficient condition under which spatial connectivity plays no role in the solution. For that result we require the following assumptions:

**Assumption 1** *Total harvest cost is a linear function of total harvest (given by  $ch_{it}$  in patch  $i$ , period  $t$ ).*

**Assumption 2** *The survival function  $\sigma_j(x)$  is linear and identical across patches (so  $\sigma_j(x) = \sigma x$ .)*

**Proposition 2** *Under Assumptions 1 and 2, and provided that an interior solution to the dynamic programming equation exists, the optimal feedback control rule satisfies the golden rule of growth in each patch in each time period and is independent of dispersal.*

**Proof.** Under Assumption 1,  $Q_i(x) = (p - c)(x - \tilde{x}_i)$ . Further under Assumption 2, the necessary condition for an interior solution to the optimal feedback rule for patch  $i$  at time  $t$  is:

$$-(p - c) + \delta E_t \left\{ (p - c) Z_{it}^\mu \mu'_i(e_{it}^*) + \sum_{j=1}^I (p - c) Z_{jt}^S \sigma Z_{it}^f f'_i(e_{it}^*) D_{ij} \right\} = 0 \quad (12)$$

Simplifying, we obtain:  $1 = \delta \left\{ \mu'_i(e_{it}^*) + \sum_{j=1}^I \sigma f'_i(e_{it}^*) D_{ij} \right\}$ . And since  $\sum_{j=1}^I D_{ij} = 1$ , this expression simplifies to:

$$1 = \delta \left\{ \mu'_i(e_{it}^*) + \sigma f'_i(e_{it}^*) \right\}. \quad (13)$$

The right hand side of equation 13 is the discounted expected growth of the stock remaining at the end of the period so that equation 13 is a golden rule of growth result. Dispersal drops out and does not affect the optimal rule.

With identical costs and survival across sites, what matters is the productivity of each site ( $\mu'_i(e_{it}^*) + \sigma f'_i(e_{it}^*)$ ), not where recruits end up. No matter where recruits end up, they are harvested and generate the same returns per unit,  $(p - c)$ . ■

#### 4.0.2 Corner solutions

We have shown that provided the stock size in every patch is sufficiently large, the interior solution to this problem is optimal, and that it entails achieving a different escapement level in each patch across space. We have also shown that under the interior solution the patch-specific escapement does not vary over time, and in the special case with no stock dependent costs and no density dependent survival, the patch-specific escapement follows precisely the aspatial ‘‘Golden Rule of Growth’’. The next proposition addresses the case in which an interior solution to the dynamic programming problem does not exist.

**Proposition 3** *Patch  $i$  should be closed to harvesting in period  $t$  if and only if  $x_{it} < \bar{e}_{it}$ , where  $\bar{e}_{it}$  satisfies*

$$-Q'_i(\bar{e}_{it}) + \delta E_t \left\{ \sum_{j=1}^I \frac{\partial V_{t+1}(X_{t+1})}{\partial x_{jt+1}} \frac{\partial x_{jt+1}}{\partial e_{it}} \right\} = 0 \quad (14)$$

**Proof.** Because  $-Q''_i(e) < 0$ , and

$$\frac{\partial}{\partial e_{it}} \left\{ E_t \left( \sum_{j=1}^I \frac{\partial V_{t+1}(X_{t+1})}{\partial x_{jt+1}} \frac{\partial x_{jt+1}}{\partial e_{it}} \right) \right\} < 0$$

we have

$$-Q'_i(e_{it}) + \delta E_t \left\{ \sum_{j=1}^I \frac{\partial V_{t+1}(X_{t+1})}{\partial x_{jt+1}} \frac{\partial x_{jt+1}}{\partial e_{it}} \right\} > 0 \quad (15)$$

for  $e_{it} < \bar{e}_{it}$ . In this case, it is optimal to increase escapement. However, we know that  $e_{it} \leq x_{it}$ , so if  $x_{it} < \bar{e}_{it}$  the maximum  $e_{it}$  that can be attained is  $e_{it} = x_{it}$ , which occurs with zero harvest. Therefore, for  $x_{it} < \bar{e}_{it}$  it is optimal to close patch  $i$  to harvesting in period  $t$ . For  $e_{it} > \bar{e}_{it}$ ,  $-Q'_i(e_{it}) + \delta E_t \left\{ \sum_{j=1}^I \frac{\partial V_{t+1}(X_{t+1})}{\partial x_{jt+1}} \frac{\partial x_{jt+1}}{\partial e_{it}} \right\} < 0$  and it is optimal to lower escapement. When  $x_{it} \geq \bar{e}_{it}$ , it is optimal to have positive harvest and have escapement of  $e_{it} = \bar{e}_{it}$ . ■

It follows immediately from Proposition 3 that if  $x_{it} < \bar{e}_{it}$  for all  $t$  then patch  $i$  should be permanently closed to harvest. In that case, patch  $i$  is part of a permanent marine protected area. Such a case could occur with stationary and deterministic distributions for all parameters and an infinite horizon. In a stationary solution, if inequality 15 holds, then this condition will hold in all subsequent periods, i.e. it will be optimal to have a permanent protected area.

Proposition 3 provides a necessary and sufficient condition for a harvest closure to be economically optimal for the sole owner. Under such a circumstance the fishery owner is still faced with the task of determining optimal harvest *outside* the closed area. This question is of central importance to policy surrounding MPAs and their design, yet it has received only scant attention in this literature. When analyzing the consequences of harvest closures two different approaches have been taken. Biologists typically assume maximal harvest outside the reserve (e.g. Hastings and Botsford (1999)). Of course in a world with stock-dependent harvest costs (such as depicted by this model) it would never be economically rational to harvest to extirpation in a patch (provided  $c(0) > p$ ). The other approach is to assume open access outside the closure (e.g. Sanchirico and Wilen (2001)). But since we are interested in the optimal behavior of a sole owner, we would like to know about optimal choices outside the reserve compared to choices in the absence of a reserve. To assist in model tractability, we will adopt the following assumption:

**Assumption 3** *The only patch that is possibly in a corner solution is patch  $k$  at time  $t + 1$ .*

**Proposition 4** *Under Assumption 3, if there is some non-zero probability that it will be optimal to close patch  $k$  to harvest at time  $t + 1$ , then for any patch  $i$  for which  $Pr(D_{ik} = 0) < 1$ , optimal escapement in patch  $i$  at time  $t$  will be higher than an equivalent case with zero probability of optimal closure of patch  $k$  at time  $t + 1$ .*

**Proof.** When patch  $k$  is in an interior solution at time  $t + 1$ , the marginal value of escapement from patch  $i$  in period  $t$  is:

$$\delta E_t \left\{ Q'_i(x_{it+1}) Z_{it}^\mu \mu'_i(e_{it}^*) + \sum_{j=1}^I Q'_j(x_{jt+1}) Z_{jt}^S \sigma'_j(\cdot) Z_{it}^f f'_i(e_{it}^*) D_{ij} \right\} \quad (16)$$

When patch  $k$  is in a corner solution at time  $t + 1$ , the marginal value of escapement from patch  $i$  in period  $t$  is:

$$\begin{aligned} & \delta E_t [Q'_i(x_{it+1}) Z_{it}^\mu \mu'_i(e_{it}^*) + \sum_{j \neq k} Q'_j(x_{jt+1}) Z_{jt}^S \sigma'_j(\cdot) Z_{it}^f f'_i(e_{it}^*) D_{ij} + \\ & \delta E_{t+1} \left[ \sum_{j=1}^I Q'_j(x_{jt+2}) Z_{jt}^S \sigma'_j(\cdot) Z_{kt}^f f'_k(x_{kt+1}) Z_{kt}^S \sigma'_k(\cdot) D_{jk} Z_{it}^f f'_i(e_{it}^*) D_{ik} \right] \end{aligned} \quad (17)$$

When patch  $k$  is in a corner solution in period  $t + 1$ ,

$$Q'_k(x_{kt+1}) < \delta E_{t+1} \left[ \sum_{j=1}^I Q'_j(x_{jt+2}) Z_{jt}^S \sigma'_j(\cdot) Z_{kt}^f f'_k(x_{kt+1}) D_{jk} \right] \quad (18)$$

Using this fact and comparing equations 16 and 17, it follows that the marginal value of escapement from patch  $i$  in period  $t$  is higher for the case when patch  $k$  is in a corner solution in period  $t + 1$  than when patch  $k$  is in an interior solution. Therefore, to satisfy the necessary conditions for an optimal solution in patch  $i$  in period  $t$ , escapement must be higher for the case where patch  $k$  is in a corner solution than when it is in an interior solution in period  $t + 1$ . ■

**Proposition 5** *Under Assumption 3, if it is optimal to have an interior solution (positive harvest) but harvest is closed in patch  $k$  at time  $t + 1$ , and assuming  $Pr(D_{ik} = 0) < 1$ , then optimal escapement in patch  $i$  at time  $t$  will be lower than when there is no harvest closure in patch  $k$  at time  $t + 1$ .*

**Proof.** When harvest is allowed in patch  $k$  at time  $t + 1$ , the marginal value of escapement from patch  $i$  in period  $t$  is as shown in equation 16. When harvest is closed in patch  $k$  in period  $t + 1$ , the marginal value of escapement from patch  $i$  in period  $t$  is as shown in equation 17. In this case the inequality is reversed as compared to the proof of proposition 4

$$Q'_k(x_{kt+1}) > \delta E_{t+1} \left[ \sum_{j=1}^I Q'_j(x_{jt+2}) Z_{jt}^S \sigma'_j(\cdot) Z_{kt}^f f'_k(x_{kt+1}) D_{jk} \right] \quad (19)$$

so that the marginal value of escapement from patch  $i$  in period  $t$  that goes to patch  $k$  in period  $t + 1$  is lower with the closure. Therefore, to satisfy the necessary conditions for an optimal solution in patch  $i$  in period  $t$ , escapement must be lower for the case where patch  $k$  is closed in period  $t + 1$  than when it is not. ■

## 5 Intuition-building examples

Many of the salient features of this model can be illustrated with a 2-patch representation of the spatial bioeconomic problem. We do so here by employing logistic biological growth with spatial dispersal and a simple parametric representation of the economic costs of harvesting (also spatially heterogeneous).

### 5.1 Biological environment

For these illustrative examples we will assume that biological growth is logistic in each patch; we capture differences in biological productivity with the carrying capacity parameters,  $K_1$  and  $K_2$ . The biological dynamics are as follows:

$$x_{1t+1} = D_{11} \left[ e_{1t} \left( 2 - \frac{e_{1t}}{K_1} \right) \right] + D_{21} \left[ e_{2t} \left( 2 - \frac{e_{2t}}{K_2} \right) \right] \quad (20)$$

$$x_{2t+1} = D_{12} \left[ e_{1t} \left( 2 - \frac{e_{1t}}{K_1} \right) \right] + D_{22} \left[ e_{2t} \left( 2 - \frac{e_{2t}}{K_2} \right) \right] \quad (21)$$

where  $D_{ij}$  is the proportion dispersal from patch  $i$  to patch  $j$  which is assumed to be deterministic in these examples.

### 5.2 Economic environment

Current value profit in a patch depends both on the quantity harvested,  $x_{it} - e_{it}$ , and on the stock at the beginning of the harvest period,  $x_{it}$ . We will assume a stock-dependent marginal harvest cost of  $\theta_i/x$ , which implies that the myopic fisherman would harvest to the level  $x_i = \theta_i p$ . Normalizing price,  $p = 1$ ,  $\theta_i$  is interpreted as the stock size in patch  $i$  at which it becomes unprofitable to harvest, so  $\tilde{x}_i \equiv \theta_i$ . Period- $t$  profit from harvesting in each patch is given as follows:

$$\pi_{1t} = (x_{1t} - e_{1t}) - \int_{x_{1t}}^{e_{1t}} \frac{\theta_1}{s} ds = (x_{1t} - e_{1t}) - \theta_1 \log \left( \frac{x_{1t}}{e_{1t}} \right) \quad (22)$$

$$\pi_{2t} = (x_{2t} - e_{2t}) - \int_{x_{2t}}^{e_{2t}} \frac{\theta_2}{s} ds = (x_{2t} - e_{2t}) - \theta_2 \log \left( \frac{x_{2t}}{e_{2t}} \right) \quad (23)$$

### 5.3 Examples

We examine a series of 6 scenarios to illustrate the key results of the previous section. Each scenario is fully characterized by 8 parameters. Parameter values for each scenario are given in Table 1 below:

Scenario	$K_1$	$K_2$	$\theta_1$	$\theta_2$	$D_{11}$	$D_{12}$	$D_{21}$	$D_{22}$
1.	80	100	10	5	1.0	0	0	1.0
2.	80	100	10	5	0.3	0.7	0.5	0.5
3.	80	100	0	0	0.7	0.3	0.4	0.6
4.	80	100	10	5	0.3	0.7	0.5	0.5
5.	80	100	10	5	0.01	0.99	0.01	0.99
6.	80	100	10	5	0.3	0.7	0.5	0.5

For each scenario, we optimize over harvest in each patch in a 4 period model,  $t = 1, \dots, 4$  under the constraint that  $e_{it} \leq x_{it}$  for patches  $i = 1, 2$  and all time periods,  $t$ .

### 5.3.1 Scenario 1

We begin with the baseline case in which there is no dispersal between patches:  $D_{ij} = 0$  for  $i \neq j$ , but where patches differ in both their biological productivity ( $K_1 = 80$ ,  $K_2 = 100$ ) and their economic costs ( $\theta_1 = 10$ ,  $\theta_2 = 5$ ). In that case the sole owner optimizes harvest in each patch independently as if he were managing two completely independent fisheries. In that case the optimal escapement in patch 1 is  $e_1^* = 43.4$  and in patch 2 it is  $e_2^* = 51.7$ . These optimal escapement levels exceed those that would be obtained in the absence of harvest costs (in which case  $e_1 = 40$  and  $e_2 = 50$ ). In this, and all of the following examples the optimal escapement in period 4 is to simply harvest to the level  $\check{x}_i = \theta_i$  in patch  $i$ .

### 5.3.2 Scenario 2

Here we add dispersal across patches in such a way that an interior solution still exists. Patch 1 receives 30% of its own production and 50% of patch 2's production. Patch 2 receives 50% of its own production and 70% of patch 1's production. Consistent with Proposition 1, the optimal feedback control rule is patch-specific, and is both time and state independent. The optimal (time-invariant) escapement in patch 1 is  $e_1^* = 45.5$ , and the optimal escapement in patch 2 is  $e_2^* = 49.1$ .

### 5.3.3 Scenario 3

Here we examine a case in which, by Proposition 2, dispersal plays no role in the determination of the optimal feedback control rule (provided that an interior solution exists). In this scenario harvest costs are assumed zero and all larvae survive to become adults, so the conditions required by Proposition 2 are met. In that case, optimal escapement levels should be driven exclusively by the biological production in each patch. In the absence of harvest costs and discounting, this implies that the optimal escapement level is that which maximizes sustainable yield, which in this model equals  $K_i/2$  in patch  $i$ . Indeed, we find that the optimal escapement levels in each patch are  $e_1^* = 40.0$  and  $e_2^* = 50$ . As expected, manipulating the dispersal terms has no effect on this solution, provided that an interior solution still exists. If dispersal to a patch is insufficient to allow the pre-harvest stock in that patch to exceed  $e_i^*$ , then this result no longer holds because an interior solution does not exist.

### 5.3.4 Scenario 4

Returning to the parameters in Scenario 2, we now examine the consequences of a one-period shock to the system. The shock takes the form of a reduction in the dispersal coefficient  $D_{11}$  at the end of period 1. We assume that shock eliminates all own-patch dispersal in that period, so that the larvae that were expected to stay in patch 1 at the end of period 1 are lost. If that shock is sufficiently large, then the larval settlement in patch 1, period 2 will be insufficient to allow the escapement target ( $e_1^* = 45.5$ ) to be met. Consistent with Proposition 3, the optimal policy is then to reduce harvest to zero in patch 1, period 2. Indeed that is the case under this scenario. Consistent with Proposition 4, this should feed back into the escapement policy in patch 2, period 1, since patch 2 also contributes to patch 1. The mere fact that there is some chance that patch 1 will have to be closed in period 2 equates to the chance that marginal returns to larvae being sent to patch 1 are larger than they would have been had there been no chance of its closure in period 2. According to

Proposition 4, this should lead to an *increase* in the escapement  $e_{21}$ . Indeed, period-1 escapement in patch 2 in this case is  $e_{21} = 51.7$ , which is larger than the escapement level of 49.1 that would have been optimal had there been no chance of closure in patch 1, period 2.

### 5.3.5 Scenario 5

In Scenario 4 we showed one way in which it can be optimal to temporarily close a patch to harvesting (due to a shock that reduces the stock to a level that is exceeded by the constant escapement optimum). Here we illustrate a quite different feature that can cause patch closure. If the dispersal matrix is such that one patch receives very few settlers (either from its own production or from drift from production in other patches), then the stock in that patch will never exceed the optimal escapement threshold level, and it will be optimal to permanently close that patch to harvesting. This case is illustrated in Scenario 5 in which nearly all dispersal is to patch 2. Patch 1 is highly biologically productive, but since the stock level never exceeds the optimal escapement level, the patch must be closed in perpetuity. Consistent with Proposition 4, the escapement in the adjoining patch is increased from 49.1 (see Scenario 2) to about 52 (but this escapement level is now time-dependent because an interior solution does not exist).

### 5.3.6 Scenario 6

Scenario 6 illustrates Proposition 5. Here we impose an arbitrarily placed reserve in patch 1 in period 2, even though it is not optimal to do so. By Proposition 5 this artificially imposed reserve should decrease the escapement (increase the harvest) in the adjoining patch (relative to the no-reserve case) in the previous period. Indeed, this is borne out, as the escapement in patch 2, period 1 is reduced from 49.1 (see Scenario 2) to 43.1.

## 6 Discussion

Fisheries collapse reflects an institutional failure which has largely been attributed to the dynamic externality of entry. Despite this recognition 50 years ago, today's fisheries are almost categorically in worse biological and economic condition than at any point in human history. Recent biological insights suggest a second, confounding externality that has been the subject of a great deal of rhetoric, but little formal economic analysis. Biologists almost unanimously favor marine protected areas as a policy tool on the largely unsubstantiated grounds that they lead to economic gains. Yet this policy does not immediately accord with economic intuition. Might MPAs deliver a first-best solution in the stochastic, interconnected world in which biological science suggests we live?

To analyze this, and other current policy questions on the effects of spatial externalities, we have developed and analyzed a spatial bioeconomic model subject to random variability and uncertainty. There were four biologically-motivated sources of stochasticity - three were random environmental shocks at different life-stages of the organism. The fourth was a random dispersal matrix that determined the dispersal and settlement of young to different patches across space. Both biological production and marginal economic profitability were allowed to vary across space. The objective was to maximize the expected value of the resource over a  $T$ -year planning horizon by identifying the optimal spatial bioeconomic feedback control rule. Surprisingly, this complicated spatio-temporal problem had an analytical interior solution.

We found that MPAs can, in fact, yield the first-best economic outcome. This result can obtain under a number of different, and realistic, bioeconomic conditions. First, heterogeneous economic conditions (e.g. high marginal harvest cost in a region) or certain biological endowments (e.g. a region with high biological productivity, but receives low dispersal) can lead to the case in which marginal bioeconomic productivity in a site is high enough to make the net marginal value of harvest in that patch negative. In such cases, an interior solution does not exist, and the patch must be closed to harvest. This result can also be obtained as a result of environmental variability or shocks to the dispersal between patches. While the ultimate reason for patch closure is the same as in the cases outline above, patches would, in this case, be optimally be closed only temporarily.

Maintaining our focus on harvest closures in particular patches, we also examined what harvest should obtain outside those closures. When harvest closures are optimal (as in the cases identified above), optimal harvest outside those patches is decreased to take advantage of the high marginal productivity of those patches. This is in direct opposition to the existing models of marine reserve creation which assume complete harvest outside reserves. On the other hand, if reserves are sub-optimally located (i.e. in places in which marginal productivity is low), optimal harvest outside the reserves should actually increase, relative to the case in which the patch was not closed. In general these results corroborate the largely unsubstantiated basic result from biological science that reserves may benefit fisheries. But the formal treatment of this problem outlined in this paper also provides a platform for more meaningful analysis of optimal spatial management in the presence of spatial externalities.

We have presented a relatively general spatial and dynamic bioeconomic model under uncertainty, and have identified an analytical solution when an interior solution exists, and some salient characteristics of the solution when an interior solution does not exist. But this analytical tractability requires that a number of limiting assumptions are made. Perhaps the two most important assumptions have to do with the timing of events and the knowledge of the adult population in each patch. An important technical requirement for us to identify a solution analytically is that the fishery owner knows the size of the adult population prior to harvest. If this variable were also a random variable, the problem would become less tractable.

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