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Land-Use Patterns and Spatially Dependent Ecosystem Services: Some Microeconomic Foundations

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ABSTRACT

This paper develops and reviews some microeconomic foundations for the provision of spatially-dependent ecosystem services from land. We focus on ecosystem services described by a production function with spatial dependencies in the primary input — the amount and pattern of land in particular uses and management. Many ecosystem service production functions are affected by spatial dependences, particularly those involving fish, wildlife, and water quality. We illustrate the various sources of demand for ecosystem services and then provide a novel development of the effects of alternative spatial dependencies on the shape of the supply curve for ecosystem services. Our analysis emphasizes that the optimal supply curve requires a mechanism to coordinate landowners' decisions and internalize the input externalities that arise from production functions being spatially dependent. Finally, we use our framework to illustrate and review some key implications for linking demand and supply for policy design.

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1 Introduction

The microeconomic foundation for much of environmental economics is based on the demand and supply of altering the output of externalities. For example, demand for pollution abatement (a positive externality) is downward sloping and represents the marginal social benefits of reducing pollution. The supply of pollution abatement is upward sloping and represents the marginal costs of reducing pollution. The efficient quantity of abatement occurs at the intersection of these supply and demand curves and forms the theoretical foundation for the efficient design of environmental policies, such as a cap-and-trade or Pigouvian tax approach to pollution reduction. As a parallel to pollution control, the environmental economics of ecosystem service provision has emphasized a Pigouvian subsidy idea of payments for ecosystem services (PES), where landowners are paid for providing positive externalities (Hanley and White, 2013). Ecosystem services are the goods and services provided by nature that are valuable to people. The efficient level of payment for a PES program occurs at the intersection of the supply and demand curves of the ecosystem service. However, the microeconomic foundations of supply and demand for ecosystem services are far less developed than for pollution control.

The purpose of this paper is to develop some microeconomic foundations for the provision of spatially-dependent ecosystem services from land. We focus on ecosystem services described by a production function with spatial dependencies in the primary input — the amount and pattern of land in particular uses and management (Section 2). We illustrate the various sources of demand for ecosystem services arising from governments, non-governmental organizations, private firms, and

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individual consumers (Section 3). We provide a novel development of the effects of alternative spatial dependencies on the shape of the supply curve for ecosystem services, and emphasize that the least-cost (optimal) supply curve may require a mechanism to coordinate landowners' decisions and internalize the input externalities that arise from production functions being spatially dependent (Section 4). Finally, we use our framework of demand and supply for ecosystem services to illustrate some key implications for linking demand and supply in a manner that can be used for efficient policy design (Section 5).

Habitat for terrestrial and aquatic species is perhaps the most prominent example of an ecosystem service whose production strongly depends on spatial dependencies in land. For example, the ability of a forested parcel to serve as habitat for nesting songbird species depends on the pattern and fragmentation of neighboring forested parcels (Robinson *et al.*, 1995; Askins, 2002). As another example, the northern spotted owl has a nonlinear relationship between its population and habitat, as its survival probability is 0% when 10% of a landscape is habitat (old growth forest), while its survival probability is 95% when 20% of the landscape is habitat (Lamberson *et al.*, 1992). In both of these cases, the marginal biophysical benefit of conserving an additional plot of land is dependent on the conservation status of neighboring land and the production function of ecosystem services from the landscape is subject to an ecological threshold.

Efficient provision of spatially dependent ecosystem services depends on optimally arranging the amount and pattern of multiple types of land uses, and there are at least three primary challenges to policy design that constructs optimal landscapes. First, private property rights systems of land ownership imply that land-use decisions across large landscapes will generally be independent and uncoordinated. Second, the dominant economic system in most parts of the world does not provide price signals for spatially dependent ecosystem services. Many ecosystem services are under supplied because of their public-goods nature, including non-exclusivity and indivisibility (non-rivalry). Finally, incomplete scientific knowledge of the link between spatial landscape patterns and ecosystem services greatly hinders the measurement of services needed to create any price signals. Combined, these institutional, economic, and scientific challenges imply a strong barrier to linking the demand for, and the supply of, spatially dependent ecosystem services.

A fundamental cause of pollution problems is the problem of externalities, while the provision of ecosystem services is often plagued by multiple complications, including externalities, spatial dependency, and the public-good nature of ecosystem services such as non-exclusivity and indivisibility. Thus, the general problem of ecosystem services could capture pollution control as a special case. Much research has focused on the importance of spatial information in pollution control. The early literature on spatial pollution (e.g., Tietenberg, 1974; Henderson, 1977; Henderson, 1996; Hochman and Ofek, 1979; Krupnick *et al.*, 1983) considers the amount of emission transported from sources (e.g., firms) to monitors (e.g., population centers), but often takes the location of firms and households as fixed. Since then a few studies have examined spatial pollution in a model that allows firms or households to move (e.g., Markusen *et al.*, 1993; Hoel and Shapiro, 2003; Elbers and Withagen, 2004; Lange and Quaas, 2007; Zeng and Zhao, 2009). These studies typically use a two-region model to examine a firm's decision to open or close a plant in response to environmental policy, and do not model either the scale or pattern-based spatial dependencies between firms' production or pollution abatement.

This paper reviews and advances current knowledge in environmental economics on the demand and supply of spatially-dependent ecosystem services. We highlight the many research requirements necessary to further develop an understanding of the role of economic and policy incentives for spatially-dependent ecosystem service provision. Since spatial dependencies characterize the production function for many ecosystem services, the design of policy for ecosystem services must take into account these spatial dependencies. Substantial efficiency losses are likely when conservation investments are based on formulas or guidelines arising from political consideration, or keyed to a specific on-site physical criterion.

2 The Role of Scope and Pattern in Defining Spatially-Dependent Ecosystem Services

It is important to consider both the geographical scope and spatial patterns of land use when defining spatially dependent ecosystem services. Geographic scope refers to the extent to which the scale of study (national vs. regional) is relevant. Spatial pattern refers to the placement or arrangement of certain land uses in a geographical area. Although scope and pattern are two different concepts, they are closely interrelated. Land use pattern emerges only at a certain geographical scope. Scope matters when location and patterns are important.

Land use patterns can be viewed and studied at the global, national, regional, and local scale. The impact of a given amount of land use change on ecosystem services can be dramatically different depending on the location and patterns of land use. At the global scope, the pattern of land use across countries matters for many ecosystem services. For example, global biodiversity depends on the location of habitat across countries. Different species have different habitat ranges while some migratory species have habitat across countries. Collaboration at the global scale is needed for effective conservation of those species. At the national scope, the pattern of resource lands across broad regions matters. For example, the amount of carbon sequestered depends on where forests are located across regions with heterogeneous forest growth rates. In this case, coordination of conservation effort at the national level will increase the benefits of conservation. At the regional scope, the pattern of urban and rural lands matters. For example, the amount of outdoor recreation produced depends on locating conservation lands in proximity to population and/or scenic landscapes. At the local scope, the pattern of land use at the plot scale matters. For example, the number of neo-tropical songbirds produced depends on the plot-scale fragmentation of habitat.

Fundamentally, scope and pattern matter for the production of biophysical output and the design of policy because of three fundamental features of landscapes and ecosystems (see Figure 1). The first fundamental feature is spatial heterogeneity in benefits and costs of land use. Spatial variations in costs and benefits of land use can be caused by spatial heterogeneity in resource characteristics such as land quality and water availability, or by the non-uniform distribution of human population over space. As an example of the later effect, other things being equal, conservation is more likely to generate a larger economic benefit in a heavily populated area than a sparsely populated area because more people can enjoy the conservation benefits in a populated area.

The second fundamental reason why scope and pattern matter is spatial interactions and spillovers across land parcels. Spatial interac-

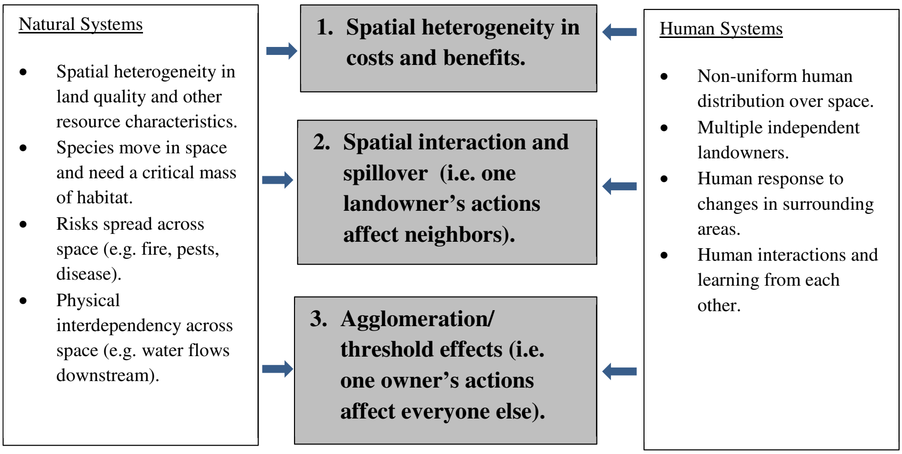

Figure 1: Three fundamental features that make location and pattern important in economic and environmental systems.

tions and spillovers can take many forms. For example, conservation upstream affects water quality downstream. Spatial interactions and spillovers also originate from some fundamental features of natural and human systems. For example, because water flows downhill, the benefit of riparian conservation depends on land use upstream. If a parcel is intensively farmed, establishing a riparian buffer will likely generate a larger environmental benefit because it will prevent nutrients from entering into the river. Likewise, because species move in space and need a critical mass of habitat for survival, one landowner's land use decisions may affect neighbors' provision of ecosystem services (Ando, 2014). Risks such as fire, pests, and diseases, spread across space (Albers, 2014).

The third fundamental reason why scope and pattern matter is the existence of threshold and agglomeration effects. Threshold effects occur when a significant environmental change occurs only after conservation reaches a certain threshold. Threshold effects exist in many conservation efforts, particularly those involving fish and wildlife. For example, to protect cold-water fish species, such as an endangered salmon run in the Pacific Northwest, conservation efforts have to reduce stream temperature below a certain threshold. Threshold effects can also be viewed as "agglomeration benefits." Each landowner will provide more environmental benefit when one additional landowner joins the conservation efforts. Because of threshold effects, the relationship between the amount of land conserved (the input) and the level of ecosystem services generated (the output) in a region can be highly nonlinear, which, as shown in later sections, poses significant challenge to the design of policy for ecosystem service provision.

Scope and pattern of land use also determine the value of ecosystem services to society. For example, a given amount of reduced soil erosion from a land conservation program likely generates larger value in a more densely populated area than in a sparsely populated area. The value of recreation benefits from conservation depends on locating conservation lands in proximity to population and/or scenic landscapes.

3 The Demand for Ecosystem Services

Assessing the demand for ecosystem services must consider the key features of ecosystem services, including the degree of rivalry and excludability. While many provisioning services such as food production are private goods, most of the supporting, regulating and cultural services are public goods, with benefits accruing to local, regional, or even global communities. For example, most benefits from water quality protection go to local communities, while most benefits from biodiversity conservation and carbon sequestration accrue to the global community. Because demand measures people's willingness to pay for various amounts of ecosystem services, understanding who benefits from the ecosystem services and how they are distributed spatially is essential for assessing the demand for ecosystem services.

Many ecosystem services would be under supplied under the free market because of their public goods nature and the free-riders problem. Thus, the public sector often purchases those ecosystem services on behalf of a group of citizens or the global community. Examples of public conservation programs abound ranging from local to global scale. For instance, New York City pays upstream landowners to protect its headwater through several conservation programs. Costa Rica's Payments for Ecosystem Services Program pays landowners for ecosystem services such as conserving wild species, storing carbon, and safeguarding water quality. The U.S. government's Conservation Reserve Program provides multiple environmental benefits, including soil erosion reduction, water quality protection, and wildlife habitat conservation, by paying farmers to convert highly erodible cropland or other environmentally sensitive acreage to resource conserving covers, such as native grasses, trees, and filter-strips. Brazil's Program of Social and Environmental Development for the Rural Family-Based Production aims to promote biodiversity conservation and create an additional source of income for rural family farmers who engage in ecologically sustainable forestry activities.

Conservation organizations and NGOs also play an important role in driving the demand for ecosystem services. For example, the Nature Conservancy uses land acquisition as a principal tool of its conservation effort and has protected approximately 15 million acres of environmentally sensitive land in the United States. The Global Environment Facility is a partnership for international cooperation for biodiversity conservation, climate change mitigation, and other ecosystem services conservation. Since 1991, the Global Environment Facility has provided $12.5 billion in grants and leveraged $58 billion in co-financing for 3,690 projects in 165 developing countries.

The private sector has to date played a secondary role in driving the demand for ecosystem services. Because many ecosystem services are global public goods, many wonder why the private sector purchases them at all. Several theories have been advanced to explain firms voluntary environmental management. These theories can be used to explain the increasing private demand for ecosystem services. The first theory emphasizes the role of regulation. It argues that the private sector is purchasing ecosystem services because they are forced by regulation or pending threat of regulation. A number of studies have found that firms facing higher regulatory pressure are more likely to participate in voluntary environmental programs (Arora and Cason, 1995; Cohen, 1997; Videras and Alberini, 2000; Khanna and Anton, 2002; Rivera and deLeon, 2004; Wu, 2009). Landowners and firms are willing to pay for some ecosystem services if it offers a low-cost way to comply with a regulation. A good example is the U.S. Critical Habitat Designation Program designed to protect endangered species. Under the program, some developers are required not only to do on-site conservation, but also to purchase land off-site to mitigate their development impact on the endangered species. Another good example is the cap-and-trade scheme built in several U.S. environmental programs that allow firms to meet their emission caps by purchasing offsets from other firms or landowners. More broadly, Canton *et al.* (2008) find that environmental regulation can affect the incentives of firms managing environmental resources or supplying pollution abatement goods to merge, leading to changes in pollution abatement efforts in other sectors.

The second explanation emphasizes market forces and argues that profit motivates firms to engage in voluntary environmental management (Wu, 2009). This framework emphasizes the effect of voluntary environmental management on firms' expected costs and returns and how the effect is influenced by external market and regulatory forces and internal firm characteristics (see reviews by Alberini and Segerson, 2002; deLeon *et al.*, 2009; Khanna, 2001; Khanna and Brouhle, 2009; Lyon and Maxwell, 2004; Reinhardt, 2005; Wu, 2009). Although the ultimate motivation is profit maximization, the underlying mechanisms can be either market driven or strategically motivated. The market-driven purposes include extracting a price premium from green consumers (Arora and Gangopadhyay, 1995), incentivizing employees (Brekke and Nyborg, 2008), and enticing investors (Ervin *et al.*, 2013). The strategic behavior theory contends that firms adopt environmental management to preempt stricter environmental regulations in the future, gain competitive advantages, or induce the government to choose a form of regulation more favorable to them (Arora and Cason, 1995). Voluntary environmental management may generate a good reputation, which may reduce regulatory pressure and thus the likelihood of stricter regulation in the future (Maxwell *et al.*, 2000; Lutz *et al.*, 2000). Voluntary environmental management may also be part of an overall business strategy. Empirical evidence to support this theory includes Claver *et al.* (2007), who found a positive relationship between environmental strategy and economic performance in a case study of a farming cooperative.

The third explanation emphasizes institutional reasons for firms to engage in voluntary environmental management. It examines how external pressures from market and non-market constituents and internal firm characteristics shape the firm's environmental efforts (see reviews by Ervin *et al.*, 2013; Annandale *et al.*, 2004; Cordano and Frieze, 2000; Delmas and Toffel, 2004; Delmas and Toffel, 2008; Marshall *et al.*, 2005; Simpson *et al.*, 2004; Nishitani, 2009). Several studies have empirically analyzed the effects of various institutional pressures on corporate environmental management (see reviews by Annandale *et al.*, 2004; Cordano and Frieze, 2000; Delmas and Toffel, 2004; Delmas and Toffel, 2008). Finally, altruism and "warm glow" may motivate people to engage environmentally friendly practices or to pay for ecosystem services even if they are public goods (Pollitt and Shaorshadze, 2013; Lutzenhiser, 1993).

Several inter-related trends are stimulating consumers' demand for ecosystem services. The first trend is the increase in consumer-driven sustainability initiatives stimulated by increased public awareness of the value of ecosystem services, including the "back to local" movement and increased demand for "clean energy," (see reviews by Alberini and Segerson, 2002; Khanna, 2001; Lyon and Maxwell, 2004). For example, the Oregon public utility Eugene Water and Electric Board has over 3,000 residential customers and 164 businesses participating in their Greenpower options. A second trend is increasing development pressure on forests and farmland, accompanied by declining natural resource management budgets. Development pressure is likely to stimulate local communities to take initiatives to protect open space and ecosystem services. For example, from 1988 to 2015, there were 2,469 conservation initiatives placed in local and state referenda in the United States, and 75.5% of those initiatives were approved, providing about $72 billion for land conservation (The Trust for Public Land, 2015).

Despite the promise of private demand, ecosystem service "markets" are constrained by a number of factors. First, non-rivalry and non-excludability post a tremendous challenge for the market of ecosystem services. Second, the mismatch of the locations of producers and consumers of ecosystem services makes it challenging to form an ecosystem service market. Although the mismatch is not unique and often occurs for traditional commodities, it creates a larger challenge for marketing ecosystem services because of their non-rivalry and non-excludability characteristics. When an ecosystem service is a public good, who has the right to sell, to buy, or to consume the good is not well defined, and the market for the ecosystem service would be hard to develop. Third, the beneficiaries of the ecosystem services provided by agricultural landscapes (often urbanites) historically have not had to pay for the provision of those services, thus raising legitimate concerns about the equity and social acceptability of payments for ecosystem services.

Fourth, the demand or willingness to pay for ecosystem services is limited by low income in developing countries. The Environmental Kuznets Curve Hypothesis implies that developed countries are more likely to demand and pay for environmental goods and services. Finally, the tools, metrics, and standards for measuring ecosystem services in a way that allows for their being sold in any marketplace — or being used in a regulatory compliance framework — remain fraught with technical and practical problems.

4 Land-Use Patterns and the Supply of Ecosystem Services

The supply of ecosystem services across a landscape will be determined by the scale and pattern of land-use and management that results from the decisions of individual landowners. This section focuses on the shape of the supply curve for ecosystem services from landscapes with multiple independent landowners. We first analyze properties of production functions of ecosystem services with spatial dependencies and then examine the characteristics of their supply functions. For ease of exposition, a parcel is either conserved or not conserved. Conserving a parcel of land increases the flow of ecosystem services relative to a baseline where the parcel is not conserved. Conserving land implies a change in the use or management of a parcel of land relative to its baseline use and management — setting a forested parcel aside from timber harvesting; converting an agricultural parcel to forested use; etc.

To analyze the properties of production functions of ecosystem services, it proves to be useful to distinguish between pattern-based spatial dependencies and scale-based spatial dependencies. Pattern-based spatial dependencies arise from the fine-scale pattern of land — the pattern of conserved land is the primary input into the production function. The defining feature of pattern-based spatial dependencies is that biophysical production on a conserved parcel is higher with more adjacent conserved land (i.e., there are spatial interactions and spillovers). For example, the breeding success of many forest songbirds depends on whether their nest is located in contiguous rather than fragmented habitat (Askins, 2002; Faaborg, 2002).

Scale-based spatial dependencies arise from an ecological threshold — when a significant environmental improvement can be achieved only after conservation land reaches a certain threshold. Unlike pattern-based spatial dependencies, biophysical production with scale-based dependencies only depends on the aggregate amount of conservation land and not its fine scale pattern. For example, many cold-water fish species such as salmon are highly susceptible to water temperature extremes; they can survive only if stream temperatures do not exceed a certain threshold (Wu *et al.*, 2000). Therefore, land conservation that does not lower stream temperatures below the threshold can have minimal impacts on fish densities. As shown below, scale-based spatial dependencies are highly relevant to land allocation and land use patterns across broad geographic regions such as watersheds.

4.1 Production Functions with Pattern-Based Spatial Dependencies

Figure 2 depicts pattern-based spatial dependencies in an example landscape with eight parcels (adapted from Figure 1 of Polasky *et al.*, 2014). In this example, each parcel is either conserved or not conserved. The opportunity cost of conservation is indicated in the top row and measured as a dollar amount. The benefits (in biophysical terms) of conservation are found on the bottom row where the first number indicates the benefits if no adjacent parcels are conserved, the second number indicates the benefits if one adjacent parcel is conserved, and so on for two or three adjacent conserved parcels. In this example, only parcels that share a side are neighbors.

	1	2	3	4
A	2.9 6 9 11	0.9 5 8 10 11	2.95 4 5 7 9	3.05 2 5 7
B	1.1 1 2 3	1.05 3 6 8 9	0.95 5 8 10 11	3.1 6 9 11

Figure 2: Pattern-based spatial dependencies in an example 2×4 landscape. (adapted from Polasky *et al.* (2014)).

The ecosystem service production function in Figure 2 is based on three simple principles. First, the landscape is pre-divided into discrete land parcels. Second, the biophysical output from conserving each parcel is higher with neighboring conservation. This principle represents the basic principles in much of wildlife ecology about the effects from habitat fragmentation. Third, the natural endowment of individual parcels gives rise to heterogeneity in biophysical production across parcels. Such heterogeneity is ubiquitous in ecosystem service production functions because parcels are heterogeneous in their natural habitat, slope, water availability, and other natural features that influence ecosystem service production. One of many possible mathematical representations of this type of production function is a variant from Lewis *et al.*'s (2009) depiction of benefits from clustered (non-fragmented) forestland, which depicts biophysical benefits from parcel i as:

$$B_i = \begin{cases} \gamma^{\alpha_0 - \alpha_i} G_i, & if\ i\ is \text{ conserved} \\ 0, & if\ i \text{ is not conserved} \end{cases}$$

where $\gamma \in [0, 1)$; α_i indicates the number of neighboring conserved parcels to parcel i; α_0 indicates the maximum number of neighboring parcels such that $\alpha_0 \geq \alpha_i$; and G_i indicates the biophysical production if parcel i is entirely surrounded by conserved parcels. The term $\gamma^{\alpha_0 - \alpha_i}$ scales the biophysical service from parcel i depending on the number of conserved neighbors.

4.2 Production Functions with Scale-Based Spatial Dependencies

Figure 3 depicts the ecosystem service production function where the scale-based spatial dependency arises from an ecological threshold. In the water temperature example, A_1 acres of forest in a watershed might correspond to a temperature above the threshold while A_2 acres of forestland might correspond to a temperature below the threshold. Biophysical benefits (e.g., fish density) have a non-linear jump between these conservation outcomes. Here, the fine-scale pattern of land in forest is less important than the total amount of acreage in forest within the watershed.

The benefit function in Figure 3 is a function of conserved acres, A. The function generally has the following properties. First, the marginal benefit with respect to conserved acres is positive, $B' > 0$. Second, the

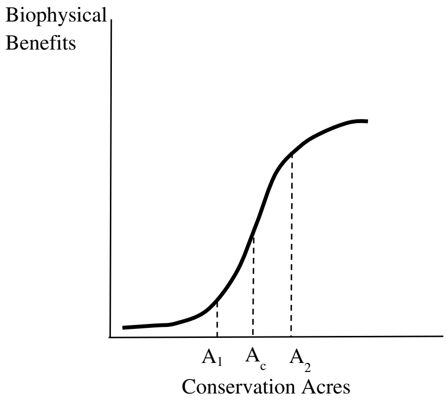

Figure 3: Production function and with scale-based spatial dependencies.

marginal benefit is increasing up to a critical value A_c, $B'' > 0$ when $A \leq A_c$; and the marginal benefit is decreasing in additional acreage added to A_c, $B'' < 0$ when $A > A_c$.

4.3 The Supply Curve with Pattern-Based Spatial Dependencies

Suppose a government agency or an environmental organization is willing to pay for an ecosystem service with pattern-based spatial dependencies, and is interested in the schedule of biophysical services supplied at different prices. The complication with deriving supply curves for pattern-based spatial dependencies arises from the fact that the cost-minimizing input selection (pattern of conservation) requires coordination across parcels. Coordination matters because the marginal benefit from conserving a particular parcel depends on whether neighboring parcels also conserve. To illustrate, we consider the eight-parcel example landscape in Figure 2. If the entire landscape were owned by a single individual, they would optimize inputs to the production function by selecting the pattern of conservation that optimally accounts for the spatial dependencies. Specifically, given a price $p$for the ecosystem service, the sole landowner selects the land-use pattern X= $(x_1, x_2, \ldots, x_N)$ to maximize their profits:

$$\max_X \pi = p \cdot B(X) - \sum_{i=1}^{N} x_i\, c_i$$

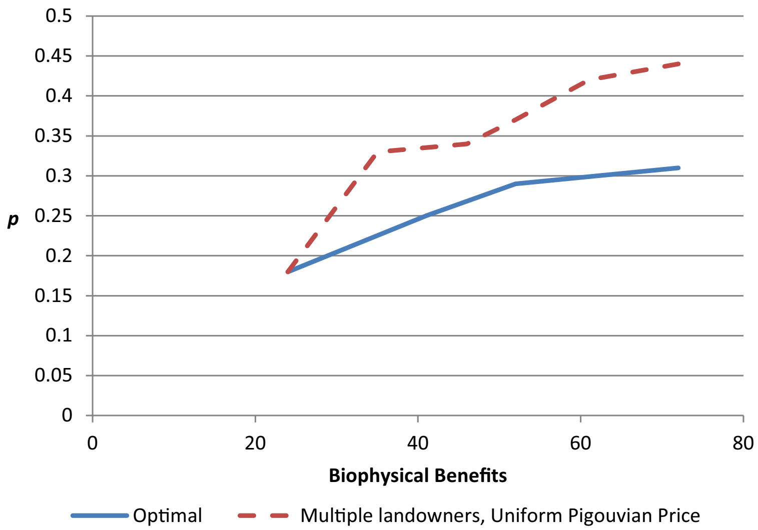

Figure 4: Supply curves for pattern-based ecosystem services derived from simple in Figure 2 (p is the price of a unit of biophysical service).

where $x_i = 1$ if parcel i is conserved and zero otherwise, c_i is the cost of conserving parcel i, and $B(X)$ is the biophysical benefit function of land-use pattern X. Figure 4 presents the sole owner's supply curve for the eight parcel simple example as the solid line.[1] Notice that this supply curve starts at a price $p = \$0.18$, as zero conservation is optimal at any price below \$0.18.

The supply curve for the sole owner shows the minimum costs for producing various amounts of the ecosystem service, and is the marginal social cost for providing the ecosystem services. However, optimally coordinating the pattern of conservation such that costs are minimized for the production of a given amount of biophysical benefit is not assured if the eight parcels are owned by eight different individuals. Because of spatial dependencies, the marginal social benefit and the marginal private benefit of conservation are different. Following Polasky *et al.* (2014), the marginal social benefit of conserving parcel j in the presence of a spatially dependent benefit equals the value of the optimal landscape with parcel j conserved (less parcel j's cost) minus the value

[1] Matlab code for optimizing the landscape in the simple example is available from the authors upon request.

of the optimal landscape without parcel j conserved. Mathematically, the marginal social benefit of conserving j equals:

$$\begin{aligned}\Delta W_j &= W_j(X_j^*) - W_j(X_{\sim j}^*) \\ &= \left[pB(X^*) - \sum_{i\neq j} x_i^* c_i\right]) - \left[pB(X_{\sim j}^*) - \sum_{i\neq j} x_{i\sim j}^* c_i)\right],\end{aligned}$$

where X_j^* is the optimal landscape with parcel j being conserved, and $X_{\sim j}^*$ is the optimal landscape without parcel j being conserved. Parcel j is optimally conserved if the marginal benefit of conserving j is at least as high as its marginal conservation cost, $\Delta W_j \geq c_j$. However, ΔW_j is affected by other parcel owners' optimal decisions and parcel j's conservation affects optimal decisions on other parcels. Any one parcel owner's decision to conserve generates a positive externality on the decision of another parcel to conserve — ΔW_j is higher if j has a (optimally) conserved neighbor. Thus, if conserving parcel j is an input into the ecosystem service production function, then it is affected by an input externality.

In contrast, individual landowners make decisions to maximize their own profit. Without coordination with other owners, the owner of parcel j will conserve his parcel if and only if

$$pb_j(x_j, X_{-j}) \geq c_j,$$

where $b_j(x_j, X_{-j})$ is the biophysical benefit generated on parcel j when it is conserved, and given the conservation status of surrounding parcels (X_{-j}). The dashed line in Figure 4 shows the total ecosystem service benefit that would be produced when the government raises the price gradually, and individual landowners make independent decisions simultaneously without coordination or strategic behavior, and will conserve their land when $pb_j(x_j, X_{-j}) \geq c_j$. We solve for the dashed line in Figure 4 in a manner similar to a Cournot equilibrium, in that landowners make their conservation decision in response to the positive input externalities generated by other landowners' conservation decisions at any given price.[2] Because individual decision makers ignore the positive

[2]As a reviewer notes, this is one possible equilibrium, as a consistent conjectures equilibrium might suggest that landowners account for how their supply decisions influence neighbor's supply decisions.

input externalities they generate for other landowners, their decisions are not socially optimal. As a result, they produce less benefit for a given price because the marginal private cost (i.e., the dashed line in Figure 4) is above the marginal social cost.

Optimal input selection with a single landowner has no input externality. Thus, offering a price p per unit biophysical service represents a standard Pigouvian subsidy payment for the ecosystem service and the supply curve is optimal, representing the minimum marginal social cost of production. However, multiple independent landowners subject to a spatially dependent production function are affected by an input externality and so offering them a standard Pigouvian price p per unit biophysical service will not generate the cost-minimizing input selection (pattern of conservation). Therefore, the supply curve for the independent landowner, the dashed supply curve in Figure 4, is generated when the input externality is ignored.[3] The quantity of ecosystem services supplied at any given price is higher if the input externality is internalized than if it is not internalized. Ignoring the input externality implicit in pattern-based spatially dependent production functions will lead to an under supply of ecosystem services even if the right price is offered for ecosystem service.

4.4 The Supply Curve with Scale-Based Spatial Dependencies

The supply curve of the ecosystem service with scale-based spatial dependencies is derived from the ecosystem service production function and from the marginal cost function for conserving land. Figure 5.a shows the marginal benefits and costs of conserving land. From the ecosystem service production function in Figure 3, the marginal biophysical benefits of conserving land are increasing at low levels of conservation and then decreasing. The marginal benefits of conserving land are simply the price per unit of biophysical service (p) multiplied by the marginal biophysical benefits (B'). Marginal costs of land are assumed upward sloping, and the marginal cost of conserving a particular parcel equals the land price

[3]The supply curve with multiple landowners and a uniform Pigouvian price is derived where payments are offered conditional on the current landscape. At a price of \$0.18, parcels A2, B2, and B3 are conserved. At a price of \$0.33, parcel A1 is conserved and its payment is conditional on A2 being conserved. Quantity supplied at higher prices is derived in a similar way.

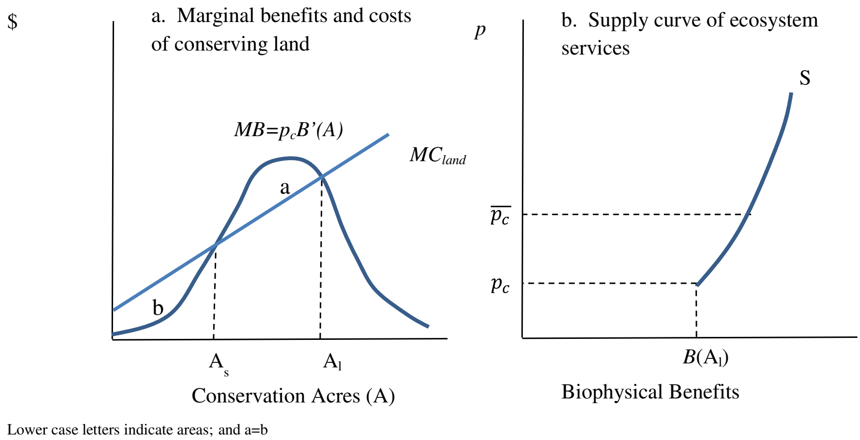

Figure 5: Marginal benefits of land and supply curve for ecosystem services with scale-based spatial dependencies (p is the price of a unit of biophysical service).

of that parcel. Figure 5(a) depicts the cutoff price p_c, where the total benefits of conservation just equal the total costs. Higher values of p simply shift the marginal benefit curve higher in Figure 5(a), but don't affect its shape. Our focus on marginal benefits and marginal costs of conserving land in Figure 5(a) illustrate that the optimal supply of ecosystem services is zero at prices below p_c, and positive at prices above p_c.

The ecosystem service supply curve derived from scale-based spatial dependencies depends on the number of individual landowners within the region. If the entire region is owned by a single landowner, the supply curve in Figure 5(b) begins at a price of p_c and slopes upward. At p_c, the landowner would receive a payment precisely equal to their cost and so would conserve A_l acres and generate biophysical benefits $B(A_l)$. However, if the landscape were owned by many individual landowners, no conservation would occur at a per-unit price of p_c. Since the marginal benefits of the first unit of conservation would be less than the marginal conservation cost, then the payment p_c offered to each independent landowner is too low to offset their conservation cost. Landowners who conserve the first A_s acres would be paid below their marginal costs of land while landowners who conserve acreage between A_s and A_l would earn rents. The landowners would need a mechanism to share rents in order to induce all landowners to conserve. Similar to the case with pattern-based spatial dependencies, landowners generate an input externality to other landowners by conserving — the marginal benefits of conservation are higher if a landowner within the same region has already conserved.

The ecosystem service supply curve for a landscape composed of many private landowners would have to begin at a price of $\bar{p_c}$, where $\bar{p_c}$ is defined as the price in which each landowner would find it optimal to conserve: $\bar{p_c}B'(0) = MC_{\text{land}}(0)$. Note that $\bar{p_c} = \infty$ if $B'(0) = 0$, that is, no ecosystem services will be supplied even if the price is very high, and it is socially optimal to supply a positive amount. At every price above $\bar{p_c}$ the ecosystem service supply curve is identical to the supply curve from a landscape owned by a single individual. We therefore see that simply offering a per-unit Pigouvian price would not generate the optimal supply of ecosystem services for a range of prices between p_c and $\bar{p_c}$, but would generate optimal supply at high prices above $\bar{p_c}$. Thus, we term the amount of conservation land $A_{\min}$ that would occur at $\bar{p_c}$ the "minimum viable conservation threshold", where $A_{\min}$ is defined by $\bar{p_c}B'(A_{\min}) = MC_{\text{land}}(A_{\min})$.

5 Policy for Ecosystem Service Provision

Efficient market supply of ecosystem services require that (a) demand and supply are well defined and linked, (b) there is no externality in the production of ecosystem services, (c) the final ecosystem products are not public goods, and (d) there is no information asymmetry between buyers and sellers. Conditions (a)–(d) above are among the conditions that must be met for efficient provision. Markets that at least partially satisfy these four conditions exist for ecosystem services like food and fiber. For example, the demand and supply of timber is well defined, the final product of timber is a private good and mature timber markets exist to convey price information to buyers and sellers. Further, the production of timber is largely determined by management on the plot of land that grows that timber and not on neighboring landowners' management. Thus, there is no input externality associated with growing timber. In such circumstances, the use of spatial information depends on its value for decision makers and may be irrelevant for setting optimal policies (see Marrouch and Sinclair-Desgagné (2012) for another such example).

Many ecosystem services are not traded in a well-defined market and so efficient provision is far from assured in the absence of explicit policy. Consider habitat for wildlife as an example, where all four conditions above are violated: (a) demand and supply are not well-defined and not at all linked; (b) the production function translating land-use decisions to habitat is affected by spatial dependencies which give rise to an input externality in production; (c) habitat conservation provides non-excludable benefits to non-landowners; and (d) landowners have private information regarding their conservation costs to produce wildlife habitat. Policy design faces the challenge of dealing with violations of all four conditions in generating the efficient production of non-market ecosystem services. We elucidate these challenges in this section and focus on insights that have been gained from environmental economics research.

5.1 Government Programs to Link Demand and Supply for Ecosystem Services

The efficient provision of ecosystem services occurs at the quantity that equates the supply of ecosystem services (the marginal social cost curve) with the demand (the marginal social benefit curve). An important issue is what is the appropriate scale with which to link supply and demand? For example, the demand for crops is global and linked with supply of crops through global commodity markets. In contrast, the demand for urban residential lots is local (e.g., within a metropolitan area) and linked with the local supply of developable land through land and real estate markets.

The appropriate scale with which to link supply and demand for non-market ecosystem services is far less obvious. Consider wildlife habitat. The demand for ocean-going (anadromous) salmon in an Oregon watershed may arise from local recreational anglers and from global seafood markets that consumes salmon for food. The demand for moose in a forest from Maine may arise from local hunters and from tourists who visit the area to see wildlife. Demand for both of these species may also arise from distant individuals with non-use values. The supply of salmon habitat in an Oregon watershed and the supply of habitat for Moose in a Maine forest are strongly affected by the timber harvest practices, development, and agricultural practices of landowners in the watershed and the forest. But there are few mechanisms to link the demand for salmon and moose from disparate regions to the local supply of this ecosystem service. The fact that individuals are not typically excluded from the benefits derived from these species makes the appropriate scale in which to match demand and supply difficult to discern.

For most non-market ecosystem services, demand is largely driven by government conservation programs — e.g. payments for ecosystem services. Thus, one practical view is that demand for non-market ecosystem services is driven by the government operating on behalf of its citizens. Government demand then provides a way to satisfy two of the four conditions of efficient provision discussed above: the problem of how to match demand and supply, and the problem that most non-market ecosystem services have public goods characteristics. Any point on the demand curve for ecosystem services reflects the government's willingness-to-pay for the marginal unit of ecosystem service provision. Like any demand curve, the government's willingness-to-pay is affected by the government's budget constraint that arises from practical limits on government spending. While government sponsored payment-for-ecosystem service programs represent an approach to match demand and supply for public goods, the government still faces the twin challenges of internalizing any input externalities that affect the production of spatially dependent ecosystem services, and designing policy to overcome the information asymmetry regarding private landowners' conservation costs. In addition, the linkage of supply and demand may be challenged by market structure. For example, a bilateral monopoly structure would arise in cases where the government bargains with large landowners (e.g., timber companies) for conservation.

5.2 Policy Design Challenges — Buying Benefits Directly

Buying benefits directly implies that a program manager can measure benefits and pay landowners accordingly, a process that implies government knowledge of the ecosystem service production function. For example, if the government can measure the tons of carbon sequestered by converting an acre of cropland in South Carolina to a loblolly pine forest, it can pay directly for the carbon sequestered. Or, if the government can measure the number of breeding pairs of Sage Grouse generated by converting an acre of cropland to native range in Oregon, it can pay directly for the birds. The ability to measure ecosystem services is crucial for programs that pay for ecosystem services, and is the impetus for current large-scale efforts at quantifying ecological production functions. For example, the INVEST open-source model from the Natural Capital Project (Daily *et al.*, 2009) aims to quantify ecosystem service production arising from a given landscape structure (e.g., land-use pattern, slope, soils, etc.).

Efficiently providing ecosystem services whose production is affected by pattern-based spatial dependencies faces the principal challenge of ensuring that the supply curve is the optimal (least cost) supply curve. Given a landscape with many independent landowners, a primary challenge for policy design is to find a mechanism to internalize the input externality, otherwise any attempt to link demand with supply will generate an inefficiently low amount of ecosystem service provision at too high a price. One approach is for the government to run a truth-revealing auction for conservation contracts. This is the approach taken by Polasky *et al.* (2014), who show that an auction that sets payments between the government and landowners equal to the marginal value of their ecosystem service provision provides landowners with an incentive to truthfully reveal their cost information, and then allows the government to implement the pattern of land-use that minimizes the costs of producing ecosystem services and hence, generate the optimal supply curve. This auction approach is an extension of insights from truth-revealing Vickery (1961) auctions and pays landowners directly for their provision of public goods. Once the government collects cost information, it then internalizes the input externality by acting like a single landowner and optimizing the pattern of land-use. However, this approach requires heavy government involvement — the government must know the ecosystem service production function, they must know the demand curve for ecosystem services, they must be able to credibly commit to running the truth-revealing auction, and they must be able to then take all this information and optimize the pattern of land use.

If the government is not able to run the truth-revealing auction of Polasky *et al.* (2014), then the environmental economics literature has also examined several second-best options that do not attempt to infer individual landowners' conservation costs. These approaches are second best because the optimal payment to a landowner must be equal to their marginal contribution to ecosystem service provision, and a landowner's marginal contribution depends on which neighbors are optimally conserved and so requires information on all neighbors' conservation costs. First, the government could offer an agglomeration bonus as part of a land conservation payment scheme (Wu and Boggess, 1999; Parkhurst *et al.*, 2002; Parkhurst and Shogren, 2007; Drechsler *et al.*, 2010). This approach aims to conserve contiguous land by offering landowners a bonus if their land is adjacent to another conserved parcel. Second, the government could partition the landscape into sections, and then design a payment system that targets payments that are uniform within but heterogeneous across sections. Since the expected marginal net benefits of conservation can be convex, corner solutions with this type of targeting program may be optimal — conserve the entire section of land, or conserve none of the section (Lewis *et al.*, 2009).

Efficiently providing non-market ecosystem services whose production is affected by scale-based spatial dependencies faces the problem of how to achieve optimal supply when prices are not high. As shown in Figure 5, there exists a range of low prices ($p_c \leq p < \bar{p_c}$) in which optimal supply is non-zero, but uncoordinated conservation by multiple landowners in response to an ecosystem service price would lead to no conservation. One solution is to simply offer a fixed price for land conservation to each landowner. If the government knows the ecosystem service production function, their demand for the ecosystem service, and the *distribution* of landowners' conservation costs, then they know the optimal conservation acreage (A_l in Figure 5). Graphically, a known demand curve could be overlain on Figure 5(b) to determine the optimal quantity and price of conservation land. Therefore, a uniform land conservation payment equal to the marginal cost of land evaluated at A_l and offered to everyone will induce the optimal supply of the ecosystem service $B(A_l)$. In contrast to supplying ecosystem services with pattern-based spatial dependencies, the optimal supply of ecosystem services from scale-based spatial dependencies can be achieved without knowledge of each landowner's conservation costs.

5.3 Conserving Land Without Full Knowledge of the Ecosystem Service Production Function

Production functions are not well-understood for many ecosystem services (Daily *et al.*, 2009). Thus, many conservation programs may attempt to simply maximize some proxy for the ecosystem service. An example would be maximizing the area of conserved land for a given budget. This approach ensures that the land with the lowest conservation costs will be conserved and can lead to highly inefficient outcomes in the presence of scale-based or pattern-based spatial dependencies. The late 1990s and early 2000s saw significant relevant research on the efficiency of alternative programs to target conservation payments, including programs that maximize land conserved (e.g., Babcock *et al.*, 1997; Wu and Boggess, 1999; Wu *et al.*, 2001).

Wu and Boggess (1999) analyzed the inefficiency associated with maximizing conservation land across multiple regions in the presence of scale-based spatial dependencies, and we adapt their analysis in Figures 6 and 7 for a two-region case. Maximizing land conservation means conserving the least costly parcels first. If the distribution of land costs is the same across regions, then land conservation will be maximized when the total budget is split equally across regions. Figure 6 illustrates the case where maximizing land conservation leads to minimum benefits. Benefits can be minimized when the budget is small enough such that the marginal benefits are upward sloping at the

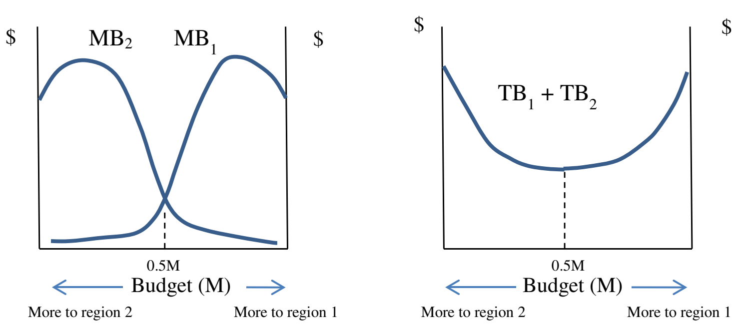

Figure 6: Maximizing land conservation across regions leads to minimum benefits.

Note: Moving to the right on the x-axis allocates more of the conservation budget (M) to Region 1 and less to Region 2. The point 0.5M represents equal allocation of the budget to both regions.

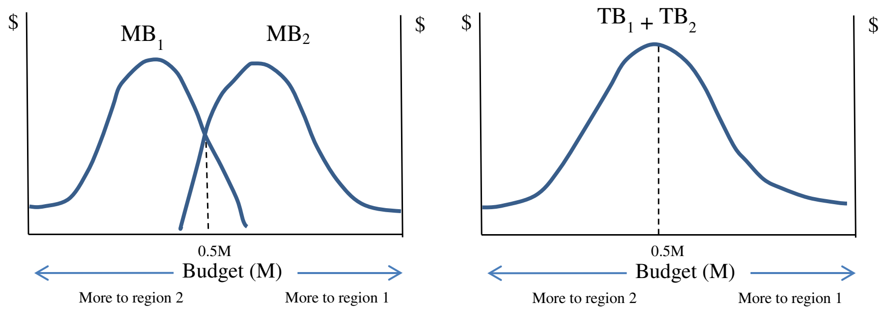

Figure 7: Maximizing land conservation also maximizes benefits.

Note: Moving to the right on the x-axis allocates more of the conservation budget (M) to Region 1 and less to Region 2. The point 0.5M represents equal allocation of the budget to both regions.

last unit conserved. At the margin, total benefits could be higher by re-allocating conservation from one region to the other.

Figure 7 illustrates the case where maximizing land conservation can also maximize environmental benefits. Benefits can be maximized when the budget is large enough such that the marginal benefits of conservation in each region are downward sloping at their last unit conserved. With scale-based spatial dependencies, maximizing land conservation is optimal only if the marginal benefits of conservation are equated across regions and downward sloping at the last unit of conservation. However, we note that the benefits of maximizing land as a proxy for ecosystem services may not be known with certainty. For example, arguments for conserving land are sometimes justified by the fact that conserving land will leave the option to discover future benefits from a species that may not be understood today (e.g., Arrow and Fisher, 1974).

Maximizing land conservation in the presence of pattern-based spatial dependencies can also be highly inefficient. Lewis *et al.* (2011) performed an empirical analysis in the Willamette Basin of Oregon to examine the inefficiency of policies aimed at conserving biological diversity that maximize conservation area by offering a uniform land conservation payment to all landowners. The benefit function measured the persistence probability of a set of 24 terrestrial wildlife species and was subject to pattern-based spatial dependencies because many of the species were sensitive to habitat fragmentation. The econometrically based landscape simulations allowed the authors to compare the results of maximizing land conservation to an optimal approach where all land costs were known and the landscape pattern was optimized. Results indicated that maximizing land conservation only achieved between 9% and 32% of the gains in biodiversity that could optimally be achieved for a given conservation cost, indicating the extreme degree of inefficiency of maximizing land conservation in the presence of an ecosystem service production function subject to pattern-based spatial dependencies. Therefore, there is likely to be strong efficiency gains from public investment that aims to understand production functions of ecosystem services that are influenced by either scale-based or pattern-based spatial dependencies.

Other proxies of ecosystem services could be to maximize the amount of core forest for songbird populations (e.g., Lewis *et al.*, 2009), or to minimize maximum daily stream temperatures for cold-water fish populations (e.g., Watanabe *et al.*, 2006). It is generally inefficient to target proxies of ecosystem services unless there is a direct correspondence between the proxy and the benefits from ecosystem services. For example, Watanabe *et al.* (2005) and Watanabe *et al.* (2006) showed that solving the budget-constrained problem of maximizing juvenile fish populations generates far different allocations of conservation efforts compared to solving the problem of meeting water temperature targets designed as a proxy for fish populations.

6 Conclusions

This paper provides some microeconomic foundations for the provision of spatially dependent ecosystem services from land. We focus on ecosystem services characterized by a production function with either scale- or pattern-based spatial dependencies. We illustrate the various sources of demand for ecosystem services arising from governments, non-governmental organizations, private firms, and individual consumers. We provide a novel development of the effects of alternative spatial dependencies on the shape of the supply curve for ecosystem services. We show that the least-cost provision of ecosystem services may require a mechanism to coordinate landowners' decisions and internalize the input externalities that arise from production functions being spatially dependent. The challenge of coordinating landowners' decisions to supply ecosystem services, in combination with the non-exclusivity and indivisibility characteristics, presents a tremendous challenge to the design of policy for the optimal provision of ecosystem services. We use our framework of demand and supply of ecosystem services to illustrate some key implications for linking demand and supply in a manner that can be used for efficient policy design.

Our development of microeconomic foundations for ecosystem services offers several unique insights about the supply and demand of ecosystem services. First, in the presence of pattern-based spatial dependencies, the marginal private cost of ecosystem services provision is above the marginal social cost. Thus, ecosystem services would be under supplied for any given price, even if the amount of ecosystem services can be accurately measured and a market exists for ecosystem services. Second, in the presence of scale-based spatial dependencies and multiple landowners, supply would be zero even if the right price is offered for ecosystem services when the amount of land in conservation is below the "minimum viable conservation threshold." Below the viable threshold, individual landowners' marginal benefits are below their marginal costs, even if the marginal social benefit is above the marginal social cost when all landowners act simultaneously. Third, while private demand for ecosystem services is increasing, the current demand for ecosystem services is mostly driven by government policies. The increasing private demand is driven by several factors, including regulation or pending threat of regulation, firms' incentives to capitalize on consumers' preferences for environmentally friendly products and services, firms' strategic behaviors to preempt environmental regulations, and institutional pressures from investors and environmental groups for environmental management. Fourth, the mismatch of the locations of producers and consumers of ecosystem services makes it challenging to form an ecosystem service market. Although the mismatch is not unique and often occurs for traditional commodities, it creates a larger challenge for marketing many ecosystem services because of their non-rivalry and non-excludability characteristics.

Our analysis also provides several insights into policy design for optimal provision of ecosystem services. First, even though there is a tremendous amount of current effort to measure the production functions of ecosystem services and the non-market values of ecosystem services, ecosystem services would still be under supplied with the creation of a market unless the input-externality issues are solved. Second, to solve the problem of input externalities, it is useful to distinguish between scale- and pattern-based spatial dependencies. In the case of scale-based spatial dependencies when the conservation level is below the minimum viable threshold, one way to implement the optimal policy is to compensate landowners for land conservation, rather than pay for ecosystem services directly. To solve the input-externalities associated with pattern-based spatial dependencies, the key to optimal policy is to design a mechanism to incentivize landowners to coordinate their land use decisions. Such coordination would allow landowners to internalize their input externalities, providing the optimal supply of ecosystem services in the face of the right price signals.

In most conservation investments, the provision of ecosystem services is likely characterized by a production function with scale- or pattern-based spatial dependencies. Optimal design of policy for ecosystem services must take into account these spatial dependencies. Formulas or guidelines based on political consideration, or keyed to a specific on-site physical criterion, are likely to result in substantial efficiency losses. While challenges are daunting, payoffs are potentially high when spatial dependencies are explicitly considered in the design of policy.

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