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Islands of Sustainability in Time and Space

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Abstract

We review the economics perspective on sustainable resource use and sustainable development. Under standard conditions, dynamic efficiency leads to sustainability of renewable resources but not the other way around. For the economic-ecological system as a whole, dynamic efficiency and intergenerational equity similarly lead to sustainability, but ad hoc rules of sustainability may well lead to sacrifices in human welfare. We then address the challenges of extending economic sustainability to space as well as time and discuss the factors leading to optimal islands of preservation regarding renewable resources. Exogenous mandates based on moral imperatives such as self-sufficiency and strong sustainability may result in missed win-win opportunities that could improve both the economy and the environment, as well as increase social welfare across generations.

JEL: Q01, Q23, Q22

Keywords: Islands of sustainability, sustainable development, sustainability science, fisheries, forests.

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1. Introduction

Since the late 1980s, the concept of "sustainability" has been making its way to the forefront of policy discussions across the globe. Yet, incorporating the notion into management plans has proved challenging. A simple internet search reveals an abundance of definitions, many of which overlap but few of which are characterized by one or more of the following: a transparent and operational framework, clear performance indicators, and tradeoffs among competing objectives. We review the many notions of sustainability and discuss the concept from an economic point of view. Although maximizing human welfare is only one of many possible approaches to sustainability, the advantage of such an approach is its ability to incorporate various disciplines into an operational framework centered around a measurable objective (e.g. Daily 1997). An incomplete economic approach that only recognizes market values maintains a concrete objective but is unlikely to provide meaningful measures of welfare in the absence of ecological foundations, while a purely ecological approach incorporates important characteristics of the ecosystem but neglects the three key pillars of *sustainability* — economic/ecological system interlinkages, dynamic efficiency, and intergenerational equity (all explained below). In the subsequent discussion, we refer to adherence to these three pillars as "positive sustainability."

Under standard conditions, dynamic efficiency — which follows from welfare maximization — leads to sustainability of renewable resources but not the other way around. Even so, dynamic efficiency does not guarantee intergenerational equity. For the eco-econ system as a whole, sustainable development ensures both efficiency and equity and leads to sustainability of the resource. Ad hoc rules of sustainability are generally not efficient and may well lead to unnecessary sacrifices in human welfare. On the other hand, most optimal paths are sustainable, provided that the three pillars are incorporated (Heal 2003).

We address the challenges of extending economic sustainability over space, starting with a discussion of *islands of sustainability*. We argue that fixing boundaries of preservation zones according to exogenous imperatives is not compatible with sustainable development, but protected areas can turn out to be part of a welfare-maximizing management program. Since the size, timing, and approach paths of the zones are endogenously determined — i.e. explained within the eco-econ framework — resource management cannot generally be characterized by rules-of-thumb.

The discussed theoretical results are based on the assumption that costs associated with defining and enforcing resource management boundaries are negligible. Yet in practice, defining boundaries may incur large fixed costs and enforcement costs may be increasing with the precision of the management instrument. Using the examples of fisheries and forest stands, we discuss some of the tradeoffs involved in defining and redefining management boundaries over time, as well as enforcing those boundaries.

The following research questions are addressed in the sections that follow. Does drawing boundaries and managing resources by moral imperatives (e.g. self-sufficiency, strong sustainability) maximize welfare? What is the role of protected areas in sustainable development? What are some of the tradeoffs involved in implementing complicated spatial and dynamic resource management strategies? In answering these questions, we incorporate several "balances" upon which the *International Journal of Sustainable Society's* vision is based. Specifically, the balances of *economic development and environmental protection* and *consumption and preservation* are operationalized.

2. From sustainable resource management to sustainable development

The word "sustainability" is generally understood to mean the capacity to be maintained or to endure. Yet it is clear from the vast academic literature on sustainability that proponents, across and even within disciplines, are not in agreement of *what* exactly should be sustained. In this section, we review the many modern (post-1987) notions of sustainability. Most, if not all, approaches promote a holistic systems perspective, but few provide an operational framework with clear performance indicators and tradeoffs among competing objectives. We argue that *positive sustainability* provides a concrete objective and quantifies tradeoffs, while maintaining a systems approach to modeling the eco-econ system.

2.1 The many notions of sustainability

The first modern representation of sustainability can be traced to Barbier (1987), published in the eve of the Brundtland Report. His illustration was a Venn diagram comprised of three intersecting circles representing biological, economic, and social systems. The area of intersection describes sustainable development — the satisfactory performance of all three systems. This was replaced by the well-known Brundtland Report (World Commission on Environment and Development 1987), which defined sustainability as, *"… development that meets the needs of the present without compromising the ability of future generations to meet their own needs."* Heal (1998) noted that this may be the "best known" definition but suggested that it is not the best, due to many possible interpretations. Definitions and images have proliferated since. There are possibly as many as 5000 definitions, as speculated by Pezzey (1997, p. 488), and 282 (and counting) images (Mann 2009). Not only do these reflect a diversity of goals, but they are mutually inconsistent (Quiggin 1997, Ravago et al. 2010).

Nonetheless, variations of the Venn approach have remained arguably the most popular, despite the fact that Barbier and company quickly distanced themselves from it (Pearce, Markandya, and Barbier 1989). Munasinghe (1994 and 2007) has reconceived the three circles into a *sustainable development triangle* -- connecting economic, social, and environmental systems, each with associated performance ideals. The popularity of the Venn/triangle portrayal may derive from its apparent promise of something for everyone, e.g. gender and income equity and widespread cultural and political goals (e.g. Hardi and Zdan 1997). Any organization with a political agenda can readily turn the rhetoric of sustainable development to its own ends and not be constrained by transparency or accountability. This all-encompassing version is non-operational, however, without distinct performance indicators of all the goals and algorithms for trading off among competing objectives.

In the field of economics, Pearce, Markandya, and Barbier (1989) proposed what later became known as *weak* and *strong* sustainability. *Strong sustainability* prohibits any level of depletion of natural capital such as trees, water, or fish. The *weak sustainability* rule requires the total value of produced and natural capital to remain constant or increase over time. Dasgupta and Mäler (1995, p. 2394) subsequently argued, however, that strong sustainability involved the category mistake of asserting the means without articulating the ends. On the other hand, Arrow et al. (2004) showed that the weak sustainability rule can be derived from the sustainability criterion of not allowing forward-looking total human welfare to decline.

Despite the proliferation of attempts, little headway has been made in developing a definition of sustainability that is acceptable both across and within disciplines. In the remainder of this section, we provide an economics perspective on sustainable resource use and sustainable development. Under standard conditions, dynamic efficiency (explained below) — which is ensured by a resource economics framework — leads to sustainability of renewable resources but not the other way around. Thus, economic objectives need not necessarily conflict with biological objectives. Sustainable development offers an approach that properly accounts for eco-econ interlinkages and ensures intergenerational equity in addition to dynamic efficiency.

2.2 Renewable resource management: from sustainable yield to dynamic efficiency

Long before the Brundtland Commission launched the modern quest for sustainable development, sustainability was a concern in resource management circles. A common prescription for the management of renewable resources was to limit extraction to maximum sustainable yield (MSY) — the amount of resource regeneration that would occur at the stock level that maximized resource growth. Provided that the initial stock level is sufficient, harvesting according to MSY will lead to a convergence to the desired stock level. But even if the initial stock level is sufficient, there are two sources of waste: ambiguity regarding the transition to the desired stock level and failure to account for the full costs of resource use. This led to a movement away from the MSY concept toward dynamically efficient resource management.

The solution to a dynamic resource management model describes the appropriate stock in the long run — which may or may not coincide with the MSY stock — as well as the welfare-maximizing transition path (Clark 2005). This dynamically efficient or *optimal* transition path maximizes the present value (PV)[1] of net social welfare, where social welfare ideally includes not only the direct consumption benefits and physical extraction costs of the resource, but also non-use benefits and environmental damage costs. Dynamic efficiency also ensures that the full costs of resource consumption are taken into account, including user[2] and externality costs (e.g. pollution).

The case of coastal groundwater on the island of O'ahu is informative. The fact that submarine groundwater discharge from the aquifer to the ocean increases with the height (head) of the aquifer means that net growth (depletion) of the aquifer depends on its own stock and the amount of withdrawal, the same condition that is met for other renewable resources. At each point in time, water is extracted until the incremental benefits of the last unit extracted equal the full incremental costs. In the face of growing demand, a single aquifer should be accumulated, then depleted, and finally stabilized at the optimal sustainable-yield (Krulce et al. 1997).

The conventional focus in resource economics on a single resource, however, omits two particular considerations that may be germane to sustainable development. First, the focus on a single resource sector omits consideration of intergenerational equity. Second, the focus on a single resource overlooks interdependence between resources that may imply different management strategies. We develop these themes immediately below and in section 3.

2.3 Sustainable development

Sustainable development promotes social welfare in the long-run, while taking a systems perspective regarding the ecological-economic (eco-econ) system. In economics, this may mean a gradual transition of natural resource stocks to their efficient long-run levels. When costs and benefits of a resource are properly accounted for, sustainable development is compatible with *eventually* sustaining the resource stock at some positive level, which may be higher or lower than its current level. Thus, rather than precluding the sustainability of existing natural resource stocks, economic optimization models provide a means for characterizing the transition path of welfare-maximizing resource use leading up to the efficient long-run stock level and corresponding sustainable yield.

Strictly speaking, sustainable economic development should include efficient sectoral composition, i.e. each good should be produced until its marginal benefit (the extra benefit generated by a one-unit increase in production) equals its marginal cost (the extra cost of producing one additional unit of output), including any negative *externality costs* of production (e.g. pollution). Nonetheless, in the spirit of Georgescu-Roegen (1971 p. 319), whereby "abstraction is the most valuable ladder in any science," the economics profession has focused on the sustainable growth of generational welfare, including the consumption of environmental amenities as well as material goods and services. The economics of sustainable growth extends growth economics to include the efficient management of natural capital stocks as well as the optimal accumulation of produced capital. Conditions for *positive sustainability* (Ravago et al. 2010, Endress et al. 2005), are derived by maximizing the net benefit from material goods and environmental amenities after deducting per unit extraction and environmental damages from the consumption of natural resources such as petrochemicals. To incorporate intergenerational equity, *the rate at which future generations are discriminated against* is set to zero, along the lines of Stern (2007) and Heal (2009). Accordingly, economics serves as a potential organizing framework for sustainability science, whereby transdisciplinary research can be organized to deliver meaningful contributions to critical issues of resource management and rigorous policy analysis (see e.g. Center for International Development 2009, Arrow et al. 2010, Roumasset et al. 2010).

The management conditions that emerge from this framework are: the extended Hotelling rule for optimal resource extraction and the Ramsey savings rule. The *Hotelling* (1931) condition requires resource extraction until the marginal benefit of using the resource is equal to the sum of *extraction*, *user*, and *externality* costs, all reckoned for the last unit extracted. The sum of these three cost variables is called *marginal opportunity cost*.[3] According to this condition, renewable and non-renewable resources can be efficiently depleted towards their efficient long-run levels, but only if their initial stocks are higher than their efficient long-run levels. The *Ramsey* condition determines savings and investment in productive capital along the welfare-maximizing path. Produced capital should be accumulated until its productivity at the margin (the amount of extra output produced when capital is increased by one unit) is equal to the growth rate of consumption times an index of society's aversion to intergenerational inequality (Ramsey, 1928). Together, these two conditions determine the environmental and produced-capital accumulation compatible with best paths for material consumption and environmental amenities. In the long run, both environmental services and productive capital are sustained at their optimal and intertemporally equitable solutions (Endress et al. 2005). Consumption is thus balanced with conservation of natural capital and investment in produced capital such as plant and equipment. Provided we do not discriminate against future generations in our calculations, the optimal path thus chosen will be sustainable, except under conditions of extreme lack of substitutability between types of capital and stagnant technical change (Endress et al. 2005, Heal 2003 and 2010).

These results inform questions of optimal management of the economic and natural resource system but require extensions to more realistic and disaggregated conditions before they can determine the details of specific parts of the system. A particularly important area for future research regards appropriate planning for the optimal and sustainable conservation and preservation of ecological resources over space and time. However, standard resource economics establishes principles for managing individual resources as if they were separable in the sense that depletion in one part of the resource system does not adversely affect other resources. To capture the essence of ecological thinking, one must extend these models such that the whole resource system is greater than the sum of its parts. This will require partnerships between social and natural sciences. The following sections may be suggestive, especially regarding the challenges of spatial sustainability.

3. Is treating protected areas as "islands of sustainability" sustainable?

Sustainable development of the eco-econ system does not imply preservation of particular protection areas with exogenously given boundaries. However, protection areas with endogenous boundaries may emerge from the optimal and sustainable program. Such boundaries are not necessarily established once and maintained forever. Rather, the optimal boundaries of protected areas and conservation zones may change over time in accordance with the three pillars of sustainability: ecological-economic interlinkages, dynamic efficiency, and intergenerational equity. In this section, we illustrate through examples that when multiple resources are interconnected over space and time, managing resources independently does not maximize social welfare. Even for a single resource, management by moral imperatives (e.g. self-sufficiency, strong sustainability) is not welfare-maximizing. Endogenously determined islands of sustainability, however, can be part of the optimal resource management program, although those islands can be changing over space and time.

As an initial example, consider the optimal use of groundwater, albeit with two coastal aquifers instead of one. As shown in Roumasset and Wada (2009), optimal management may involve temporary preservation of one of the aquifers and full reliance on the other in order to reduce natural leakage of groundwater along the interface of the freshwater lens and underlying seawater. Once the aquifer in use reaches its maximum sustainable yield, however, the preserved aquifer should be put into use, until it too reaches its MSY.[4] The optimal path can be implemented through block pricing (discussed in detail in section 5) that sets the second block equal to the full incremental cost. Additional increases in demand can be met through desalination. An important part of sustainable resource use is thus the ordering of resource use. Some resources may be put off limits to enhance their growth and placed into use at a later time. The following two sections explore these themes in the context of fisheries and forests, noting as well how exogenous mandates may waste resources relative to the optimum.

3.1 Fisheries

Within the past couple of decades, establishment of marine reserves (no-harvest zones) has been increasingly promoted as a spatial fishery management strategy. Generally, proposals include either specification of permanent closed zones or rotating harvest zones, according to which various areas may alternate between being open and closed to fishing over time. Potential benefits of protected areas include increased biodiversity, biomass, and catch, as well as providing a hedge against management failure (Scientific Consensus Statement, 2001). However, many analyses of marine reserves focus exclusively on biological aspects, when in fact behavioral responses to economic incentives are equally important drivers of transitional and equilibrium patterns of biomass and fishing effort over space and time. For example, defining conservation zones according to whether a particular spatial patch is a de facto source may yield unexpected results, inasmuch as fish dispersal may be due more to economic circumstances than to underlying biological characteristics (Sanchirico and Wilen 1999, Smith and Wilen 2003).

Simplistic assumptions about economic behavior are often inadequate for correctly characterizing complex dynamic and spatial bioeconomic systems. For example, assuming that fishing effort is fixed and uniformly distributed over space tends to bias management decisions toward reserve creation, even if doing so is suboptimal (Smith and Wilen, 2003). Nevertheless, marine reserves can be part of a welfare increasing fishery management program under certain circumstances. If the objective is to increase both aggregate harvest and biomass in an open access system, then a reserve can do so if the dispersal benefits to the open areas are large relative to the forgone harvest in the reserve (Sanchirico and Wilen 2001). If the management decision includes aggregate fishing effort and the location of marine reserves, then the present value of rent from the fishery is maximized by keeping all areas open to fishing (Sanchirico 2004). When there are biological productivity effects after the creation of a reserve (i.e. an increase in the intrinsic growth rate of the preserved area), however, the optimal solution may entail closing a portion of the fishable habitat. In that case, low productivity and/or high cost patches are more likely to have lower opportunity costs of closure (Sanchirico 2004).

In general, closing an area to fishing is optimal when the value derived from spillover from the reserve outweighs the value of fishing in the patch. In other words, the loss in profit from a fish leaving is weighed against the gain in profit from the fish being caught in another area, and the change in fishing costs due to stock reallocation. If the regulator is assumed able to set effort limits over space (i.e. the resource is not open access), then a particular area is more likely to be an optimal reserve if it is a net exporter and has higher fishing costs. These characteristics are neither necessary nor sufficient, however. Closures of low productivity areas can be optimal when patches with high biological productivity tend to contribute a relatively larger share to total profits. Likewise, a low cost area may be an optimal reserve if the strength of the spillover effect from the reserve outweighs the loss in profitability from closing the low cost patch (Sanchirico et al. 2006). Clearly, rule-of-thumb site selection based on a particular patch's characteristics (e.g. preserve the highest biomass source) is not necessarily welfare maximizing.

A case can be made for rotating harvest zones when growth and dispersal parameters for the relevant population are uncertain (Costello and Polasky 2008, Costello et al. 2010). The timing and pattern of the temporary closures are still dependent on dispersal characteristics of the resource, as well as variations in economic conditions across space and behavioral responses to economic incentives. As is the case for permanent closures, rules-of-thumb for selecting rotating closure sites tend not to maximize the expected present value of profit from harvest.

The discussion thus far has treated spatial units or patches as predefined, in the sense that reserve-based management involves only site selection, not determination of the optimal size, spacing, location, and timing of the reserve sites. While larger reserves are always preferred from a conservation standpoint, more and smaller, closely-spaced reserves can enhance fishery profits by maximizing larval export from the reserves to the fished areas (Gaines et al. 2010). Thus, the tradeoff between conservation and fishery profits is mediated by the interaction of all four aforementioned factors, which even further highlights the point that rules-of-thumb for reserve-based management are not welfare maximizing. For example, optimality may entail multiple, nearly equivalently sized reserves, containing source patches of various reproductive strength, whereas a rule-of-thumb might prescribe protection of the largest/strongest source(s) and allow fishing in the sinks.

As Wilen (2004) notes, fishery management systems must adapt to perpetually improving fish-finding technology by becoming “more spatial”. Traditional management zones will be divided into smaller and smaller areas to more precisely internalize connectivity externalities. Conceptually, as the predefined size of the spatial units approaches zero in the limit, protected zones (if optimal) will expand/contract endogenously and continuously over space and time. Thus, permanent closure of an arbitrarily sized spatial unit is likely to be optimal only by coincidence and, in most cases, only for an instant in time. However, defining and redefining a management boundary over time would be logistically difficult in practice. The transaction costs associated with such a boundary should therefore be weighed against the potential gains of spatial-dynamic management. In section 6, we discuss some practical implications of endogenous management boundaries, including relevant tradeoffs.

3.2 Forests

Forests provide amenities (e.g. biodiversity from untouched wilderness areas, recreation from forest parks) when preserved and revenue when extracted for consumption. The allocation of forestland into forested areas, parks, and wilderness preservation zones will depend on the relative profitability that each land-use brings. A number of factors — including timber prices, input costs, extraction, transportation and technology — determine the economic rent for each land-use. All of these factors are related to remoteness of the land area as measured by how far it is from the city center. Thus, economic rent varies over space (von Thunen 1826), i.e. the nearer the land area is to the city center, the higher the economic rent.

Figure 1 extends von Thunen’s model to include dynamics in finding the optimal land-use allocation between forest and wilderness. The distance from the city center is drawn on the horizontal axis, measured from right to left. Wilderness areas produce positive rents even at a relatively far distance from the city center, but the rent gradient (Wilderness$_1$) is nearly flat, which means that the benefits from biodiversity are not largely dependent on distance. Forested areas on the other hand, generate positive rents starting from a relatively closer distance to the city center, but the rent gradient (Forest$_1$) is relatively steep due to, for example, transportation costs. The frontier of harvest is determined where the rents from forest extraction are equal to the rents from wilderness preservation, i.e. where the two gradients intersect. The corresponding land-use zones can be traced out as concentric circles (bottom quadrant of Figure 1). The broken line represents the harvesting frontier or the boundary of the forested area determined by the intersection of the two rent gradients, Forest_1 and Wilderness_1.

Over time, one or both rent gradients shift due to improved technology, increasing timber prices, or changing preferences. These changes affect the rents to be had from either land use, holding the spatial characteristics of the land constant. When one or both of the gradients shifts, the frontier of harvest changes as well. Figure 1 illustrates a dynamic shift in the forest and wilderness rent gradients to Forest_2 and Wilderness_2 respectively. This dynamic change corresponds to a shift in the boundary of forested area, now covering the potential harvested area in the Figure 1.

When both dynamic and spatial variations are combined, the condition that determines the frontier, i.e. equalization of rent gradients, holds in every period. This means that the preservation boundary will shift endogenously over time to maintain that equimarginality condition. The figure shows how the wilderness area shrinks as forest harvesting moves further and further away from the city. Assuming constant demand, the forested area expands to its steady state limit, i.e. the long-run equilibrium (explained below).

The economic rents arising from spatial variation and exogenous changes over time are the ultimate drivers of any land-use decisions. These also serve as the basis for harvesting decisions within a particular land-use. How forest growth cycles over time depends on extraction decisions and regeneration. Considering this spatial aspect, harvests may cycle back to the edge of the city when harvesting of the now secondary forest begins. In this case, when both space and time effects are taken together, patterns of extraction in the harvest area across space may vary over time, with high levels of extraction near the city center in some periods and high levels of extraction in areas farther from the center in other periods (Robinson et al. 2008). In the steady state, regrowth in the previously harvested areas will just balance extraction of mature trees, such that the preservation boundary remains fixed. The steady state limit is represented in the figure by the solid black line of the potential forested area.

Given that the problem is two-dimensional rather than one-dimensional, there still remains the question of design choice. For example, one could simply expand harvest in a circle around the city center, with the park and wilderness area along the fringe, as in Figure 2a. On the one hand, it minimizes transaction costs for logging and keeps park areas pristine. On the other hand, it increases transactions costs for parks, if they provide recreational value rather than just existence/biodiversity amenities. Over time as per capita income increases, a change in preference may occur such that people demand more luxury goods. An urban park may emerge near the center of the city (see Figure 2b). Furthermore, a demand for eco-tourism could also arise which could be allocated at the penultimate zone. While this design avoids putting a disproportionately large burden of the transaction costs on park users, it may be less flexible with regard to expansion or contraction of the preservation boundaries. Which design is better will depend on how rent gradients vary over time and space.

4. Should islands be managed for self-sufficiency?

An island is an area where sustainability can be reached at a local or regional level. The premise of the “Islands of Sustainability” (IOS) concept is that development can begin within well-defined boundaries ("islands") which in turn act as a catalyst for the spatial expansion of sustainable development. At least two schools of thought have emerged in the IOS literature. The first was pioneered by Wallner et al. (1996) and focused on the process of becoming an IOS. This process focuses on the management of capital flows into a region and managing those flows within the region. Bebbington (1997) takes an alternative approach to IOS by considering what characteristics have led seemingly similar island regions to different destinies: how some places have avoided the vicious cycle of poverty, environmental degradation, and out-migration, and others have fallen into it.

In contrast to IOS, "Island Sustainability" is specifically focused on the sustainable development of small island economies (Kerr 2005, Kakazu 2009). Island economies have their own natural boundaries and are sometimes mistakenly viewed as isolated from other economies. As such, sustainable development of island economies is equated to autonomy or independence (e.g. Kerr 2005) and increasingly to self sufficiency. But foregoing the gains from trade violates dynamic efficiency and impoverishes the future (Bhagwati et al., 1998), thereby violating the pillars of sustainability reviewed in section 2. Exactly as envisioned by the World Commission on Environment and Development (1987), failure to exploit opportunities for economic development may degrade the environment (as increasing numbers of landless workers are pushed onto environmentally-fragile lands) and as fiscal crises render environmental conservation infeasible. For example, the quest for "energy independence" in the island state of Hawai'i may require mandates and high subsidies that raise the cost of living and divert scarce tax revenues away from critical environmental issues such as watershed conservation. On the other hand, an island economy can be regarded as a natural unit of analysis for sustainability science. For example in Hawai'i, the watershed (ahupua'a) is described as a slice of the earth that goes from the mountain to the sea and is a traditional subdivision of land. For these ahupua'a, it may make sense to abstract from some interconnections between areas but not others. Upland watershed conservation, for example, may be usefully studied within ahupua'a (Roumasset et al. 2010).

5. Benefits, costs, and distribution

If beneficiaries are identifiable, then one sensible approach is to distribute the costs of conservation and preservation to facilitate inter- and intra-generational equity (the third pillar of *positive sustainability*), while maintaining dynamic efficiency. In general, distributing costs and benefits from improvements in the efficiency of resource-management does not conflict with sustainability and promotes rectificatory justice (Roumasset and Endress 1996) — i.e. justice that ensures the current generation does not gain at the expense of future generations.

There may be situations where preservation imposes costs on a particular group and yields benefits to a different group. For example, creation of a marine reserve would impose costs on fishermen in that area if they have to travel further to fish as a result, while fishermen in adjacent areas benefit because the total fish stock goes up. Another example is watershed conservation. Designating an area as conservation land for reforestation imposes a cost on the landowner, who would prefer to use the land for something more profitable, whereas groundwater users downstream would enjoy the benefits of higher recharge and hence reduced resource scarcity. One way to achieve the desired distribution is through win-win pricing — i.e. pricing that incentivizes behavior which is beneficial to both the environment and human welfare simultaneously (e.g. Pitafi and Roumasset 2009, Wada 2010).

Measuring the benefits of preservation comes with its own set of difficulties, mostly related to missing markets and measurement challenges. Here we are taking an anthropogenic viewpoint, whereby ecosystem services are valued according to their services to humanity. While this type of valuation is well established in the literature (see e.g. Clawson 1959, Chichilnisky and Heal 1998 and Heal 2000, and Rosen 1974) a debate over its merit remains. Most notably McCauley's (2006), "Selling Out on Nature." McCauley's key concern was the consequences of monetizing nature. McCauley and others suggest that people should be motivated to preserve nature for nature's sake, not only because of its value to humans.

For the case of watershed conservation, win-win pricing can finance the optimal level of investment in conservation projects, compensate landowners, and ensure that the optimal rate of resource extraction is maintained over time. Correct win-win block pricing is equivalent to charging the efficiency price of groundwater (i.e. where the marginal benefit and scarcity value of water are equal), implementing a non-distortionary lump-sum tax on water consumers, and ensuring a lump-sum payment to landowners to leave them as well off as the status quo.

In Figure 3, benefits are measured as consumer surplus or the area above the price and below the demand curve, or equivalently how much a consumer's willingness to pay for water exceeds what he/she actually pays. For expositional clarity, we suppose that the first price block is set equal to the marginal extraction cost of groundwater (Figure 3a), although that need not be the case. Win-win pricing is illustrated by the thick, solid line in Figure 3b. The second block is adjusted downward relative to the status quo and set equal to the scarcity value of groundwater — which takes into account not only the physical costs of extraction and distribution but also the marginal user cost (see endnote 2) — to ensure that the optimal quantity (q') is extracted. At the same time, the first block is shifted to the left to ensure that sufficient revenue is raised to cover investment costs. Area B indicates the gain in consumer surplus resulting from the lower second block price, and area A represents the loss in consumer surplus resulting from the smaller first block. The adjustments should be made such that areas A and B offset, and excess revenue (area C) is enough to finance conservation investment and to compensate landowners.

Even if natural boundaries like watersheds or islands are considered, taking mandates of sustainability can result in missed win-win opportunities to improve the environment and economy simultaneously. It is precisely because optimal management generates a large discounted stream of welfare relative to sustainable (but not optimal) management that redistributions can achieve environmental improvements as well.

6. Practical implications of endogenous management boundaries

The conclusions drawn from our discussion of theoretical models thus far are implicitly based on the assumption that costs associated with defining and enforcing management boundaries are negligible. In practice, however, transaction costs are likely to be increasing with the precision of the management instrument. In this section, we discuss some of the tradeoffs involved in defining and redefining management boundaries over time, looking specifically at our examples of fisheries and forest stands.

Of particular importance are the institutional costs of resource governance. Fisheries, for example, may be managed by common property, regulated private property, government fiat, or left unmanaged as open-access resources (Ostrom 1990), and the optimal form of governance may depend on characteristics of demand and the resource such as its growth rate (Copeland and Taylor 2009). Moreover, the optimal governance of the resource evolves with scarcity value. Given that institutional governance involves set-up costs, as well as the continuing costs of decision-making, enforcement, and conflict-resolution, it may be efficient to postpone governance and exploit the resource beyond its long-run optimal level. Once the governance institution is in place, the resource is allowed to recover from said *overshooting* (Roumasset and Tarui 2010).

Currently, every coastal nation has jurisdiction over all economic resources (e.g. oil, minerals, fish) within its exclusive economic zone (EEZ), which is defined as the area extending 200 nautical miles from shore. However, enforcement of regulations on fishing effort and no-take zones is difficult and costly (High Seas Task Force, 2006). Even with established property rights, the cost of monitoring such a large area in its entirety will generally outweigh the resulting benefits generated. In other words, if the cost of monitoring is explicitly included in the objective function, the welfare-maximizing solution will likely not be characterized by perfect enforcement over the entire region. The conceptual framework discussed in previous sections still applies, however. Fish harvest and marine protected areas (if optimal) should be selected to maximize the PV of social welfare. As the scarcity value of fish rises and/or technological advancements reduce enforcement costs over time, it becomes more likely that the benefits of adjusting the management boundaries and increasing enforcement outweigh the associated transaction costs. As illustrated in Figure 4a, management of the entire EEZ at the outset is not welfare-maximizing. In the future, however, the optimal enforcement boundary shifts (Figure 4b), as might the size of any no-harvest zones.

For a terrestrial protected area such as a forest, continuously shifting management boundaries are less feasible. In some instances, the land outside of the protected area will already be owned and/or cultivated. In that case, boundaries need to be forward looking, and the social welfare function should account for benefits accruing from existing land uses. Expanding the management boundary can still be optimal if the benefits of doing so exceed the costs, including compensation to landowners for the opportunity cost (i.e. the value of the land's best alternative use) of privately owned land. Inasmuch as management boundaries can be increasing or decreasing over time, temporary property arrangements (e.g. leases) should also be considered.

Clearly, implementation of flexible management boundaries is logistically complicated in practice. Moreover, since accessibility, resource characteristics, and monitoring technologies vary widely among regions, the optimal management solution will be site-specific. Nevertheless, we feel that our general conclusions are still valid, especially if future advances in technology reduce transaction costs associated with spatial-dynamic resource management.

7. Conclusion

In contrast to the multitude of definitions for the term "sustainability", positive sustainability is operational and consistent with the broader theme of sustainability science. Other definitions rule out some strategies as unsustainable without clear criteria of choosing amongst the remaining strategies. Rather than treating sustainability as an objective constraint, positive sustainability provides a specific growth pattern based on three principles: dynamic efficiency, a systems approach to economic-ecological interlinkages, and intergenerational equity. Dynamic efficiency is based on a central principle of policy science: the maximization of intertemporal social welfare. The economic-environmental system is necessarily accounted for in the social welfare function, since environmental amenities as well as resource extraction costs and environmental damages affect society's well being today and in the future. The final pillar, intergenerational equity, is achieved by non-discrimination towards future generations. Doing so prevents excessive consumption of today's resources that would deprive future generations of equal opportunity. In most cases, the socially optimal path is sustainable, but management by moral imperatives (e.g. self-sufficiency, strong sustainability) is likely to waste resources and undermine sustainable development.

Protected areas as islands of sustainability can be compatible with the general principles of sustainable development, for example for fisheries with high biological productivity, high pelagic spillover effects, and high harvesting costs. Similarly, distant forestry areas might be permanently set aside for preservation when the gains to biological diversity outweigh the lost present value of commercial forest development. In other cases, temporary bans on fishing in particular zones or postponing the development of groundwater aquifers may be welfare-increasing when more resource growth is gained by protection than is lost through the increased pressure on other areas. In other cases, such as spatial forestry development, areas may be either temporarily or permanently preserved. All such cases involve tradeoffs between demand and multiple productivity parameters. Designating a particular site as a protected area based on one or two parameters (e.g. the site with the highest or fastest-growing biomass) would be unlikely to maximize welfare.

Finding an efficient management strategy is further complicated by the difficulty of incorporating administration costs. While protecting many small fishing areas takes full advantage of connectivity externalities, enforcing fishing bans on many small areas may be inefficient once enforcement and other administration costs are accounted for. Again the tradeoff between costs and gain in potential welfare must be accounted for.

While analytical frameworks for dynamic efficiency and intergenerational equity have been developed, many research challenges remain in characterizing ecological-economic linkages. Developing and solving deterministic models already often proves demanding, but many aspects of the environment are profoundly uncertain. In the case of climate change, for example, we are unsure about everything from the exact relationship between anthropogenic behavior and changes in temperature and precipitation patterns, to the exact impact of climate change on terrestrial ecosystems, to what that implies in terms of social damages. Incorporating uncertainty into a positive sustainability framework indicates the need for a complex adaptive systems approach. Our inability to solve these complex management problems is both a call for research and an appeal to modesty. In some cases, available solutions may only inform intuition about why a particular protection proposal may have unintended consequences that undermine sustainable development. In others, sustainability science may only provide an input to a dialogue among stakeholders.

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Figure 1. Optimal forestland use allocation in time and space.

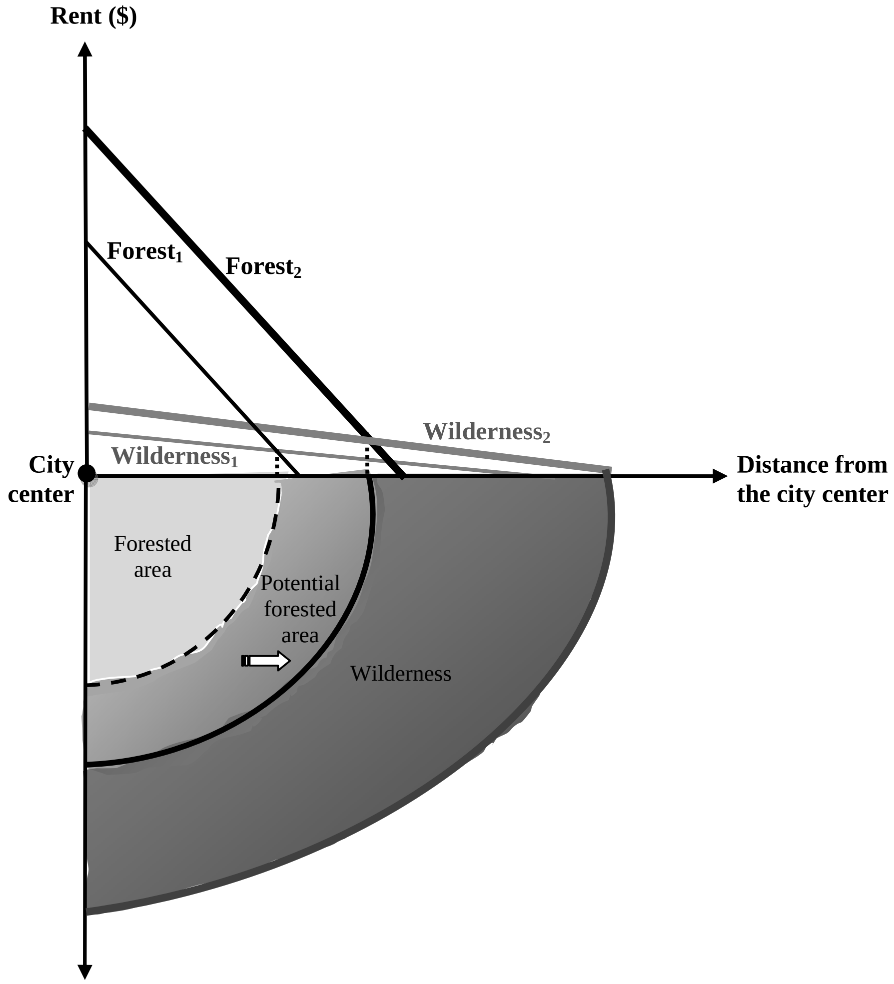
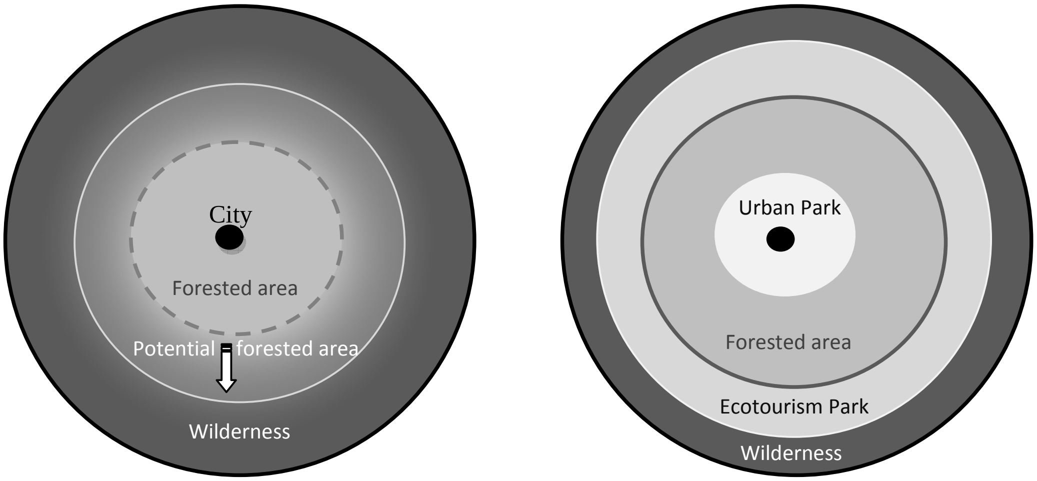


Figure 2. Alternative Allocations of Forest and Wilderness



(a) Design 1: Preservation area on fringe (b) Design 2: Emergence of urban park

Figure 3. Welfare gains from win-win pricing of groundwater. (a) The status quo price is too high. (b) Win-win block pricing requires a reduction in the length of the 1st price block and a decrease in the height of the 2nd price block such that the gain in consumer welfare (B) offsets the loss (A) and the remaining revenue surplus (C) is sufficient to finance conservation investment and compensate landowners.

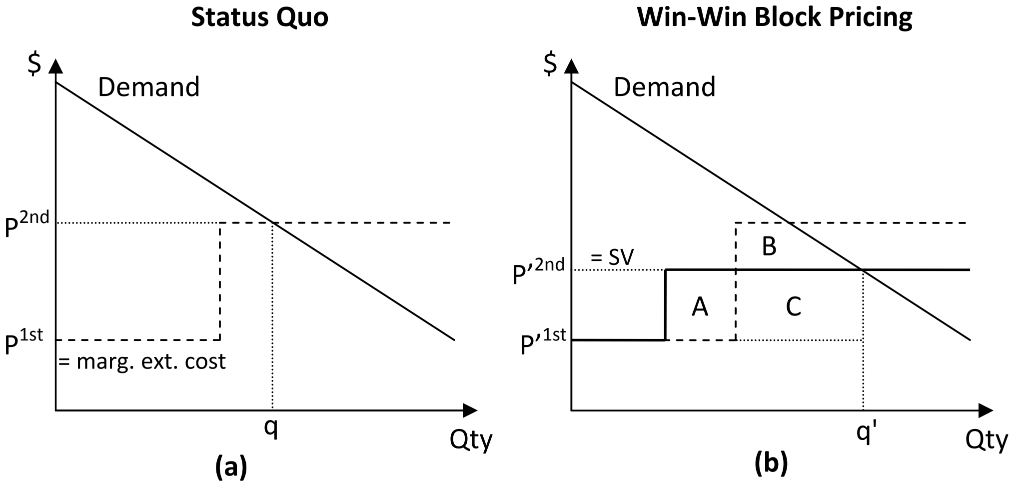
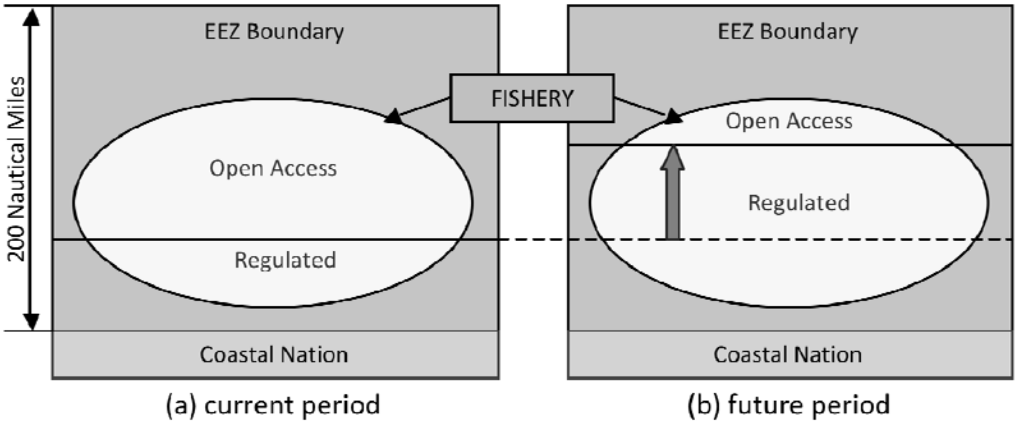


Figure 4. Given transaction costs of management, the optimal enforcement boundary (OEB) for a coastal nation is small relative to its Exclusive Economic Zone (EEZ). As the scarcity value of fish rises over time, the OEB expands, although it may never converge entirely to the EEZ boundary.



(a) current period (b) future period

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[1] Present value is a concept used to compare dollar amounts from different time periods. Management policies generate a stream of benefits and costs over time, which must be discounted appropriately before being added or compared. The discount rate (*r*) sometimes refers to the risk-free interest rate, but often includes a risk premium when uncertainty is involved. As a simple example, if a policy generates *X* dollars every year at a cost of *C* dollars per year until year *T*, then the PV of net benefits accruing from the policy is the sum $\sum_{t=0}^{T}(X-C)(1+r)^{-t}$, where time zero denotes the current period. Of all feasible policies, the one that generates the largest net PV is optimal.

[2] Marginal user cost is defined as the cost of using the resource now in terms of forgone future benefits. Intuitively, extracting a unit of the resource for consumption today increases stock-dependent extraction costs in all future periods and forgoes capital gains that could be obtained by leaving the resource *in situ*.

[3] This is the "Pearce equation," which applies both to fund pollution, such as acid rain that is largely dispersed in a single period, and to stock pollution, such as greenhouse gases.

[4] While MSY is not economically optimal for most resources, it is often gives the optimal long-run stock for groundwater. The few feet added to extraction by a drawdown of the aquifer is typically small relative to the lift required even if the aquifer is fully recharged. As a result the pumping-cost increase is dominated by the decreased leakage such that the MSY is efficient in the long run.