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Abstract

This paper investigates economic aspects of marine protected areas (MPAs) that are closely related to the underlying marine biota. Many marine scientists recognize that enough is now known about the marine biology for the scientific siting of MPAs to protect marine environments that create associated economic values. Marine scientists have identified several objectives of MPAs. These include protection of genetic and biodiversity, increase in population levels and structures (e.g., age, size, fecundity), enrichment of ecosystems by promoting species interactions, and the protection of continental shelf landscapes from invasive human actions. Indeed, some marine scientists and fisheries economists view MPAs as an 'insurance policy' against over-fishing and other human uses of oceanic resources that have damaged so many of the world's fisheries. The economic analysis presented here pays attention to optimal zoning, policies to maintain sustainable economic rents, and the optimal policing of MPAs.

Journal of Economic Literature Classification: Q2

Keywords: economic rent, marine protected areas, oceanic resources, optimal policing, sustainability

SUSTAINING THE ECONOMIC RENT OF OCEANIC RESOURCES: THE CASE OF MARINE PROTECTED AREAS

This paper investigates economic aspects of marine protected areas (MPAs) that are closely related to the underlying marine biota. Many marine scientists recognize that enough is now known about marine biology for the scientific siting of MPAs so as to protect the marine environment and thereby creating associated economic values. Indeed, perhaps even ahead of firm scientific evidence, about 1,300 MPAs have already been established worldwide (Boersma and Parrish, 1999).

In some respects the appearance of legislation creating the institution of the MPA is the last 'throw of the dice' by governments exasperated by the failure of fishing interests to create their own institutions efficiently to manage fish stocks and marine environments. On this view, the creation of a MPA within a nation's exclusive economic zone is an action by a sovereign state to claim the right to manage resources that belong to the citizenry as a whole - not just to fishing interests. Thus, as a tool for oceanic management the MPA is second best in the sense that in many, perhaps, all, jurisdictions it usually operates under the constraint that first-best oceanic policies are off the board. Exactly what are first-best policies in oceanic management may be difficult to define, but fisheries economists could point, for example, to landing fees (Gylfason and Weitzman, 2003) and to the creation of transferable property rights (e.g. Scott, 1988) as having certain desirable properties for the management of reproducible oceanic resources. Space considerations preclude discussion of the relative merits of these first best policies, however, one advantage is that they do not close-off areas of the ocean from human exploitation. Properly designed landing fees or property rights, at least in theory, would allow fishers and others to enjoy the sustainable economic rent of the whole of oceanic space, rather than leaving them dependent on biological and associated economic spillovers from no take zones. Be this as it may, the MPA is a political and legal reality and this paper offers an economic analysis of the efficient management and optimal policing of biological and economic spillovers from a central no-take zone.

Also relevant to the discussion of the MPA as an economic entity is that, according to marine scientists, they offer an type of 'insurance policy'. The insurance is against over-fishing and other invasive human uses of oceanic space that can cause population crashes, reduced genetic and bio-diversity and severely degraded population structures and ecosystems. Taking account of this aspect what is important economically is not only the expected level of sustainable economic rent derivable from the creation of a MPA but also its variability around the mean over-time. What is preferred is a high expected level of sustainable economic rent in combination with low variability around that expectation. Both of these factors make it imperative that a MPA is both properly situated in oceanic space according to scientific principles and that it is large enough - relative to habitat size or range of a target species or, even, ecosystem, to stabilize the underlying biota.

The rest of this paper proceeds as follows: Section 2 outlines biological considerations pertinent to the placing of a MPA. Section 3 offers a stylization of the level of sustainable economic rent as a function of both the amounts of spillovers from a no-take zone and the extent of human invasive activity. Section 4 discuses the idea that zones in a multi-zone

MPA should be chosen so as to equalize the marginal social costs of human activity between the zones. Section 5 models sustainable rent creation in oceanic space. Section 6 discusses the need for the policing of MPAs and it also offers a model of optimal policing. This model optimizes for the amount of policing activity, expenditure on policing, sustainable rent protected per police boat, and the amount of sustainable rent that it is socially optimal to allow to be destroyed given high policing costs. Section 7 considers some extensions of this model. Finally, section 8 offers conclusions.

2: MPAs and biological considerations

Biological factors are critical in the placing of a MPA - though non-biological factors sometimes can be important, as when a MPA is sited over an historic shipwreck. Economic rents earned from fishing, sports diving and marine tourism, to a large extent depend upon the underlying marine flora and fauna. In particular, a MPA should to be sited where it has maximum effect on the biota and oceanic habitat - both within its boundaries and in adjacent (and perhaps distant) areas through what can be called 'biological spillovers'. A further important question concerning MPAs that is heavily bound up with biological considerations is its appropriate size. Thus, even an appropriately sited MPA may have minimal effect on the biota if it is too small to give sufficient protection.

Spatial placing of a MPA is largely a matter of using the relevant biological model. Allison, Lubchenco and Carr (1998), describe four biological models of population replenishment as is illustrated in figure 1. The ellipses show marine populations, the heavy arrows high rates of recruitment between populations, and the broken arrows weak (though positive) recruitment rates. A MPA over any population center in model A could help to protect that particular population's self-replenishment but without biological spillover to other populations (e.g. some invertebrates, live bearing fish, tunicates and many seaweeds). In model B, biological spillovers are large as there is strong recruitment between spatially separated but quite nearby populations (e.g. abalone and some shallow swimming rockfish). Biological spillovers are also strong in model C, but in this case only from a source population that supplies fish or propagules to quite distant populations that have only weak biological spillovers between themselves - such dependencies may be quite general across species being largely dependent on preponderant currents. Finally, model D indicates separate widely disbursed populations that are indirectly linked via a disbursed larva pool (e.g. some rockfish, sea urchins and lobsters). Accordingly, in biological models B, C and D both primary and secondary biological spillovers are present. Protection of a given source population creates a primary spillover to a secondary population that, because it too becomes more healthy generates a second (or, indirect) spillover to other populations - and, perhaps back to the first population.

As we have said, proper spatial siting is critical. This is illustrated in model B where populations 2 or 3 are clearly preferable to populations 1 or 4 because of their greater interconnectedness within the larger ecosystem. In addition, in model C targeting populations 2, 3, or 4 would have only weak biological spillovers, while a MPA over population 1 could have large beneficial effects.

Another detailed analysis that can be used to indicate scientific markers for the siting of potential MPAs is that of Auster and Shackell (2000). They survey research on temperate and boreal demersal fish assemblages in the northwest Atlantic. Their main conclusion is that these zoological assemblages can be stable in both oceanic space and over time - though they do note that assemblage boundaries can change if the taxa are disturbed by exogenous events such as over-fishing or changes in ocean conditions such as water temperature. Nevertheless, these authors claim that "fish assemblage boundaries can serve as the primary filter for selection of MPA sites" (Auster and Shackell, 2000, page 423). This is an important claim given that they were referring to research on, so called, 'low topology' continental shelf areas - where boundary markers are much less obvious than in high topographic areas such as coral and other reefs, and kelp forests. These authors also identify other site selection markers. Thus, sites should be chosen as far as possible with mixed ocean floors (sand, rock, gravel, cohesive sediments) with the aim of maximizing both the number of species included and species interactions - so promoting the development of a wider ecosystem than just one or a few target species. Moreover, these authors, along with others, say that there is a case for setting some MPAs over spawning areas and were juveniles congregate.

Recent research by Bellwood and Hughes (2001) on coral reefs describes biological spillovers outward from a central area. They find, *inter alia*, that the most important predictor of diversity in coral and fish species on the coral reefs researched by them was the incidence of suitable reef habitats within 600 km of the site - biological spatial interconnectedness being maintained by the movement of fish and plankton. Indeed, these findings are supported in the research of several other marine scientists - see Knowlton (2001, and references therein).

Scientific work on still more marine environments also points to what an economist might call "biological external economies", upon which, in theory at least, economic values can be placed. A prominent reference is Ward, Heinemann, and Evans (2001) who survey research on the effect of MPAs on marine biology. Their findings are consistent with the biological models described in figure 1. Eighty-nine papers are surveyed and these are found to offer evidence on a "reserve effect", a "spillover effect" and an "export effect" of MPAs. The "reserve effect" occurs within a MPA. The improved habitat offered by protection from invasive fishing activity has been recorded to cause greater spawning, settlement, and larval and juvenile survival, lower fish mortality, and greater mean age, density, biomass and reproductive potential. Resulting from these is also a "stability effect" that takes the form of reduced yield variability and chances of population crashes. Translating these biological-physical effects into economic terms, economic values within a MPA are known to increase in 'before-after' comparisons. The "spillover effect" is in the form of a net movement of larvae, young fish and adults out of a MPA that causes increased local fish density and local fish catches. Finally, the "export effect" refers to the net outward movement of larvae such that there is increased regional recruitment and increased regional catch. Thus, again, as both the spillover and export effects potentially increase economic values outside of a MPA there is an external economy from one geographic area to another.

Appropriate size of a MPA

A relevant consideration is the appropriate size of a MPA. Ward, Heinemann, and Evans (2001) judge from their research that between 20 percent and 70 percent of a fishing ground depending on circumstances needs to be protected in order to have a measurable effect on fish biomass. The potentially large scale of MPAs for some oceanic taxa is referred to by Kenchington (1990). He points out that "in terrestrial environments, most ecological communities can be addressed by survey and management scales of 10^1 to 10^4 meters. [However], these scales are generally appropriate [only] for fixed or territorial components of inter-tidal and benthic communities but for planktonic species scales of 10^4 to 10^6 meters are appropriate while for nektonic and migratory species scales of 10^4 to 10^7 apply" (page 33).

Also, following Kenchington (1990) the appropriate size of a MPA depends upon two variables: the size of a marine animal or plant's site habitat and their dispersal ranges. Thus, site habitat is small - just a few meters - for corals and also, during the nesting stage, for animals such as turtles and seabirds. However, it is large - with a scale of hundreds of kilometers - for pelagic creatures such as tuna and whales. The second dimension, dispersal during a distribution or migratory phase may be quite different in scale from the habitat dependence phase. For example, following Boersma and Parrish.(1999), while corals have high site fidelity, during the distribution phase, ocean currents can carry larvae hundreds of kilometers. Similarly, many reef fish have larger habitats than coral polyps, but smaller dispersal ranges than pelagic creatures. A MPA would need to target at least one of these two dimensions.

Having identified the existence of the biological benefits and spillovers of MPAs attention now turns to an economic analysis of MPA zoning.

3: The basic economic model

The following economic examination of MPAs is concerned with several factors, namely the case for no-take zones and spatially graduated admission of human activities, the effect of zoning on sustainable economic rents, and the optimal policing of a MPA. To analyze these factors a simple model is developed based upon the following equation:

$$V = f(x, h) \qquad f_x < 0, f_h < 0 \tag{1}$$

Where V is the monetary value of sustainable economic rent available from a well sited and well managed MPA. The term x signifies distance from the center of a no take zone which is itself cited in the center of the MPA, and h is the rate of a pre-defined human activity, say, fishing using a given technique.

The negative signs on the partial derivatives, f_x and f_h, indicate, respectively, that sustainable rent falls as distance from the center of a MPA increases, and that higher rates of human activity degrade economic rent. The first of these assumptions is consistent with the biological studies cited earlier in that biological spillovers from a no take zone decline with distance. Also, it is a matter of common observation that $f_h < 0$, namely that over-fishing degrades economic rent.

The economic analysis of the features described by equation (1) proceeds sequentially beginning with how the impact of human activity, in combination with oceanic biological conditions, makes restricted zoned access rational economic policy.

4: Zoning

The economic case for zoning activities - banning some or all human activities from specific area follows from non-convexity in the production possibility frontier (Helfand and Rubin, 1994). Thus, a pair of activities is incompatible when the opportunity cost of one, measured in terms of what is given up of the other, falls. An example is trawling and the richness of an ocean floor habitat. Even one pass of a trawler can so substantially destroy a rich habitat as to render it almost worthless from an ecological point of view (Auster and Shackell, 2000). A similar non-convexity can also exist between coral reef habitat and tourism since the constant dropping of anchors can substantially degrade a reef.

Given declining marginal cost of an activity the job of a zoning board, using some sort of estimate of willingness to pay, is to determine the appropriate allocation of a given tract between incompatible activities. A corner solution would be to separate incompatible activities to different zones. This is exactly what has happened in the ocean zoning of the GBRMP (Day, 2002) where there is a fine separation of human activities into 6 distinct zones. It is also the case with many other MPAs around the world where, for example, all fishing activity is band within a defined zone with regulated fishing, or even open access, allowed outside of that zone.

Using equation (1) the case for zoning can also be modeled as an attempt by policymakers to equate the marginal social cost of a given human activity across ocean space. As mentioned before, $f_h < 0$ signifies that a given human activity destroys sustainable rent.[1] Therefore, dV/dh measures the marginal social cost of the given human activity. Marginal social cost can be supposed to vary according to spatial variations in oceanic conditions. For example, trawling in an area that badly affects ocean floor habitat will have a higher social cost than in an area where natural habitat conditions are not so rich. Thus, in *absolute* terms, according to oceanic conditions:

$$\frac{dV^1}{dh} > \frac{dV^2}{dh} > \frac{dV^3}{dh} > \ldots. > \frac{dV^n}{dh} \qquad (2)$$

where the superscript designates a numbered zone. If the objective is to minimize the total social cost of a human activity, or to accept some given amount of sustainable rent degradation, maintenance of the inequalities in equation (2) is not rational policy.[2] Rather the human activity should be shunted out of those zones where its marginal social cost, measured by dV^i/dh, is relatively high to where it is lower, so reducing the total social cost of the activity.[3]

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[1] The negative effect of the given human activity on sustainable rent could be modeled to occur only after some threshold level of activity has been surpassed.

[2] This statement ignores the policy cost considerations discussed elsewhere in this paper.

[3] The interesting zoning model of Barry Field (1989) also assumes that economic rationality requires that zoning should aim to equate marginal social costs (or benefits) between the zones. However, his model is not appropriate for the ocean zoning issues discussed here. In particular, the Field model assumes that a population of economic agents is restricted in small subgroups to defined subdivisions of a larger geographic area. This is clearly not the case with fishers who have freedom to move between zones. Moreover, he assumes that within any given subdivision, the economic agents situated there bargain with each other to restrict the external diseconomies that may be occurring within the subdivision - though it can happen, this is generally not the case with users of ocean space. Moreover, in the Field model there are no external economies between zones. Again this is contrary to the assumptions used here were biological and economic spillovers are prevalent. The Field model is appropriate to the situation that he had in mind.

5: Modeling a rent bubble

In this section attention turns to the modeling of sustainable economic rent and the economic consequences of biological spillovers. There are several ways to model the economic consequence of a MPA with associated biological and economic spillovers. A simple model is used here that illustrates the main points.

In figure 2 distance from the center of a closed zone is measured on the x-axis and rent per square unit area (say, per square yard) of ocean floor is measured in dollars on the y-axis. The function f(x) measures sustainable economic rent per unit area as depending on absolute distance from the center of the closed zone. This declining function is consistent with the assumption that the value of spillovers from the closed zone declines with distance. In equation (1) $f_x < 0$. It should be emphasized that figure 2 represents a cross section through the center of a "designated geographic area" shown in figure 3. The function f(x) can be thought of as the outer edge of an "bubble" of sustainable economic rent that exists in three-dimensional space with its highest point centered over the origin. The rate of economic rent, f(x), is a sustainable in the sense that human users can obtain it period after period. For example, rent is sustainable if fishers take only the annual growth in biomass, or, if hobbyist divers do not interfere with the oceanic objects that they view.

That is, in application to terrestrial landscapes where economic agents, say, a tribe - as in the seminal work on property rights by Demsetz (1967), are restricted from ranging over an entire geographic area.

As the baseline case, suppose that the designated geographic area in figure 3 is initially inefficiently managed to the extent that fishers and other human users of it reduce economic rent everywhere to zero. This assumption is consistent with the theory of the open access fishery as discussed, for example, by Gordon (1954). It is also approximately consistent with the analysis of fisheries that use a total allowable catch in combination with fishing restrictions such as of type of gear, number of boats, or workers per boat. Thus, in order to capture the increased economic rents afforded by the catch limit, fishers engage in rent destroying practices such as capital stuffing and derby fishing (see OECD, 1997).

In order to increase economic rent from the baseline (zero) level a closed zone is introduced over a biologically productive area chosen on the basis of the considerations discussed in section 2. In figure 2 the distance $0x_1$ indicates the closed zone. It is assumed that, with time, the biological productivity of the closed zone increases - ultimately to its maximum monetary level, I_{MAX}. Such an assumption is consistent with the relevant field studies discussed in Ward, Heinemann, and Evans (2001).

An observed problem with closed zones that are not accompanied with other zoning measures is that fishers will fish intensively right up to the edge of the closed zone. This is an example of "fishery displacement" by fishers excluded from the no take zone. Such intensive fishing effort (and possibly other human activities such as diving and anchor damage) destroys the potential sustainable economic rent beyond x_1. If this is the case the rent profile becomes $I_{MAX}Ax_1x_2$ - which is obviously less than it could be along f(x).

While the managers of some fisheries appear to be content with this state of affairs, others are not. Thus, US authorities governing the Gulf of Maine off the northeastern US coast allow fishing right up to the boundary of the closed zones, but in Australia's Great Barrier Reef Marine Park closed zones may be further protected by an adjacent restricted zone (Day, 2002).

Such a restricted zone is shown in figure 2 as the distance x_1 to x_2. As a matter of policy, the objective of the restricted zone is taken to be to preserve as much of the sustainable economic rent as possible, subject to a policing cost constraint - as is discussed later. Accordingly some human activities are allowed in the restricted zone, but not others. Such zoning restrictions are consistent with equation (2) and the discussion in section 4.

We are interested in the amount of sustainable economic rent created in the restricted zone through biological and associated economic spillovers from the closed zone. To find this we need to calculate the volume, V, which is a monetary measure of sustainable economic rent, created under f(x) between x_1 and x_2 rotated around the y-axis.[4]

The necessary integration exercise yields:

$$V = 2\pi \int_{x1}^{x2} x f(x) dx \qquad \boxed{3}$$

---

[4] The required element of volume is $dV = 2\pi dx f(x)$.

To evaluate this equation the function f(x) needs to be defined. Thus, for illustrative purposes assume that $y = I_{MAX} - x/4$. The intercept here is the maximum amount of sustainable economic rent that can be created in the water column above the richest square unit area measured on the ocean floor. This maximum is assumed to be in the center of the closed zone - which is a biologically reasonable assumption if the closed zone is properly situated according to the principles discussed earlier.

In this particular numerical illustration the economic rent that can be created in the restricted zone is given by:

$$V = 2\pi \int_{x1}^{x2} x(I_{MAX} - \frac{x}{4})dx \tag{4}$$

and

$$V = 2\pi \int_{x1}^{x2} I_{MAX} x dx - 2\pi \int_{x1}^{x2} \frac{x^2}{4} dx \tag{5}$$

This economic rent, V, is the maximum sustainable rent that can be created through biological spillovers assuming those fishers and other human users of the restricted zone abide by the rules of the restricted zone. That is, they don't partake of illegal activities that reduce economic rent below f(x).

6: Policing activity

It is reasonable to assume that without policing activity fishers and other human users of the restricted zone will reduce the level of sustainable economic rent. We are now interested, therefore, in the benefits of policing activity in the restricted zone. If illegal activity does occur rent is reduced below f(x) in figure 2. This cost is modeled as reducing the *actual* intercept, I, of f(x) below I_{MAX} - the whole f(x) function shifting downward.

The cost of illegal activity in the restricted zone is calculated in two steps. First, evaluation of the previous equation yields:

$$V = 2\pi I_{MAX}(\frac{x_2^2 - x_1^2}{2}) - \frac{\pi}{2}(\frac{x_2^3 - x_1^3}{3})$$

Secondly, the change in economic rent for an effective downward shift in the intercept caused by illegal activity is:

$$\Delta V = 2\pi(\frac{x_2^2 - x_1^2}{2})\Delta I \qquad \boxed{7}$$

Where ΔI has been substituted for ΔI_{MAX} since the latter is a fixed quantity but the actual intercept will be lower than this if illegal activity occurs. On rearrangement,

$$\frac{\Delta V}{\Delta I} = 2\pi(\frac{x_2^2 - x_1^2}{2}) > 0 \qquad \boxed{8}$$

In other words, a reduction in the intercept has a direct negative effect on the value of sustainable economic rent.

The optimum expenditure on policing effort depends on its respective benefits and costs. The benefit of policing effort is the containment of I as close as possible to I_{MAX}, subject to the constraint of policing cost. Letting the number of police boats be the measure of policing effort, the total benefit of policing is:

TB = economic rent saved per police boat x number of police boats (9)

A TB function reflecting diminishing returns to policing shown in figure 4. Notice that policing effort POL_X coincides with V_{MAX} - the maximum economic rent created by the MPA - i.e. equation (5).

The total cost of policing effort is simply

TC = cost per boat x number of police boats (10)

TC is drawn as a simple increasing linear function.

It is clearly indicated in figure 4 that the optimum number of police boats (the measure of policing effort) is POL_1, being determined where marginal benefit equals marginal cost. Other noteworthy features of the equilibrium solution are a) the distance AB measures the net benefit of policing effort; and b) V_{MAX} - V_1 measures the sustainable economic rent lost due to continuing illegal activities. In other words, given policing costs, it is not optimal to maximize economic rent along f(x).

7: The effect of some exogenous events on the equilibrium solution

The forgoing discussion can be used to show the effects of three exogenous shocks on, respectively, optimal policing effort, the net benefit of policing and the amount of sustainable economic rent given up when policing effort is optimized. To begin with, notice in figure 5 that an upward rotation of TB_1 to TB_2 increases net benefit from AB to CD, reduces lost economic rent due to continuing illegal activity from $V_{MAX} - V_1$ to $V_{MAX} - V_2$ and reduces the total cost of policing from its level at B to its level at D. Clearly, anything that causes the TB function to rotate upward creates several worthwhile benefits.

The factors than can cause an upward rotation of TB in figure 5, implying an increase in rent saving per police boat, are as follows. First, better policing techniques, or, the introduction of rules that make policing easier (e.g. requiring fishers constantly to report their positions) will raise policing productivity. Since in equilibrium there are fewer police boats at POL_2, but more economic rent is protected from degradation, $V_2 > V_1$, rent saving per police boat must have increased. That is, each remaining police boat will be intercepting a larger amount of illegal rent extraction.

Secondly, rent saved per police boat may be increased through better education of fishers and other human users of a MPA about the biological and economic damage that illegal activities can cause. Assuming that such education reduces illegal activity, it is reasonable to suppose that the remaining illegal fishing boats will be able to gather more illegal rent per boat due to the relief from the external diseconomy of over-fishing by the other illegal fishing boats that have removed themselves. It is possible to extend this argument to account for other considerations. For example, rent saved per police boat might not increase if, due to there being fewer illegal fishers, the latter become much harder to catch. Then better education that has the effect of persuading some illegal fishers to desist may not raise rent protect per police boat. Indeed, it could lower it. If this were to happen, rotating TB_1 to the right, the opposite of what policymakers presumably desire would occur - net benefit of policing would fall and rent lost to illegal activities would rise. The solution to this counter-intuitive result would be *not* to educate users about the biological and economic values of the resources that they are exploiting. However, such an outcome would seem to be so unlikely that we will set it aside.

Thirdly, tougher laws against illegal activities will rotate TB upward in figure 5. The argument here is similar to the previous discussion in relation to the effect of better education. Thus, if tougher laws reduce illegal activity, rent saved per police boat will increase.

8: Conclusions

This paper has considered some of the main economic consequences of marine protected areas (MPAs). It began by arguing that the institution of the MPA (and its associated enabling legislation) is a second-best policy. This policy has been widely adopted to protect marine environments in the face of rent-seeking fishing interests that have effectively blocked the adoption of potential first best sustainable rent increasing policies such as fish landing fees or transferable property rights.

A key consideration in the establishment of a MPA is the use of the correct biological model - otherwise it may not be sited to maximize the biological and economic payoffs. Assuming that this issue is resolved, the paper went on to discuss the principles of optimal zoning - zones should be designed and policed so as to equalize between them the marginal social cost of human activity. It was further argued, given that the policing of a MPA involves positive marginal cost, that it is generally not optimal to equalize marginal social costs at the zero level. Rather some sustainable economic rent may have to be given up because of cost of catching the last (hopefully, few) illegal human users is too high. Any conservationist who would assert that the state should maintain an unadulterated marine environment should be aware that the cost of obtaining this objective might simply be too high.

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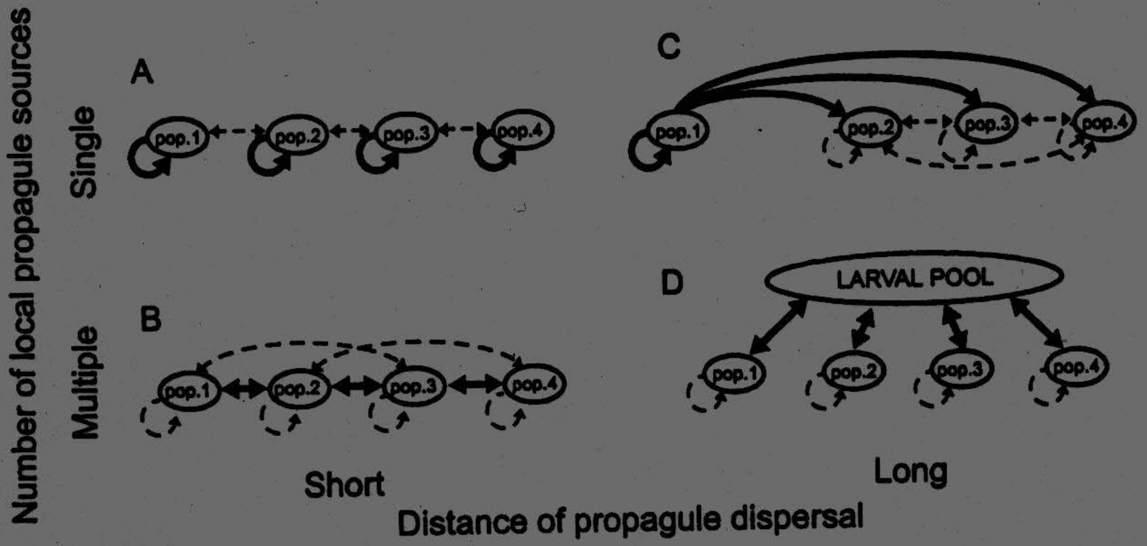


Models of population replenishment. Patterns are distinguished by the distance of propagule dispersal and the number of local propagule sources for a given local population. Ellipses represent isolated adult populations (pop.). Bold lines indicate high recruitment rates within or between isolated adult populations. Broken lines indicate low recruitment rates. (A) Short-distance dispersal/single source, or self-replenishment pattern; (B), short-distance/multiple source, or limited-distance pattern; (C), long-distance dispersal/single-source pattern; and (D), long-distance/multiple-source pattern.

Figure 1

FIGURE 2: POTENTIAL SUSTAINALE ECONOMIC BENEFITS OF A CLOSED ZONE

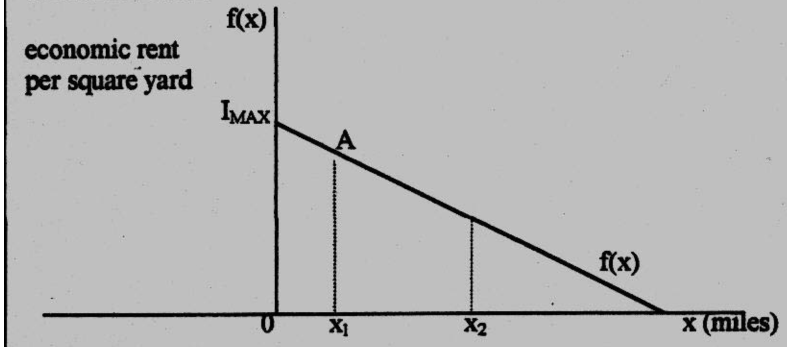
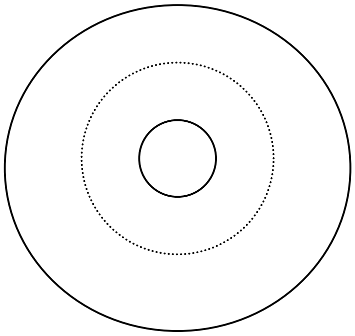


Figure 3: A designated geographic area with a central closed zone



Inner circle represents a closed zone. Inner ring with broken line boundary represents a restricted zone. Remainder of area is unzoned.

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Figure 4: Optimal policing effort

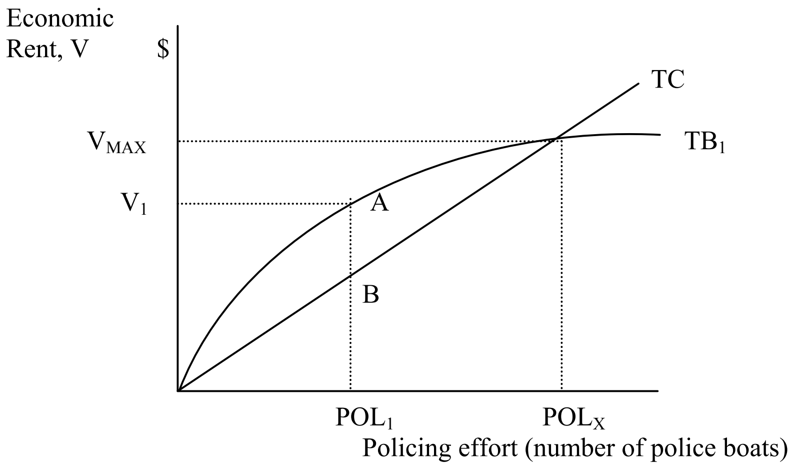

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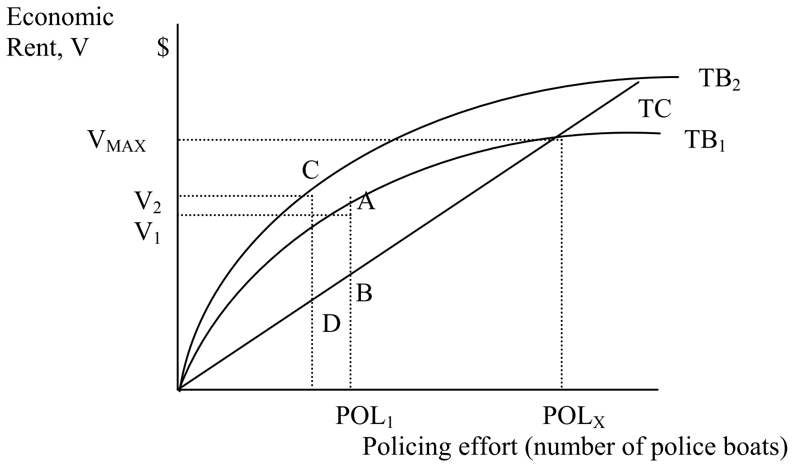
Figure 5: The effect of higher policing productivity



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