Can reserves increase profits?
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Abstract
Reserves (areas closed to extraction) are increasingly being adopted as a management tool. Two primary arguments are used for their implementation. The first is a biological argument that biodiversity can prosper inside the reserve. The second is that by ceasing harvest inside a reserve we may generate such a large production of individuals, that “spillover” into the harvested region will actually increase profits from harvesting - even relative to optimal management in the absence of a reserve. This rationale does not immediately accord with economic intuition. We examine, in an analytical framework that is quite general, whether reserves can actually increase profits from exploitation.

Over the past several decades there has been a major expansion of protected areas (“reserves”) in which extractive economic activities, such as timber harvesting, hunting or fishing, are banned or restricted. In 2005, 11% of land and 1% of the oceans are in reserve; new reserves are being added at an increasing rate. One justification for expanding reserves is to achieve biological objectives: reserves are a means to conserve biodiversity. However, sometimes a stronger claim is made that reserves increase the value of extractive economic activity; these claims are largely unsubstantiated by economic analysis. For example, in justifying marine reserves, biologists have claimed that not only is the reserve good for the fish, but it is good for the fisherman (Hastings and Botsford 1999). That this is so does not immediately accord with economic intuition.

In this paper, we investigate the effect of reserves on the economic profit from harvesting. Harvesting of renewable resources, such as fisheries, involves complicated tradeoffs over space and time. Economic analyses of harvesting typically use a bioeconomic model that incorporates basic principals of biological growth within an economic framework to determine the present value derived from harvests (see e.g. Clark (1990)). For the most part, such bioeconomic models are aspatial. However, reserves involve ceasing harvesting in some places in order to expand harvests elsewhere. Spatial considerations, therefore, are of central importance. A potential confounding factor that may qualitatively change the nature of reserves is variability in the system (Conrad 1999). Therefore, our model will be a stochastic dynamic spatially explicit model. We use this model to determine the optimal spatial dynamic management of a renewable resource.

One way to operationalize this spatial harvest strategy is to assign property rights - either over fish or over space. There is significant debate about how zoning the oceans would work practically, and whether the public is willing to entrust resources, previously held in the public trust, to private agents. It turns out that achieving a first-best using property rights would involve a complicated coordination problem (Hansen and Libecap 2004). We will abstract away from this coordination problem and instead focus on the optimal spatial harvest from the perspective of the sole owner. This problem quickly gets complicated. The coupling of stochastic environmental conditions and life-history characteristics of harvested species introduces spatial connections between patches. Economic conditions can vary across space further complicating analysis. Despite these complications we are able to obtain sharp results.

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While the spatial features captured here exist in both terrestrial and marine environments, we will focus this analysis on marine systems. For most commercially important species large numbers of larvae are produced at one location and drift to other locations, sometimes thousands of kilometers away. This inherent dispersal process introduces a spatial connection in production of larvae which means that harvest in one location may impose an externality on other locations. To achieve a first best outcome this spatial externality must be accounted for. The current economics literature provides little guidance about how to efficiently do so.

One approach is to assign rights, either over fish or over patches of ocean. To effectively internalize the spatial externality using property rights will require coordination in such a way that some patches are harvested at a rate that would otherwise have been individually sub-optimal. In some instances (which are not too rare) ceasing harvest in certain patches can actually increase profits from harvesting.

Within this framework, we are able to find: (1) The optimal interior solution harvest strategies for the sole owner (or equivalently for all sea owners in a coordinated rights-based economy), (2) Conditions under which dispersal is irrelevant - in which case no coordination is required in order for a property rights mechanism to achieve the first best solution, (3) Conditions under which it is optimal to close a patch to harvest, (4) The optimal response of harvest in non-closed areas, given that some patches are optimally closed and (5) The optimal response of harvest in non-closed areas, given that some patches are arbitrarily (i.e. suboptimally) closed.

The paper is organized as follows. We will begin with a discussion of the background (section 1) and institutions (section 2) which motivates the problem of spatially managing renewable resources and reviews the economics and biological literature on that subject. We then provide a simple two-patch illustrative example in section 3 which is the easiest way to demonstrate our main point and intuition before turning to our fully fledged model (section 4). The optimal interior solution is given in section 6, as are a number of analytical results pertaining to the focus of this paper on reserves (harvest closures). A discussion is provided in section 7.

1 Background

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 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.¹

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 environ-
mental, 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 man-
gement 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? And in particular, would
a private property rights approach, that emphasizes coordination between seaowners, achieve the
first best solution in such a spatially complex environment? That is the focus of this paper.

2 Institutions for spatial resource management

As early as the 1990’s biologists had substantiated that the marine environment was more com-
plicated 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 ma-
rine 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.

Two basic kinds of institutions have been proposed, and we will briefly review those here. The
first kind of institution maintains the traditional central-planner approach to fisheries management,
but does so with spatially-heterogeneous harvest policies that account for the spatial connections
described above. The most fantastic of the associated policies is the Marine Protected Area (MPA)
in which certain areas of ocean are completely closed to harvesting. While this approach does not
immediately accord with economic intuition, its economic consequences have not been carefully
analyzed, and we will do so here. The second kind of institution that attempts to account for
spatial externalities departs significantly, at least in principle, from the centrally-planned fishery by
assigning, either formally or informally, property rights to particular swaths of ocean. Prominent

¹Wilen (2000) provides an informative and thorough history of the contributions of economists to institutional
policy design.
in many diverse fisheries around the world, the private property approach to fisheries management appears to be gaining popularity and yet, surprisingly, as received little formal analysis on its economic consequences.

### 2.0.1 Marine Protected Areas

The basic scientific insight that patches of ocean are connected via larval dispersal spawned what 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 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). Brown and Roughgarden (1997) were the first to examine a metapopulation model in an economic optimization framework, and instead of smooth diffusion, they assume a common larval pool. 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 or a common larval pool, the linkages between 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. Conrad (1999) uses a similar model to Sanchirico and Wilen, except his dispersal model does not allow for patchiness. He obtains simulation results that corroborate his unproven claim that “Unless we somewhat artificially introduce an intrinsic value for biomass in the sanctuary, there would be no rationale for a marine sanctuary in a deterministic world with perfect management” (p. 212). In an empirical investigation, Smith and Wilen (2003) examine the economic implications of closing a patch to fishing, paying particular attention to fishermens’ decisions about whether and where to fish. They find that taking these spatial decisions into account can significantly diminish the attractiveness of area closures. 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.

2.0.2 Assignment of spatial property rights

Defined generally, property rights can take many forms in fisheries management. Rights could be assigned to harvest a certain quantity of fish, at certain times, or in certain locations. Our focus is on the third approach of assigning spatial property rights to certain areas of the ocean. This kind of property rights assignment has been in use, and has been successful, for centuries in fisheries all over the world. Many of these success stories historically involved the informal assignment of rights, though in most cases, these rights have now been institutionalized. Here we provide a brief overview of the kinds of institutions deployed in the assignment of spatial property rights in fisheries.

- **Artisinal Fisheries of Chile.** With an annual revenue of around $170 million, Chilean Artsains harvest around 40 fish and invertebrate species, the most prominent being the loco snail, whose population declined rapidly in the 1980’s (Hilborn et al. 2005). By the last 1980’s the population of loco snails was sufficiently low to induce complete closure of the fishery from 1989-1992. This prompted a high-level discussion of alternative fishery management regimes. Out of this discussion arose a territorial fishing rights provision that was incorporated into the Fisheries Act of 1991 in which exclusive access to particular fishing grounds is granted to fishermen’s organizations. The success of the Chilean Artisinal fisheries is a widely cited example of the benefits of territorial use right in fishing (TURF).

- **Fishing Cooperatives of Baja California, Mexico.** Many small, remote fishing communities on the Pacific coast of Baja California, Mexico have secured from the federal government exclusive access to harvest in particular areas of ocean. The most prominent species are small pelagic fish, lobster, and abalone. The cooperatives are responsible for drafting their own fishery management plan, as well as for monitoring and enforcement. This is an example of cooperative management where management plans are jointly developed between fishing groups and government. The coordination problem has been overcome, in part, by organizing into federations. For example, the 9 cooperatives of the Vizcaino Peninsula organized into a federation to coordinate processing, marketing and distribution, as well as accounting for any spatial externalities across cooperatives. Some areas of particularly high net productivity are voluntarily closed to harvesting.

- **Geoduck Fishery of Washington State** The Geoduck is the largest bivalve in North America with an average size of 2 pounds, and a maximum size of about 14 pounds. Washington auctions off the harvest rights on a bed-by-bed basis. Fisheries management takes place on a very small spatial scale. Department of Natural Resources selects the beds to be auctioned. The auction item includes the time, location, equipment, and pounds that are allowed to be harvested. Implicitly, there are closed areas - only harvest 2.7% of the surveyed harvestable biomass.

- **“Ambushi” Fishermen of Okinawa, Japan.** Many Pacific Island communities have had de facto ownership of reefs and areas of sea which are culturally sanctioned. Stake netting (“Ambushi”) fishermen have a complex community structure that provides for exclusive access to particular fishing grounds. The coordination problem is solved by an elaborate system where a senior fisherman calls a meeting of all fishermen (typically during a typhoon when they will not be fishing anyway) to discuss use rights, new fishing locations, and the spatial distribution of harvest (Akimichi 1984). Occasionally harvest will be prohibited in an area because such harvest would significantly affect overall yield. According to an oral history of this fishery,
“...the spread net not only intercepts activities of fishermen in the neighborhood, but also takes fish in advance as they retreat from shallow to deep waters...a newcomer cannot claim site 13, as the occupancy of site 13 inevitably reduces the catch in territory V” (Akimichi 1984).

This illustrates the ability of institutions to account, at least in part, for spatial externalities.

These examples are illustrative that (1) spatial territorial rights systems have been used, in some cases for centuries, to effectively manage spatially disaggregated renewable resources, (2) at least in some cases, harvest closures of certain areas may be optimal, and (3) coordination among sea owners or even designing the spatially optimal policy for a sole owner, may be quite complicated. The remainder of the paper is devoted to modeling, and carefully analyzing the optimal spatial harvest strategy, with a particular focus on if, and under what conditions, reserves (complete harvest closures) can increase profits from harvesting.

3 An illustrative example

Here we will preview the main result of this analysis with the aid of an illustrative example. Suppose a single fisherman has control over a closed system consisting of two patches of ocean, called A and B. Owing to ocean currents, larvae tend to drift towards patch B. All larvae produced in patch B will end up in patch B, and some fraction $\theta$ of larvae produced in patch A end up in patch B. The remaining $1-\theta$ proportion produced in A will stay in A. Harvest cost is linear, and price is constant, so this sole owner seeks to choose a harvest strategy for patches A and B that maximizes the net present value (at discount rate $\delta$) of that harvest over an infinite horizon. The period-$t$ production from patch A is given by the increasing and concave function $F(X_t - H_t)$, where $X_t$ is the patch-A stock at the beginning of period $t$, and $H_t$ is the harvest in patch-A. Then, in period $t$, the contribution of patch-A to patch-$B$ is $\theta F(X_t - H_t)$ and the equation of motion in patch-A is $X_{t+1} = (1-\theta)F(X_t - H_t)$.

As a benchmark, consider the case in which these patches are completely independent (i.e. $\theta = 0$). In that case, we can apply standard bioeconomic results to each patch independently. In patch A, the owner would continue harvesting fish as long as the rate of growth rate of the resource $(F'(X_t - H_t))$ exceeds the interest rate, $\delta$. This is the standard “golden rule” in resource economics which is a simple comparison of the rates of return - one from financial markets and one from biological production. The basic point here is that when patches are unconnected, steady state harvest is positive and a closure of one of the patches would only reduce profits.

This story can get more complicated when spatial connections exist ($\theta > 0$). In that case, we have to consider not only how harvest in one patch will affect future stock in that patch, but how the consequent spillover will affect future stock in the other patch. Fortunately, under the simplifying economic assumptions in this example, this problem has a simple solution. It turns out that because profits are linear in harvest, the optimal strategy in each patch is to harvest down to the point where the growth rate of the resource equals the interest rate. The simple intuition for this result is as follows: because marginal profit from harvest is constant, the location of harvest does not affect current period profit, all that matters is the total quantity of harvest. Consequently, the optimizing fisherman seeks to harvest to the golden rule point in each patch, and in so doing, will harvest the spillover from one patch to the other.

Does this imply that reserves cannot be optimal in this environment? No. Suppose that patch-A is closed. Let the steady state stock in patch-A, in the absence of harvest, be given by $X^K$. The equation of motion implies $X^K = (1-\theta)F(X^K)$, and the rate of growth of the resource in patch-A is $F'(X^K) - 1$. If $\theta$ is near 0, $X^K$ is large, and by the concavity of $F()$, $F'(X^K) - 1$ is small. Pursuant to the argument above, when the growth rate of the resource is smaller than the interest rate, harvest should continue. So when $\theta$ is sufficiently small, harvest should continue in patch-A (it would be economically sub-optimal to close patch-A). However, if $\theta$ is sufficiently large, then $X^K$ is small and $F'(X^K) - 1$ will be large. If it exceeds the interest rate, then the optimizing fisherman would actually like to harvest less in patch-A. Because of a non-negativity constraint on harvest, the best the fisherman can do is to completely close patch-A to harvesting. The economic intuition is that the growth rate in patch-A is large, so the optimizing harvester should close patch-A to harvest, opting
instead to harvest its spillover upon arrival in patch-B. Under this simple two-patch bioeconomic setup, it is optimal to completely close patch-A to harvest if and only if: $F'(X^K) - 1 \geq \delta$. This is illustrated in figure 1 for the cases of high spillover, $\theta_1$, which implies a low steady state stock ($X^K_1$) in patch-A and for low spillover $\theta_0$, which implies a low steady state stock ($X^K_0$) in patch-A.

Figure 1: The growth rate in patch-A when patch-A is closed. With low spillover ($\theta_0$) the growth rate is low, so the patch should not be closed. With high spillover ($\theta_1$) the growth rate is higher than the discount rate, so the patch should be closed.

This simple example has omitted many important real-world details which will be included in the subsequent analysis. First, the economic model is too simple because it assumes homogeneity across space and it assumes that marginal harvest cost is not stock-dependent. More generally, we would like to adopt a model in which marginal harvest cost is decreasing in stock size to reflect the difficulty in finding fish that are less dense. And to account for issues such as travel distance from port, we will allow harvest cost to be heterogeneous across space. Second, this simple model has only two patches and the environmental conditions are known and are deterministic. More realistically, when including multiple patches and a stochastic environment, model results may become significantly complicated.

4 The spatial bioeconomic problem

Our primary interest is in deriving an optimal spatial fishery harvest strategy in a generalized environment. And in particular, we would like to know how this optimal solution can be achieved - either by a sole owner or by coordination among a collection of sea owners. This will inform the design of appropriate property rights institutions for correcting the spatial externality. Our focal resource is a near-shore fishery for which breeding adults are sessile but young are dispersed across space. Examples of such resources include sea urchin, abalone, and rockfish, but the model
also applies to terrestrial species with similar characteristics (e.g. plants and trees). 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 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.

5 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.

5.1 Spatial fish biology

We focus attention on biological resources for which adults are sessile, and progeny are mobile, which is a realistic assumption for species such as lobster, urchin, rockfish, trees, and plants, but not for highly migratory or mobile species such as tuna, wildebeest, and whales. The stock of adults in patch $i$ at the start of period $t$ is $x_{it}$, which is assumed to be known at time $t$. The stock of adults in patch $i$ at time $t$ is subject to harvest, $h_{it}$, yielding a 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. Reproduction in each patch yields a number of “young” ($Y_{it}$) produced, which is a function of the number of reproducing adults, $e_{it}$. For marine species, this is larval production. For terrestrial plant species, this is seed production. The number of young produced depends on a spatially distinct average growth function $f_i(e)$, where $f_i'(e) > 0$ $f_i''(e) < 0$. Because reproductive success is influenced by stochastic processes (e.g., nutrient availability, rainfall), the number of young is also a function of a spatially distinct period-$t$ multiplicative random variable, $Z_{it}$. The number of young produced in patch $i$ at time $t$ is:

$$Y_{it} = Z_{it} f_i(e_{it})$$  \hspace{1cm} (1)

where the distribution of $Z_{it}$ 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 then disperse across space. The stock of young that successfully settle in patch $i$ in period $t$ depends on production of young in all patches and on dispersal. 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 deterministic. However, biologists have recognized that random fluctuations in the environment affect dispersal (e.g., ocean currents, wind patterns) making the dispersal kernel random. Denote by $D_{ji}$ a random variable indicating the percentage of young that originate in patch $j$ and settle in patch $i$ (so $\sum_j D_{ji} \leq 1$, with an inequality if there is some mortality of larvae during dispersal). Total settlement to patch $i$ is:

$$S_{it} = \sum_{j=1}^I Y_{jt} D_{ji}$$  \hspace{1cm} (2)

Following settlement, individuals are sessile. Survival to adulthood in patch $i$ depends on the number of settlers and on stochastic events. Survival of settlers is equal to $Z_{it}^S \sigma_i(S_{it})$, where $Z_{it}^S$ is a spatially distinct random variable and the spatially distinct function $\sigma_i(S_{it})$ describes the average survival to adulthood in patch $i$. Again, we assume that the distribution of $Z_{it}^S$ is known and is independent across periods.
Adult survival depends upon the density of adults after harvest, $e_{it}$, and stochastic events. Adult survival is given by $Z_{it}^{\mu} \mu_i(e_{it})$, where $Z_{it}^{\mu}$ is a spatially distinct random variable and the spatially distinct function $\mu_i(e_{it})$ describes average survival as a function of the number of adults after harvest. We assume that the distribution of $Z_{it}^{\mu}$ is known and is independent across periods.

We assume that the expected value of all multiplicative shocks ($Z_{it}^{f}$, $Z_{it}^{S}$, $Z_{it}^{\mu}$) is equal to 1 and that the support is bounded below by 0. We also assume that the random variables ($Z_{it}^{f}$, $Z_{it}^{S}$, $Z_{it}^{\mu}$, $D_{ji}$) are independent of each other and of calendar time.

Pulling together the various parts of the biological model, we can summarize the equation of motion for the stock of adults. The number of adults in patch $i$ in time period $t + 1$ is a random variable given by:

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

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

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 patches. Importantly, the stock size in any patch $i$ in time period $t + 1$ may depend on escapement in all $I$ patches, $e_{jt}$, $j = 1, ..., I$, and on the random variables in all $I$ patches, $Z_{jt}^{f}$ and $D_{ji}$, $j = 1, ..., I$, as well as patch specific random variables, $Z_{it}^{\mu}$ and $Z_{it}^{S}$. The biological model is summarized in Figure 2.

Figure 2: Timing of biology and exploitation of a spatially-distributed renewable resource subject to random variability.
5.2 Spatial economics

Following Reed (1979), Clark and Kirkwood (1986), and others, we assume an elastic demand at price, \( p \) per unit harvest, and a marginal cost of harvest function, \( c_i(s) \), that is a non-increasing function of the current stock, \( c_i'(s) ≤ 0 \). By indexing \( c_i(·) \) 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. 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: \( ph_{it} - \int_{x_{it}}^{e_{it}} c(s)ds \). The patch-\( i \) period-\( t \) payoff from harvest \( h_{it} \) written in terms of escapement, \( e_{it} \), is shown in Figure 3.

![Figure 3: Marginal economic conditions in any given patch.](image)

The bioeconomic objective is to maximize the expected net present value of harvest from \( I \)-patches over a \( T \)-period (possibly infinite) horizon:

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

(5)

where \( \mathbb{E} \) is the expectation operator and \( \delta \) is the discount factor. The maximization problem is subject to the equation of motion for stock in each patch \( i = 1, 2, ... I \). The objective is to identify a feedback control rule \( h^*_i(x_t) \) that is an \( I \)-vector function of state-dependent controls that yields the optimal patch-specific harvest as a function of the vector of patch-specific stocks in any given period, \( t \).

6 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
An optimization problem is provided that an interior solution exists, the period \( \tau \) is state separable, independent of the state vector.

Lemma 1 defines state separability to prove the following lemma.

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

\[
V_t(x_t) = \max_{e_t} \sum_{i=1}^{I} \left[ p(x_{it} - e_{it}) - \int_{x_{it}}^{x_{it+1}} c(s) ds \right] + \delta E_t \{ V_{t+1}(X_{t+1}) \}. \tag{6}
\]

which is subject to spatial state transitions given by equation \( \tau \). The continuation value is a function of the vector of subsequent stocks, \( X_{t+1} \equiv [X_{t+1} X_{2t+1} \ldots X_{It+1}] \). 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 \( \bar{x}_t \) be the stock level to which a purely myopic harvester would extract the resource. Therefore, \( \bar{x}_t \) is either zero or the level of stock at which marginal profit is zero (\( p = c(\bar{x}_t) \)), whichever is larger. The patch-\( i \) period-\( t \) profit from harvesting down to \( \bar{x}_t \) is given by the following function:

\[
Q_t(x_{it}) \equiv p(x_{it} - \bar{x}_t) - \int_{\bar{x}_t}^{x_{it}} c_i(s) ds \tag{7}
\]

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

\[
V_t(x_t) = \max_{e_t} \sum_{i=1}^{I} \left[ Q_t(x_{it}) - Q_t(e_{it}) \right] + \delta E_t \{ V_{t+1}(X_{t+1}) \}. \tag{8}
\]

which is subject to biological state transitions given in \( \tau \). We represent optimal solutions to this problem by \( e_t^*(x_t) \). We assume concavity of returns in \( e_t \) so that there is a unique solution \( e_t^*(x_t) \). Under the assumptions of our model, we can guarantee concavity when \( f''(.) \) is large in absolute value (highly concave growth function) relative to \( c_i(\cdot) \).

6.0.1 An interior solution to the spatial bioeconomic problem under uncertainty

We begin the derivation of the interior solution to the dynamic programming problem 8 with a useful definition.

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

We use state separability to prove the following lemma.

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:

\[
V_t(x_t) = \max_{e_t} \sum_{i=1}^{I} \left[ Q_t(x_{it}) - Q_t(e_{it}) \right] + \delta E_t \{ V_{t+1}(X_{t+1}) \}. \tag{9}
\]

The necessary condition for an interior solution is:

\[
-Q_t'(e_{it}) + \delta E_t \left\{ \sum_{j=1}^{I} \frac{\partial V_{t+1}(X_{t+1})}{\partial X_{jt+1}} \frac{\partial X_{jt+1}}{\partial e_{it}} \right\} = 0 \tag{10}
\]
The necessary condition is also sufficient given the assumption of concavity of returns in the vector of controls (escapement). 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 current period 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 $c_{it}$. Note that in an interior solution $c_{it} < x_{it}$. Using the definition of the evolution of stock (Equation 4) we note that $X_{t+1}$ is a function of $c_{t}$ but not of $x_{t}$. Therefore, the terms in the bracket are independent of $x_{t}$. 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 $c_{it}^*$ is independent of $x_{t}$ 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 $j = 1, ..., I$. Using this fact along with the state transition equations (equation ??), we can rewrite the necessary condition for patch $i$ at time $t$ as follows:

$$-Q_i'(c_{it}^*) + \delta E_t \left\{ Q_i'(x_{it+1})Z^i_{it}\mu_i'(e_{it}) + \sum_{j=1}^{I} Q_j'(x_{jt+1})Z^i_{jt}\sigma_j'(\cdot)Z^j_{it}f^i_j'(e_{it})D_{ij} \right\} = 0 \quad (11)$$

Since the distribution of shocks is independent of time, as is biological growth, dispersal and economic returns, the optimal choice, $c_{it}^*$, 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, $Q_i(x) = (p - c)(x - \bar{x}_i)$. Further under Assumption 2, the necessary condition for an interior solution to the optimal feedback rule for patch $i$ at time $t$ is:

$$-(p - c) + \delta E_t \left\{ (p - c)Z^i_{it}\mu_i'(e_{it}^*) + \sum_{j=1}^{I} (p - c)\sigma_j Z^j_{it}f^i_j'(e_{it}^*)D_{ij} \right\} = 0 \quad (12)$$
Simplifying, we obtain:  
\[ 1 = \delta \left\{ \mu'(e_{it}^s) + \sum_{j=1}^I \sigma f'_j(e_{ij}^s)D_{ij} \right\}. \]
And since \( \sum_{j=1}^I D_{ij} = 1 \), this expression simplifies to:
\[ 1 = \delta \left\{ \mu'_i(e_{it}^s) + \sigma f'_i(e_{it}^s) \right\}. \] 
(13)

The right hand side of equation 13 is the discounted expected growth of the stock remaining at the end of the period. Equation 13 can be interpreted as a golden rule of growth. 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 \( \mu'_i(e_{it}^s) + \sigma f'_i(e_{it}^s) \), not where recruits end up. No matter where recruits end up, they are harvested and generate the same returns per unit, \((p - c)\).

Assumptions 1 and 2 are only used in Proposition 2. In general, with density dependent survival (non-linear \( \sigma_i(S_{it}) \)), differences in survival rates, or differences in harvest cost across sites, dispersal will matter. It is only under special conditions given by assumptions 1 and 2 that expectations about dispersal do not affect the optimal solution.

### 6.0.2 Corner solutions

Provided that stock size in every patch is sufficiently large \((x_{it} > \bar{x}_i)\), the interior solution to this problem is optimal. 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 
\[ -Q'_i(\bar{e}_{it}) + \delta E_t \left\{ \sum_{j=1}^I \frac{\partial V_{t+1}(X_{t+1})}{\partial x_{jt+1}} \frac{\partial x_{jt+1}}{\partial e_{it}} \right\} = 0 \] 
(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 
\[ -Q'_i(e_{it}) + \delta E_t \left\{ \sum_{j=1}^I \frac{\partial V_{t+1}(X_{t+1})}{\partial x_{jt+1}} \frac{\partial x_{jt+1}}{\partial e_{it}} \right\} > 0 \] 
(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:

\[
\delta E_{t} \left\{ Q'_{i}(x_{it+1})Z_{it}^e\mu_{i}^{J}(e_{it}) + \sum_{j=1}^{I} Q'_{j}(x_{jt+1})Z_{jt}^{S}\sigma_{j}^{J}(\cdot)Z_{it}^{f}(e_{it})D_{ij} \right\} \tag{16}
\]

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

\[
\delta E_{t+1}[Q'_{i}(x_{it+1})Z_{it}^e\mu_{i}'(e_{it}^*) + \sum_{j \neq k} Q'_{j}(x_{jt+1})Z_{jt}^{S}\sigma_{j}'(\cdot)Z_{it}^{f}(e_{it}^*)D_{ij}] + \nonumber
\]

\[
\delta E_{t+1} \left[ \sum_{j=1}^{I} Q'_{j}(x_{jt+2})Z_{jt+1}^{S}\sigma_{j}'(\cdot)Z_{t+1}^{f}(x_{kt+1})Z_{tk+1}^{S}\sigma_{k}'(\cdot)D_{jk}Z_{it+1}^{f}(e_{it}^*)D_{ik} \right] \tag{17}
\]

When patch \( k \) is in a corner solution in period \( t + 1 \),

\[
Q'_{k}(x_{kt+1}) < \delta E_{t+1} \left[ \sum_{j=1}^{I} Q'_{j}(x_{jt+2})Z_{jt+1}^{S}\sigma_{j}'(\cdot)Z_{t+1}^{f}(x_{kt+1})D_{jk} \right] \tag{18}
\]

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

\[
Q'_{k}(x_{kt+1}) > \delta E_{t+1} \left[ \sum_{j=1}^{I} Q'_{j}(x_{jt+2})Z_{jt+1}^{S}\sigma_{j}'(\cdot)Z_{t+1}^{f}(x_{kt+1})D_{jk} \right] \tag{19}
\]
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.

It is optimal to close a patch when the marginal productivity of the patch is high so that not harvest gives a higher return in terms of discounted expected future returns from harvest than does current harvest. In this case, getting more settlement in this patch yields a high return so that other patches that contribute larvae to this patch through dispersal have higher returns, which means it is optimal to have higher escapement (lower harvest). On the other hand, when a patch is close arbitrarily when it is not optimal to do so, the patch will have low productivity. Other patches that contribute larvae to this patch through dispersal will have lower returns, which means it is optimal to have lower escapement (higher harvest).

7 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 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 uncer-
tainty, 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.

The rapid worldwide increase in reserve designation is driven in part by a largely unsubstantiated assumption that creating reserves can increase profit from harvest. While we have shown that reserves can indeed increase profits, our analysis also emphasizes that careful design, by incorporating economic, rather than just biological reasoning, is essential to their success and efficiency.

References


