

Implementing the optimal provision of ecosystem services

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Many ecosystem services are public goods whose provision depends on the spatial pattern of land use. The pattern of land use is often determined by the decisions of multiple private landowners. Increasing the provision of ecosystem services, though beneficial for society as a whole, may be costly to private landowners. A regulator interested in providing incentives to landowners for increased provision of ecosystem services often lacks complete information on landowners' costs. The combination of spatially dependent benefits and asymmetric cost information means that the optimal provision of ecosystem services cannot be achieved using standard regulatory or payment for ecosystem services approaches. Here we show that an auction that sets payments between landowners and the regulator for the increased value of ecosystem services with conservation provides incentives for landowners to truthfully reveal cost information, and allows the regulator to implement the optimal provision of ecosystem services, even in the case with spatially dependent benefits and asymmetric information.

environmental economics | land conservation | spatial model

Ecosystems provide many goods and services that contribute to human well-being (“ecosystem services”). For example, ecosystems regulate local climate through effects on water cycling and temperature and global climate through carbon sequestration, mediate nutrient cycling and processes that enhance soil fertility and improve water quality, and provide opportunities for recreation and aesthetic appreciation (1, 2). Because many ecosystem services, including climate regulation and water quality improvement, are public goods available to everyone without charge, private landowners are often uncompensated for their contribution to ecosystem service production, and underprovision of these services is a likely result.

Incentive payments equal to the value of ecosystem services provide a potential solution to the underprovision of ecosystem services. When the property right to develop land is held by landowners, a payment for ecosystem services (PES) can provide the landowner with incentives to conserve. Two prominent examples of PES programs are Costa Rica's 1996 National Forest Law that pays landowners to conserve forests for carbon sequestration, water quality improvement, habitat, and scenic beauty, and China's Sloping Lands Conversion Program that pays farmers to convert cropland to forest. When the property right to develop is held by government, auctioning development rights provide incentives to weigh impacts on ecosystem services relative to benefits from development. Examples of development rights include timber auctions on government-owned forests in the United States and Russia.

An optimal incentives policy will result in land being put to its “highest and best use,” which here is defined as the land use that maximizes total benefits to society, including the value of ecosystem services. Optimal incentive programs, or other policies that involve provision of public goods from landscapes, must overcome three related challenges. First, provision of ecosystem services often depends on the spatial configuration of land use. For example, in comparing landscapes with the same overall

amount of habitat, the success of many species tends to be higher on landscapes where habitat is clustered rather than fragmented (3). Second, the optimal provision of a public good on landscapes requires coordination among multiple private landowners. When spatial configuration matters, the contribution of each private land parcel to aggregate ecosystem service provision will be a function of decisions of other landowners; thus, optimal land-use decisions are interdependent. Third, landowners typically have private information about their cost for undertaking actions to increase ecosystem service provision. The cost of increasing ecosystem service provision on a particular land parcel will depend on parcel or landowner characteristics, such as land productivity or landowner skills, knowledge, and preferences, which are often known only by the landowner. In other words, there is asymmetric information between an agency representing the interests of society as a whole in providing ecosystem services (hereafter, the “regulator”) and the landowners whose decisions affect the provision of these services.

The combination of spatially dependent benefits and multiple landowners with private cost information makes achieving optimal land use exceedingly difficult. Simple top-down regulatory approaches, such as zoning, will often fail to achieve the optimal land-use pattern because the regulator does not have information about cost and so does not know the optimal solution to target. Simple PES or other incentive-based approaches will also fail to achieve the optimal land-use pattern because they do not account for spatial interdependence of benefits. An optimal solution requires taking into account the information of landowners and the spatial interdependence of benefits across landowners.

In contrast, when the regulator has complete information about the cost to landowners of increasing ecosystem service provision either simple regulatory or incentive schemes can achieve an outcome that maximizes the net benefits from the

Significance

Many ecosystem services are public goods available to everyone without charge, but the provision of these services often depends on the actions of private landowners who may bear cost to provide services. How to design incentives when the provision of services depends on the landscape pattern of conservation and where landowners have private information about costs presents a difficult challenge. Here we apply results from auction theory to design a payments scheme that achieves optimal provision of ecosystem services with spatially dependent benefits and asymmetric information. The auction mechanism works equally well whether property rights reside with the landowners so that the regulator pays landowners to conserve, or with the regulator so that landowners pay the regulator to develop.

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landscape. When the landowners' costs are known, the regulator can determine what land uses are optimal and can either mandate this outcome via regulation or offer payments to induce landowners to choose this outcome. This approach works equally well with spatially dependent or spatially independent benefits. Finding an optimal solution with spatially dependent benefits can be challenging, but spatial dependency by itself does not pose an insurmountable obstacle to optimal implementation.

It is also the case that asymmetric information by itself does not prevent implementation of optimal incentive programs, although it does prevent optimal implementation via top-down regulation. When there are no spatial dependencies, the contribution of a parcel to the value of ecosystem services depends only on the characteristics of the land parcel itself. The regulator can implement an optimal solution by offering a payment equal to the parcel's contribution to the value of ecosystem services provided. Only landowners with private costs below their parcel's incremental value will want to conserve land. In this case, the optimal solution is obtained despite asymmetric information. Neither regulation nor simple incentive mechanisms, however, achieve an optimal solution with the combination of asymmetric information and spatially dependent benefits.

Here we present an incentive scheme that achieves optimal provision of ecosystem services with spatially dependent benefits and asymmetric information. Our approach applies results from the mechanism design literature in economics on the optimal provision of public goods (4–7). Vickrey (4) showed how to design an auction to give all participants an incentive to truthfully reveal private information on how much an item is worth to them. The Vickrey auction was extended by Clarke (5) and Groves (6) to more complex situations in which multiple items are auctioned. In a Vickrey–Clarke–Groves auction, each participant in the auction has a dominant strategy to set their bid equal to their private valuation for the items at auction. In our mechanism, each landowner simultaneously submits a bid, and has a dominant strategy to set the bid equal to their opportunity cost of conservation. A landowner's parcel will be developed if and only if the opportunity cost is greater than the incremental value of ecosystem services from conserving their land. If the bid is accepted, the payment between the regulator and the landowner is set equal to the value of their parcel's contribution to ecosystem services. Because the payment amount is independent of the landowner's bid, it is a dominant strategy for landowners to bid exactly their opportunity cost. With this cost information, the regulator can identify the set of parcels that maximizes the net benefits from the landscape, determine the incremental benefits generated by each parcel selected for conservation, and set payments accordingly. With spatially dependent benefits, the value generated by an individual parcel, and hence a payment between a landowner and the regulator, is a function of land uses on all parcels and so can only be determined once all bids have been submitted.

Economists and others have recognized that implementing optimal land use with spatially dependent benefits and private information is challenging (8) (see *SI Text, Relationship to Previous Literature on Spatially Dependent Provision of Ecosystem Services Under Asymmetric Information*, for a more in-depth literature review on this topic). One strand of literature investigates the ability of incentive policies to affect the spatial pattern of land use and associated levels of ecosystem services (9, 10), but none have identified a general mechanism for achieving an optimal solution in this setting. A separate strand of literature finds numerical solutions for optimal land use assuming the regulator has complete information as well as control over all land-use decisions (11, 12). Several prior papers study auctions for land conservation mostly with an emphasis on how auctions can be used to reduce government expenditures (13, 14). Our study is most closely related to papers on information-revealing mechanisms in the spirit of Vickrey–Clarke–Groves auctions applied to optimal pollution control and optimal harvesting of common property resources (15–17).

A Simple PES Example

We start with a simple example of a landscape composed of a 2×4 grid of land parcels (Table 1) to set ideas and demonstrate the challenge of finding the optimal land-use pattern with spatially dependent benefits and asymmetric information. Each parcel can either be “conserved,” in which case it provides ecosystem services that are public goods, or “developed,” in which case it provides a private monetary return to the landowner. The cost of conserving a parcel (foregone development value), measured in monetary terms, is indicated by the top number in each parcel, whereas the ecosystem services provided by conserving the parcel, measured in biophysical terms, are indicated along the bottom (Table 1). The first number is the ecosystem services provided when the parcel is conserved and benefits are spatially independent, or when benefits are spatially dependent but no adjacent parcel is conserved. When benefits are spatially dependent, the second number is the level of ecosystem services provided when one neighboring parcel is also conserved, and so on for two and three conserved neighboring parcels. Only parcels that share a side (not corners) are considered neighbors. The monetary value of a unit of ecosystem service is denoted by V . The value of ecosystem services provided by a conserved parcel is equal to V multiplied by the biophysical units of ecosystem services provided.

For comparison purposes, we start with the case of no spatial dependencies and complete information about costs. Given a value of V , the optimal solution can be found by comparing the benefits ($V \times$ units of services) to costs on each parcel and conserving parcels whose benefits are at least as great as costs. For example, with $V = 0.25$, the benefits from conserving A2 are $0.25 \times 5 = 1.25$, which is greater than the cost of 1. The criterion is also satisfied for B3 but is not satisfied for other parcels. If $V = 0.33$, B2 is optimally conserved along with A2 and B3.

We next add spatial dependencies but continue to assume complete information about costs. Because the level of the services increases when we add spatial dependencies, the solutions to the spatially independent and spatially dependent net benefits maximization problems at a given value of V are not comparable. Consider the optimal landscape when $V = 0.25$. The optimal solution can be determined by enumerating all possible conservation combinations and determining which combination yields the highest net benefits (code for finding the optimal landscape can be found in [Dataset S1, SI 5](#)). In this case, the optimal solution is to conserve A1, A2, B1, B2, and B3, which yields benefits of $(11 + 10 + 3 + 9 + 8) \times 0.25 = 10.25$, and costs of $3 + 1 + 1 + 1 + 1 = 7$, generating net benefits of 3.25. For comparison, the next highest potential net benefits is achieved by conserving A2, B2, and B3, which generates net benefits of 3. Comparing the net benefits from these two potential solutions highlights the role of spatial dependencies in determining the optimal landscape. Adding A1 and B1 to the configuration of A2, B2, and B3 increases ecosystem service provision because (i) two new parcels are conserved and (ii) the addition of A1 increases the provision on neighboring parcel A2 and B1, whereas the addition of B1 increases the provision on neighboring parcels A1 and B2.

With complete information about costs of conservation, the regulator can implement the optimal solution by targeting payments to the parcels that make up the optimal solution (e.g., A2

Table 1. Costs and biophysical provision of services from land conservation

	1	2	3	4
A	3 6 9 11	1 5 8 10 11	3 4 5 7 9	3 2 5 7
B	1 1 2 3	1 3 6 8 9	1 5 8 10 11	3 6 9 11

and B3 in the spatially independent case, and A1, A2, B1, B2, and B3 in the spatially dependent case). The only requirement is that payments equal or exceed landowners' costs. Thus, to conserve A1, A2, B1, B2, and B3, the regulator needs to offer payments of at least 3, 1, 1, 1, and 1, respectively. This type of targeting approach works whether benefits are spatially independent or spatially dependent.

With incomplete information about costs, however, another approach is needed. In the case of spatially independent benefits, the regulator can still obtain the optimal solution using a payment to each landowner equal to the benefits generated by their parcel when conserved. To implement the solution from above involving A2 and B3, all landowners are offered 0.25× the ecosystem services provision of their parcel. This amount is greater than or equal to costs only for A2 and B3 and, thus, only these two landowners agree to conserve their parcels.

Implementing the optimal solution is much more complex with both asymmetric cost information and spatially dependent benefits. In this case, the regulator cannot achieve an optimal solution simply by targeting payments or setting them equal to a parcel's contribution to benefits. With spatially dependent benefits, the benefits of conserving any individual parcel cannot be determined without knowledge of which other parcels are also conserved. However, without information about costs, the regulator cannot identify the set of parcels that are optimal to conserve. For example, net benefits decrease when either A1 or B1 are separately added to the configuration of A2, B2, and B3. However, adding both A1 and B1 to the configuration of A2, B2, and B3 increases net benefits from 3 to 3.25. If, however, the costs of conserving B1 were 2 instead of 1 then it would not be optimal to conserve either A1 or B1. The optimal landscape cannot be determined without cost information for each parcel.

A regulator that only uses available information on benefits may obtain a solution that is far from optimal because parcels with high benefits may also have high costs and generate relatively low net benefits. For example, A3 always provides higher benefits than B1 with any number of conserved neighbors, and yet B1 is optimally conserved and A3 is not. Starting with the optimal landscape, if A3 is conserved rather than B1, net benefits fall from 3.25 to 2.25.

In sum, with spatially dependent benefits, the problem of finding the optimal land-use pattern that provides the highest level of net benefits cannot be solved on a parcel-by-parcel basis. Finding the optimal solution involves calculating benefits across the entire landscape to factor in spatial dependencies and requires information about costs. Simple mechanisms sufficient for cases without asymmetric information or spatially dependent benefits do not solve the problem with both asymmetric information and spatially dependent benefits. We develop an alternative approach that applies the logic of the Vickrey–Clarke–Groves auction to solve this problem in the next section.

The Subsidy Auction Mechanism

There are $i = 1, 2, \dots, N$ land parcels in a landscape, each owned by a different individual. On each parcel, the landowner chooses between a land use that potentially provides a greater level of ecosystem services but lower direct monetary return to the landowner ("conservation") or one that provides a low level of ecosystem services but higher direct monetary return ("development"). Let $x_i = 1$ when parcel i is conserved and 0 when parcel i is developed. The binary vector $X = (x_1, x_2, \dots, x_N)$ describes the landscape pattern of conserved and developed parcels. It is straightforward to expand the number of land-use alternatives available to landowner, but doing so complicates notation without adding more insight.

The function $B(X)$ converts the landscape pattern (X) into the monetary value of ecosystem services provided on the landscape. Because of spatial interdependence, the increase in B when parcel i is conserved may be a function of the pattern of conservation on other parcels $j \neq i$. We assume the regulator knows $B(X)$. Our results hold whether or not landowners know $B(X)$.

For many ecosystem services, benefits from ecosystem services are determined by ecological functions operating at landscape scales so that the regulator will often have better information about benefits than individual landowners.

The owner of parcel i earns a return $c_i \geq 0$ if the parcel is developed and 0 if the parcel is conserved (i.e., c_i is the cost of conservation). We assume that c_i is known only by the owner of parcel i , whereas all other landowners and the regulator only know the distribution of possible values of c_i . Because we solve for the dominant strategy equilibrium, assumptions about the distribution of c_i do not affect the analysis (17).

The regulator wishes to implement the land-use pattern, $X^* = (x_1^*, x_2^*, \dots, x_N^*)$, that maximizes net social benefits. The optimal land-use pattern is given by

$$X^* = \arg \max \left[B(X) - \sum_{i=1}^N x_i c_i \right].$$

If the regulator knew each c_i then, in principle, this solution could be solved without the auction mechanism. In practice, finding the optimal solution can be a difficult problem, and search algorithms that find good, although not necessarily optimal, solutions are often used (12). However, without knowledge of costs, the auction is needed to reveal costs to determine the optimal solution.

In the subsidy auction, each landowner i simultaneously submits a bid s_i . Upon receiving the bids the regulator decides which bids to accept and which to reject. If the bid of landowner i is accepted, parcel i is conserved and the regulator pays the landowner an amount p_i . If the bid of landowner i is rejected, parcel i is developed and the landowner receives c_i . We assume no collusion in bids across landowners, and elaborate on the importance of this assumption in the discussion section.

To determine which bids to accept and the amount of payment to a landowner whose bid is accepted, the regulator first calculates the expected social benefits of conserving parcel i , ΔW_i . To do this calculation, the regulator assumes that the bid of landowner i is equal to the cost of conserving parcel i (i.e., $s_i = c_i$). Because the regulator knows the benefits function for the landscape $B(X)$, observing s_i (assuming that $s_i = c_i$) means the regulator can calculate the expected social net benefits of conserving parcel i . The regulator calculates the expected social benefits of conserving parcel i , ΔW_i with the following steps:

- 1) Solve for the set of parcels to conserve that maximize social net benefits assuming that parcel i will be conserved, $X_i^* = (x_{1i}^*, x_{2i}^*, \dots, x_{i-1i}^*, 1, x_{i+1i}^*, \dots, x_{Ni}^*)$;
- 2) Solve for the set of parcels to conserve that maximize social net benefits assuming that parcel i will not be conserved, $X_{\sim i}^* = (x_{1\sim i}^*, x_{2\sim i}^*, \dots, x_{i-1\sim i}^*, 0, x_{i+1\sim i}^*, \dots, x_{N\sim i}^*)$;
- 3) Find the social net benefits when parcel i is conserved net of the cost for parcel i : $W_i(X_i^*) = B(X_i^*) - \sum_{j \neq i} c_j x_{ji}^*$;
- 4) Find the social net benefits when parcel i is not conserved: $W_i(X_{\sim i}^*) = B(X_{\sim i}^*) - \sum_{j \neq i} c_j x_{j\sim i}^*$;
- 5) Take the difference between $W_i(X_i^*)$ and $W_i(X_{\sim i}^*)$:

$$\begin{aligned} \Delta W_i &= W_i(X_i^*) - W_i(X_{\sim i}^*) \\ &= B(X_i^*) - \sum_{j \neq i} c_j x_{ji}^* - \left[B(X_{\sim i}^*) - \sum_{j \neq i} c_j x_{j\sim i}^* \right]. \end{aligned}$$

The regulator accepts the bid from landowner i if and only if $\Delta W_i \geq s_i$ and pays landowner i $p_i = \Delta W_i$ if and only if the bid is accepted. We assume that the auction mechanism is common knowledge.

Note that each landowner does not know the exact value of $\Delta W_i = p_i$ when bids are submitted because this amount depends

The Simple Example Revisited

To illustrate the auction mechanism (subsidy or tax), we return to the simple example from section 2 with $V = 0.25$. As discussed previously, X^* entails the conservation of parcels A1, A2, B1, B2, and B3, providing total net benefits of $B(X^*) = 3.25$. Table 2 shows the calculation of conservation payments under the auction mechanism. For each parcel, we compute the optimal landscape with parcel i (X_i^*), the net benefits of X_i^* without including the cost of parcel i ($W_i(X_i^*)$), the optimal landscape without conserving parcel i ($X_{\sim i}^*$), and the net benefits of $X_{\sim i}^*$ ($W_i(X_{\sim i}^*)$). From Table 2 we can see that the optimal subsidy, $p_i = \Delta W_i$, is greater than or equal to the cost of conservation, c_i , for optimally conserved parcels, and $p_i = \Delta W_i < c_i$ if parcel i is optimally developed. With the subsidy mechanism, the regulator pays landowners the sum of ΔW_i for optimally conserved parcels (a total payment of 13). With the tax mechanism, the landowners who develop collectively pay the regulator the sum of ΔW_i for all nonconserved parcels (a total payment of 7).

Discussion

This paper examines the implementation of incentives through an auction mechanism when ecosystem service provision depends on the spatial pattern of conservation across multiple landowners, each with private information about their cost of conservation. Spatial dependencies characterize many ecosystem services, with habitat provision, pollination, and nutrient filtering for clean water being three prominent examples. Because the opportunity cost of conservation will almost always depend on landowner characteristics that are privately known, such as landowner skills and preferences, asymmetric information is an important feature of most voluntary conservation programs. Spatial dependencies imply that the benefit of conserving a given parcel will depend on the optimal pattern of conservation (i.e., what other parcels are also conserved), but this cannot be determined without information on each landowner's cost. Hence, an optimal incentives policy for spatially dependent ecosystem services cannot be implemented without first addressing the problem of asymmetric information.

The auction mechanism proposed in this paper applies the principles of a Vickrey–Clarke–Groves auction and provides a surprisingly simple solution to the optimal provision of ecosystem services. The mechanism differs from traditional approaches by breaking the problem into two stages. First, the auction mechanism is used to generate information on each landowner's cost. Second, the regulator uses the cost information to find a solution to the landscape level conservation problem and implements this solution by targeting payments between the regulator and landowners. Basing payments to be equal to the increase in social benefits with conservation of the parcel, an amount that is independent of the landowner's bid, the auction mechanism applies the fundamental insight of the Vickrey–Clarke–Groves auction to break the link between a landowner's bid and their payment, thereby inducing truthful revelation of cost in the bidding stage.

Several additional issues deserve attention in connection with the auction mechanism developed in this paper: (i) potential

collusion among landowners in bidding, (ii) the commitment of the planner to set payments equal to social benefits of conservation, and (iii) the case where it is costly to raise and distribute program funds (i.e., there is a concern about the distribution of rents), or where there is a fixed conservation budget.

In the auction it may be possible, although extremely difficult in practice, for landowners to collude and, thereby, raise the net payments the group receives from the regulator. For example, in the subsidy auction, a group of landowners could potentially underbid to be awarded a conservation contract that would not occur with truthful bidding. Underbidding as a team can be profitable even though it might not be socially optimal. Consider a slight variation in the two-parcel example given above with $B(0, 0) = 0$, $B(1, 0) = B(0, 1) = 2$, $B(1, 1) = 8$. Now assume that $c_1 = c_2 = 5$ (rather than 3). Here the optimal the solution is to conserve neither parcel. However, if each landowner bids 2 rather than their cost of 5, the regulator will choose to conserve both parcels. The regulator will pay each landowner 6 because $\Delta W_i = W_i(X_i^*) - W_i(X_{\sim i}^*) = (8 - 2) - 0 = 6$. Successful collusion requires both landowners to change their bids in a coordinated fashion. This outcome is similar to each player in a Prisoner's Dilemma game having a dominant strategy to defect while both are better off with cooperation. However, underbidding in this fashion is risky because it is possible that landowners will be paid less than their cost. In general, successful collusion has high information requirements. To guarantee success, a group of landowners would need to compute the optimal solution to predict the planner's outcome. However, to compute the optimal solution, the landowners would need private information about the costs of other landowners as well as information about benefits. Landowners would also require an approach to share collusive profits such that team members do not wish to deviate from the collusive strategy (17).

Truthfully bidding cost is a dominant strategy for each landowner when the regulator commits ex ante to setting payments equal to the social value of ecosystem services. However, if landowners believe the regulator will renegotiate after bids have been submitted, then truth-telling is no longer necessarily a dominant strategy. For example, in the subsidy auction there would be an incentive to inflate bids to mitigate the potential for downward renegotiation of payments. Therefore, implementation of the auction mechanism requires that the regulator can credibly commit to the payment plan.

Under the subsidy auction mechanism, payments are based on the contribution of a landowner's parcel to the increase in the value of ecosystem services provided, which will in general be larger than the landowner's cost. The difference between benefits and cost, also referred to as "information rents," reflect the fact that landowners must be paid something to disclose their private information. Information rents are an unavoidable feature of incentive schemes in the presence of asymmetric information. Payments to landowners of anything less than full benefits in an effort to reduce information rents risks having some landowners for whom conservation is socially beneficial choose not to conserve. Spatial dependencies can increase the

Table 2. Optimal payments in the simple example

Parcel	Cost	X_i^*	$W_i(X_i^*)$	$X_{\sim i}^*$	$W_i(X_{\sim i}^*)$	ΔW_i
Optimally conserved parcels						
A1	3	A1–A2, B1–B3	6.25	A2, B2–B3	3	3.25
A2	1	A1–A2, B1–B3	4.25	B2–B3	1.5	2.75
B1	1	A1–A2, B1–B3	4.25	A2, B2–B3	3	1.25
B2	1	A1–A2, B1–B3	4.25	A2–A3, B3	0.75	3.5
B3	1	A1–A2, B1–B3	4.25	A1–A2, B1–B2	2	2.25
Nonconserved parcels						
A3	3	A1–A3, B1–B3	5.75	A1–A2, B1–B3	3.25	2.5
A4	3	All	5	A1–A2, B1–B3	3.25	1.75
B4	3	A1–A2, B1–B4	6	A1–A2, B1–B3	3.25	2.75

