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Implementing the Optimal Provision of Ecosystem Services

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Abstract: 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, while 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 (PES) 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.

Significance Statement: 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 the regulator so that landowners pay the regulator to develop.

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1. Introduction

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 under-provision of these services is a likely result.

Incentive payments equal to the value of ecosystem services provide a potential solution to the under-provision 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 U.S. 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 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, though 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). Vickery (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 Vickery auction was extended by Clarke (5) and Groves (6) to more complex situations in which multiple items are auctioned. In a Vickery-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 is larger 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. Since 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 Supplementary Information Text S1 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 ecosystems 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 Vickery-Clark-Groves auctions applied to optimal pollution control and optimal harvesting of common property resources (15-17).

2. 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, while 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 0.25×5 = 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 the Supplementary Information SI Text 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)*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, while 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 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 times 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. But 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, on the other hand, 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 Vickery-Clarke-Groves auction to solve this problem in the next section.

3. The Subsidy Auction Mechanism

There are $i = 1, 2, \ldots, N$ 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 $X = (x_1, x_2, \ldots, x_N)$ 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, while 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, $X^* = (x_1^*, x_2^*, \ldots, x_N^*)$, that maximizes net social benefits. The optimal land use pattern is given by:

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

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 often search algorithms that find good, though not necessarily optimal, solutions are used (12). However, without knowledge of costs, the auction is needed to reveal costs in order 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., $s_i = c_i$). Since 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, $X_i^* = (x_{1i}^*, x_{2i}^*,\ldots, x_{i-1i}^*, 1, x_{i+1i}^*, \ldots, x_{Ni}^*)$;
2) Solve for the set of parcels to conserve that maximize social net benefits assuming that parcel i will not be conserved, $X_{\sim i}^* = (x_{1\sim i}^*, x_{2\sim i}^*,\ldots, x_{i-1\sim i}^*, 0, x_{i+1\sim i}^*, \ldots, x_{N\sim i}^*)$;
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 $W_i(X_i^*)$:

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

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 in part on what other landowners bid. However, landowner i understands that the payment p_i is independent of the bid s_i as the landowner's bid is not used in steps 1-5 above. The bid level only affects whether or not the bid is accepted, not the amount of the payment if the bid is accepted.

If benefits are spatially-independent, then ΔW_i is only a function of conservation on parcel i. The only change between X_i* and $X_{\sim i}$* is that parcel i is conserved in X_i* and developed in $X_{\sim i}$*. With spatially-dependent benefits, however, this need not be the case. Removing a conserved parcel from the optimal solution may require a reconfiguration of conserved and developed parcels. For example, suppose there are two parcels {1, 2} with $B(0, 0) = 0$, $B(1, 0) = B(0, 1) = 2$, $B(1, 1) = 8$, $c_1 = c_2 = 3$. In this case it is optimal to conserve both parcels so that X_i* = (1, 1). If, however, parcel i is left out of the solution, then it is better not to conserve parcel j as conserving one parcel alone generates benefits of 2 but costs of 3. Therefore, $X_{\sim i}$* = (0, 0).

4. Results

We first show that it is a dominant strategy for each landowner to bid their cost $s_i = c_i$ under this subsidy auction mechanism (Proposition 1) and then that the subsidy auction mechanism yields an optimal solution (Proposition 2).

Proposition 1: Under the subsidy auction mechanism described above, it is a dominant strategy for each landowner i to bid $s_i = c_i$. (See SI Text S2 for a formal proof).

The intuition for Proposition 1 can be seen by plotting the range of potential payments to parcel i (p_i) versus the range of potential bids (s_i) in relation to the cost c_i (Figure 1). When the landowner overbids ($s_i > c_i$), there is a possibility that the bid will be rejected ($s_i > p_i$) even though $p_i > c_i$ so that the landowner would be better off with conservation. When the landowner underbids ($s_i < c_i$), there is a possibility that the bid will be accepted ($s_i \le p_i$) even though $p_i < c_i$ so that the landowner would be better off with development. Bidding the opportunity cost, $s_i = c_i$, eliminates risk of losses from both over- and under-bidding.

For the landowner, it does not matter whether the benefits of conservation are simple or complex; what matters is whether or not their bid will be accepted, and if it is accepted that the payment from conservation (p_i) is higher than the payment from development (c_i). Truthful bidding is the dominant strategy given the auction mechanism. This result relies on the independence of payments and bids: $p_i = \Delta W_i$ does not depend on s_i. The bid only affects whether or not the bid is accepted, not the payment itself. The payment to landowner i depends on the value of increases in ecosystem services with conservation, and the bids of landowners *other than i*. This is true whether or not other landowners bid accurately. The landowner then should choose to have the bid accepted if and only if $p_i \ge c_i$ which they can guarantee by choosing $s_i = c_i$.

Truthful revelation of costs is needed for implementation of the optimal solution with spatially-dependent benefits. The conservation decision on some parcel j can affect the expected benefits of conserving parcel i. Thus, without exact information about costs on each parcel the regulator's solution may deviate from the optimum. With cost information, the regulator can choose which bids to accept and make the associated payments to get to an optimal solution.

Proposition 1 shows it is a dominant strategy for each landowner to choose $s_i = c_i$. The following proposition shows that the auction mechanism achieves an optimal solution.

Proposition 2: When benefits are spatially-dependent, the subsidy auction mechanism generates the optimal solution when the regulator 1) accepts bids if and only if $s_i \le \Delta W_i$ and 2) pays landowner *i* $p_i = \Delta W_i$ if the bid is accepted. (See SI Text S3 for a formal proof).

In an optimal solution it must be the case that the social benefits of conservation are at least as great as the costs of conservation for all conserved parcels, and less than for all developed parcels. Defining net benefits, ΔW_i, as the difference between the highest net benefits when parcel *i* is included (but excluding the cost of parcel *i*) and the highest net benefits when parcel *i* is not included, ensures that this is the proper rule defining an optimum. If $c_i \le \Delta W_i$ then it is optimal to conserve parcel *i*, as it implies the net benefits of conserving parcel *i* are non-negative. When the converse is true, then parcel *i* should not be conserved.

Together, propositions 1 and 2 show that the regulator can implement an optimal land-use pattern with spatially-dependent benefits through the auction mechanism described. Spatially-dependent benefits can make finding an optimal solution more difficult and magnifies potential losses from mistakes but does not interfere with the incentive mechanism that enables the regulator to implement the optimal solution.

5. The Auction Tax Mechanism

One concern with PES is about the cost of payments that the regulator must give to landowners. Note that the regulator typically pays landowners an amount that exceeds their opportunity cost and may lead to large budget outlays. An alternative to PES is to require the landowners to pay the regulator for the right to develop. In this case, the landowner submits a bid (s_i) for the right to develop. The regulator decides whether to accept a bid and allow development, in which case the landowner must pay a tax equal to the loss in the value of ecosystem services with development, ΔW_i. The auction tax mechanism differs from the auction subsidy mechanism in that bids are accepted when $s_i > \Delta W_i$ instead of $s_i \leq \Delta W_i$. The auction tax mechanism generates the same incentive to set the bid equal to opportunity cost as in the auction subsidy mechanism, $s_i = c_i$, because the payment is independent of the bid. This tax mechanism also generates the same optimal land-use outcome as the subsidy mechanism: conservation occurs if and only if $c_i \leq \Delta W_i$. The main difference between the auction tax mechanism and the auction subsidy mechanism described above is that the landowner pays the regulator when development occurs instead of the regulator paying the landowner for conservation. An efficient outcome can occur with different assignment of initial property rights (18). The definition of initial property rights affects the distribution of benefits and costs but not efficiency. A government concerned about its budget could use a mix of taxes and subsidies to make the overall conservation program approximately revenue neutral. However, the mix of taxes and subsidies must be set independent of landowners' bids to maintain the incentive properties of the auction; as such, the government cannot guarantee a balanced budget (19).

6. 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 earlier, 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 non-conserved parcels (a total payment of 7).

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 Vickery-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, though 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 in order 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. But, 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 size of information rents (see SI Text S4 and SI Figures 1 and 2 for more analysis of the information rents generated in our simple example). Several empirical studies have shown that PES programs in Costa Rica and Mexico pay landowners more than their opportunity cost of conservation, including payments to some landowners who would conserve their land even in the absence of a payment (20-21). Paying landowners the entire benefit of conserving their land is akin to a willing buyer and seller agreeing on a price equal to the buyer's maximum willingness-to-pay, even if that price is far greater than the seller's willingness-to-accept. However, the efficiency of the trade is only affected by the presence or absence of the trade, not the price at which the trade occurs as this only determines how rent is distributed between the buyer and the seller.

Economists have studied mechanisms designed to reduce information rents associated with environmental policies (see 22 for a survey and 23 for a recent application). Mechanisms to reduce information rents involve a tradeoff between maximizing social net benefits and reducing the budgetary costs of the regulating agency. Reducing information rents is implemented by agencies trying to stay within a budget. If the regulator must stay within a fixed budget, there is no guarantee that the (unconstrained) optimum can be obtained. In this case, there can be parcels for which social net benefits of conservation are positive but that cannot be afforded. It is a general finding of the mechanism design literature that no balanced-budget mechanism can be found to always implement the optimal solution (19). Intuitively, by changing their bids, landowners can affect which parcels can be afforded and so they may try to alter their bids to manipulate the outcome of the auction.

The tax auction mechanism completely avoids the budget constraint problem because instead of paying landowners to conserve, the regulator is paid by landowners who want to develop. The tax mechanism generates revenue because the property rights to develop are held by the regulator, whereas the subsidy mechanism generates budgetary costs because the property rights to develop are held by the landowners. As in Coase (18), an optimal solution can be achieved with the property right being held by either party.

In general, even with complete information about conservation benefits and costs, solving for the optimal land-use pattern can be difficult when there are spatial dependencies. Benefits functions may be highly non-linear and the discreteness of the choice problem (e.g., conserve or develop) introduces further complications. Furthermore, the optimal solution may not be unique. In some applications, researchers use heuristic methods to find good – though not necessarily optimal – solutions (12, 24-25). Lewis et al. (10) apply such methods to a large-scale integer programming problem for the Willamette Basin of Oregon. They approximate the optimal solution under the assumption that the regulator has complete information about costs and evaluate a range of targeted PES policies under the assumption that the regulator knows only the cost distribution. They find that the net benefits under the (approximate) optimal solution are always larger – and typically much larger – than those generated by the targeted PES policies. These results suggest that the proposed auction mechanism will greatly outperform policies that are developed with incomplete information about costs. Regardless of whether the optimum is found, or just approximated, the auction mechanism developed in this paper can be used to implement the desired solution identified by the regulator.

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References

1. Daily G (1997) *Nature's Services: Societal Dependence on Natural Ecosystems*. (Island Press Washington, DC).

2. Millennium Ecosystem Assessment (2005) *Ecosystems and Human Well-being: Synthesis* (Island Press Washington DC).

3. Fahrig L (2003) Effects of habitat fragmentation on biodiversity. *Annu Rev Ecol Evol S* 34: 487-515.

4. Vickrey W (1961) Counterspeculation, auctions, and competitive sealed tenders. *J Financ* 16(1): 8-37.

5. Clarke E (1971) Multipart pricing of public goods. *Public Choice* 11(1): 17–33.

6. Groves T (1973) Incentives in teams. *Econometrica* 41: 617-631.

7. Groves T, Ledyard J (1977) Optimal allocation of public goods: A solution to the 'free rider' problem. *Econometrica* 45: 783-809.

8. Drechsler M, Watzold F, Johst K, Shogren JF. 2010. An agglomeration payment for cost-effective biodiversity conservation in spatially structured landscapes. *Resour Energy Econ* 32(2): 261-275.

9. Parkhurst GM, Shogren JF, Bastian C, Kivi P, Donner J, Smith RBW. 2002. Agglomeration bonus: An incentive mechanism to reunite fragmented habitat for biodiversity conservation. *Ecol Econ* 41: 305-328.

10. Lewis DJ, Plantinga AJ, Nelson E, Polasky S (2011) The efficiency of voluntary incentives policies for preventing biodiversity loss. *Resour Energy Econ* 33(1): 192- 211.

11. Church RL, Stoms DM, Davis FW (1996) Reserve selection as a maximal coverage problem. *Biol Conserv* 76: 105– 112.

12. Polasky S, Nelson E, Camm J, Csuti B, Fackler P, Lonsdorf E, White D, Arthur J, Garber-Yonts B, Haight R, Kagan J, Montgomery C, Starfield A, Tobalske C (2008) Where to put things? Spatial land management to sustain biodiversity and economic production. *Biol Conserv* 141(6): 1505-1524.

13. Stoneham G, Chaudhri V, Ha A, Strappazzon L (2003) Auctions for conservation contracts: An empirical examination of Victoria's Bush Tender Trial. *Aust J Agr Res Econ* 47(4): 477-500.

14. Kirwan B, Lubowski RN, Roberts MJ (2005) How cost-effective are land retirement auctions? Estimating the difference between payments and willingness-to-accept in the Conservation Reserve Program. *Am J Agr Econ* 87(5): 1239-1247.

15. Kwerel E (1977) To tell the truth: Imperfect information and optimal pollution control. *Rev Econ Stud* 44(3): 595-601.

16. Dasgupta P, Hammond P, Maskin E (1980) On imperfect information and optimal pollution control. *Rev Econ Stud* 47(5): 857-860.

17. Montero JP (2008) A simple auction mechanism for the optimal allocation of the commons. *Am Econ Rev* 98(1): 496-518.

18. Coase R (1960) The problem of social cost. *J Law Econ* 3: 1-44.

19. Walker M (1980) On the nonexistence of a dominant strategy mechanism for making optimal public decisions. *Econometrica* 48(6): 1521-1540.

20. Alix-Garcia JM, Shapiro EN, Sims KRE (2012) Forest conservation and slippage: Evidence from Mexico's national payments for ecosystem services program. *Land Econ* 88(4): 613-638.

21. Robalino J, Pfaff A (2013) Ecopayments and deforestation in Costa Rica: A nationwide analysis of PSA's initial years. *Land Econ* 89(3): 432-448.

22. Lewis TR 1996. Protecting the environment when costs and benefits are privately known. *Rand J Econ* 27(4): 819-847.

23. Mason CF, Plantinga AJ (2013) The additionality problem with offsets: Optimal contracts for carbon sequestration in forests. *J Environ Econ Manage* 66(1): 1-14.

24. Nalle DJ, Montgomery CA, Arthur JL, Polasky S, Schumaker NH (2004) Modeling joint production of wildlife and timber. *J Environ Econ Manage* 48(3): 997-1017.

25. Nelson E, Polasky S, Lewis DJ, Plantinga AJ, Lonsdorf E, White D, Bael D, Lawler J (2008) Efficiency of incentives to jointly increase carbon sequestration and species conservation on a landscape. *Proc Natl Acad Sci USA* 105(28): 9471-9476.

Figure 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

Figure 2: Illustration of potential losses from over- and under-bidding. The landowner would like to conserve if and only if $p_i \geq c_i$. Any bid (s_i) and price (p_i) combination under the 45 degree line results in bids being rejected. Any bid (s_i) and price (p_i) combination over the 45 degree line results in bids being accepted. The triangles show potential losses from over- or under-bidding.

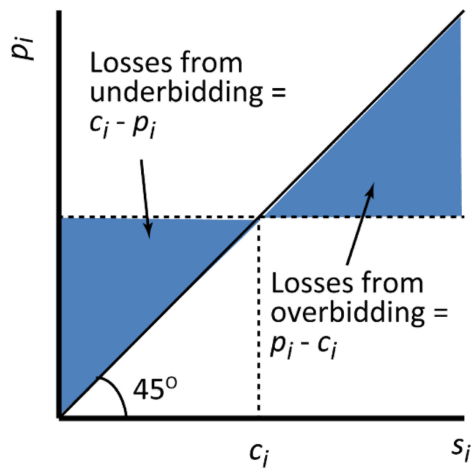

Figure 3: Optimal payments in the simple example

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
	Non-Conserved 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

SUPPORTING INFORMATION

SI Text

SI 1. Relationship to Previous Literature on Spatially-Dependent Provision of Ecosystem Services under Asymmetric Information

Previous studies have examined incentive policies to affect the spatial pattern of land use and associated levels of ecosystems services, but none have identified a general mechanism for achieving an optimal solution in this setting. For example, Smith and Shogren (1) evaluate an optimal contract scheme for land preservation with asymmetric information but consider only the special case of two adjacent landowners. Parkhurst et al. (2), Parkhurst and Shogren (3), and Drechsler et al. (4) have studied an “agglomeration bonus” that provides an additional payment to landowners who conserve adjacent habitat.

There is also a large literature devoted to finding optimal landscape patterns assuming full information. A number of studies solve for the reserve network that maximizes quantitative biodiversity indices subject to various constraints (e.g., 5 – 9). In some cases, these studies account for spatial dependencies in the objective function (e.g., 10 – 14).

Lewis and Plantinga (15) and Lewis et al. (16) consider alternative approaches for targeting afforestation payments designed to reduce forest fragmentation when the regulator does not have full information on landowners’ willingness-to-accept (WTA) to participate in afforestation. Lewis et al. (17) consider a suite of policies that target enrollment based on observable parcel characteristics that proxy for marginal benefits and costs. They evaluate the performance of the policies relative to the solution when the regulator has full information about WTA and show that these targeted policies typically achieve a small fraction of the benefits that are obtained by an optimal conservation policy under full information. While solving for the optimal landscape with spatial dependencies can be difficult even with full information, Lewis et al. (17) find that even an approximately optimal solution developed under full information greatly outperforms policies developed under incomplete cost information.

The use of auctions in the context of conservation has been examined in a set of papers (18 – 22). This literature has emphasized the role of auctions in reducing information asymmetry (18), the link between the information structure in auctions and landowner incentives (20), and the ability of auctions to reduce costs to the government (21). These papers typically consider auctions in which payments are linked to the bids submitted by landowners, giving incentives for landowners to inflate bids. In a study of U.S. Conservation Reserve Program (CRP) contracts, Kirwan et al. (21) find evidence that landowners systematically inflate their bid above cost. Our auction mechanism differs from the prior conservation auction literature in that we build from the fundamental insight from the Vickery-Clarke-Grove auction literature and decouple payment from the landowner's bid.

SI 2. Proof of proposition 1

Suppose the landowner bids $s_i = c_i$. If $s_i \leq \Delta W_i$, the landowner's bid will be accepted and the landowner will receive a payment $p_i = \Delta W_i \geq c_i$. If $s_i > \Delta W_i$, the landowner's bid will be rejected and the landowner will receive c_i. We prove that bidding $s_i = c_i$ is a dominant strategy by showing that this strategy generates equal or greater payoffs than overbidding ($s_i > c_i$) or underbidding ($s_i < c_i$) over the range of possible values of ΔW_i.

Overbidding ($s_i > c_i$)

Case (i): $\Delta W_i \geq c_i$. When $\Delta W_i \geq c_i$, then either a) $\Delta W_i \geq s_i$, in which case the landowner's bid will be accepted and the landowner will receive a payment $p_i = \Delta W_i \geq c_i$, which is the same outcome as bidding $s_i = c_i$, or b) $\Delta W_i < s_i$, in which case the landowner's bid will be rejected and the landowner will earn a payoff of $c_i \leq \Delta W_i$. In particular, when $c_i < \Delta W_i < s_i$, overbidding, $s_i > c_i$, generates a lower payoff for the landowner than bidding $s_i = c_i$.

Case (ii): $\Delta W_i < c_i$. When $\Delta W_i < c_i$, then $s_i > \Delta W_i$ and the landowner's bid will be rejected. The landowner will develop the land and earn c_i, which is the same outcome as would have occurred had the landowner bid $s_i = c_i$.

Therefore, overbidding, $s_i > c_i$, is dominated by bidding $s_i = c_i$.

Underbidding ($s_i < c_i$)

Case (i): $\Delta W_i \geq c_i$. When $\Delta W_i \geq c_i$, then $s_i < c_i$, the landowner's bid will be accepted and the landowner will receive a payment $p_i = \Delta W_i \geq c_i$, which is the same outcome as bidding $s_i = c_i$.

Case (ii): $\Delta W_i < c_i$. When $s_i \leq \Delta W_i < c_i$, the bid is accepted and the landowner receives a payment $p_i = \Delta W_i < c_i$. Thus, bidding $s_i < c_i$ generates lower payoffs than bidding $s_i = c_i$. If $s_i > \Delta W_i$, the landowner's bid is rejected and the landowner earns c_i, which is the same outcome as would have occurred had the landowner bid $s_i = c_i$.

Therefore, underbidding ($s_i < c_i$) is dominated by bidding $s_i = c_i$. *QED*

SI 3. Proof of Proposition 2

With full information about costs, the regulator can solve for X^* that maximizes social net benefits. Proposition 1 proves that landowners have a dominant strategy to bid $s_i = c_i$ under this auction mechanism. Given that landowners bid truthfully, $s_i = c_i$, we show that the auction generates the optimal solution.

In an optimal solution it must be the case that $\Delta W_i \geq c_i$ for all conserved parcels in X^* and $\Delta W_i < c_i$ for all developed parcels in X^*, otherwise net social benefits could be increased by making a different choice about the conservation of parcel i. The social net benefits of conservation conditional on parcel i being included in the solution is given by:

$$NB(X_i^*) = B(X_i^*) - \sum_{j=1}^{N} (x_{ji}^*) c_j$$

where X_i^* includes the optimally chosen set of other parcels $j \neq i$. The net social benefits of conservation conditional on parcel i not being conserved is given by:

$$NB(X_{\sim i}^*) = B(X_{\sim i}^*) - \sum_{j=1}^{N} (x_{j\sim i}^*) c_j$$

If the inclusion of parcel i increases net social benefits, then

$$NB(X_i^*) - NB(X\sim_i^*) \geq 0$$

$$W_i(X_i^*) - c_i - W(X\sim_i^*) \geq 0$$

$$\Delta W_i \geq c_i$$

In the auction mechanism, parcel i will be conserved if and only if $\Delta W_i \geq s_i$. Because landowners bid truthfully (Proposition 2), so that $s_i = c_i$, we have that parcel i will be conserved if and only if $\Delta W_i \geq c_i$. *QED*

SI 4. Simulating the simple landscape

In the text we illustrate the problem of finding the optimal landscape pattern with spatially-dependent benefits and asymmetric information on cost. Further, we describe how the auction mechanism works on a 2 x 4 grid of land parcels with arbitrarily chosen parameter values (Figure 1). Here we explore the performance of the auction mechanism on the simple landscape over a large range of monetary values for a unit of ecosystem service (V) and random draws of cost for conservation on a given parcel (c_i). Each time we solve for the optimal landscape we record payments to landowners, conservation cost (the sum of cost across parcels that are awarded a conservation contract), and information rents (the payment to the landowner minus the cost).

Our simulation of optimal landscapes uses the following process,

1. We set an initial value of V: $V = 0.02$
2. We randomly select a c_i value for each parcel on the landscape over the integer range [0,4].
3. Using the spatial distribution of ecosystem services values from Figure 1 we solve for the optimal landscape and record all the relevant data, including $B(X^*)$, sum of conservation payments, the sum of conservation costs, and sum of information rents.
4. We conduct steps 2 through 3 1,000 times.
5. We increase V by 0.02 units and repeat steps 2 through 4.
6. The simulation stops once steps 2 through 4 have been conducted for $V = 1$.

In Figure S1 we graph the simulated mean and 5th and 95th percentile values of aggregate conservation payment and conservation opportunity cost on optimal landscapes over the range of modeled V (the MATLAB code for this simulation is found in SI Text 5).

As V increases parcels receive higher conservation payments. At V values of 0.4 and greater all parcels on the 2 x 4 landscape are optimally conserved no matter the distribution of costs. At very low values of V the information rents generated on the landscape are relatively low. For example, from $V = 0.02$ to $V = 0.30$ and at simulation means (the black diamonds and black circles), the aggregate information rent generated on the optimal landscape (the vertical distance between black diamonds and black circles) is on par with the optimal landscape's conservation cost. However, as V increases to the point and beyond where the entire landscape is optimally conserved ($V > 0.4$) and conservation opportunity costs do not change as V increases, information rents generated on the landscape grow quickly.

We also use the simulation to determine the effect of landscape heterogeneity on information rents. Specifically, does a more uniform distribution of costs across the landscape lead to increased or decreased information rents? To answer this question use a mean-preserving spread on the random distribution of cost to isolate the impact of WTA variance on information rents. We calculate the average ratio of aggregate information rent to conservation cost generated on the optimal landscape over two dimensions, the value of V and the variance in WTA values (Figure S2). (The MATLAB code for this simulation is in SI Text 6.)

At low levels of V, greater heterogeneity in cost across the landscape generates greater information rents on average. At the highest levels of V, greater homogeneity in cost leads to slightly higher information rents. This latter result can be explained by the fact that low levels of variance in cost means that few to no low cost parcels are present on the landscape while increasing V means that is optimal to pay all parcels a conservation payment. At the same time payment levels are increasing as V gets larger. Therefore, a combination of high payments across all parcels and little to no low cost anywhere on the landscape means the regulator can expect relative aggregate information rent to be very high.

SI 5. MATLAB code for this simulation graphed in Figure S1

```
% The code is constructed for a 2 x 4 landscape with spatially dependent
% benefits.  The rows are labeled A and B in the paper and the columns are
% labeled 1 through 4 in the paper.  A letter-number combination, for
% example, A4, gives the parcel's address on the map.

% The C matrix gives conservation costs.

% The B1 matrix gives the conservation benefit (b) when no neighboring
% parcel is conserved.

% The B2 matrix gives the conservation benefit (b) when one neighboring
% parcel is conserved.

% The B3 matrix gives the conservation benefit (b) when two neighboring
% parcels are conserved.

% The B4 matrix gives the conservation benefit (b) when three neighboring
% parcels are conserved.

% To solve the spatially-independent problem define B1 and then set
% B1=B2=B3=B4.

iterations=0;
for z = 0.02:0.02:1
iterations = iterations + 1;

for zz = 1:1000

C = randi([0,4],2,4);                % WTA for each parcel is randomly assigned on the
                                     % uniform distribution (0,4).
B1 = [6 5 4 2; 1 3 5 6];             % User input.
B2 = [9 8 5 5; 2 6 8 9];             % User input.
B3 = [11 10 7 7; 3 8 10 11];         % User input.
B4 = [0 11 9 0; 0 9 11 0];           % User input.

V = z %User input.

% Find optimal landscape. (Find X-star-i) vector, net benefit, etc.  This
% calls the function 'findoptimal.m.'
conserveoption=ones(2,4);
[NB,BSumFinal,Pattern,FinalB,CSum]=findoptimal(C,B1,B2,B3,B4,V,conserveoption);
OptNB=NB; OptBSum=BSumFinal; OptPattern=Pattern; OptB=FinalB;

% OptPattern gives a value of '1' in a cell if the parcel is optimally conserved and
% a 0 otherwise.

%Find W(X-star-i) for each conserved parcel i.
for j=1:2; for k=1:4;
    index=ones(2,4); index(j,k)=0; BV(j,k)=BSumFinal-sum(sum(C.*Pattern.*index));
end; end;
W=BV.*Pattern;  % The matrix 'W' gives the values of "W(X-star-i)".
                % The value for each parcel is given at the parcel's location
                % on the landscape.
```

```
% Find X-star-~i for each conserved parcel i.
count = 0;
Wnoti=zeros(2,4);
for j=1:2; for k=1:4;
    if OptPattern(j,k)==1
       count = count + 1;
       conserveoption=ones(2,4);
       conserveoption(j,k)=0;
       [NB,BSumFinal,Pattern,FinalB,CSum]=findoptimal(C,B1,B2,B3,B4,V,conserveoption);
       OptNBnoti(count,1)=NB; OptBSumnoti(count,1)=BSumFinal; OptPatternnoti(((count-
1)*2)+1:count*2,1:4)=Pattern; OptBnoti(((count-1)*2)+1:count*2,1:4)=FinalB;

      % Find W(X-star-~i) for each conserved i.
      Wnoti(j,k)=BSumFinal-sum(sum(C.*Pattern));  % The matrix 'Wnoti' gives the
                                                  % values of "W(X-star-~i)".
                                                  % The value for each parcel is given
                                                  % at the parcel's location on the
                                                  % landscape.
end; end; end


% Calculate Delta-W(i)and calculate other solution data
deltaWi = W - Wnoti;             % Payments given out to each parcel owner.
sumdeltaWi(iterations,zz) = sum(sum(deltaWi)); % Sum of payments.
finallandscape=zeros(2,4);       % Initialize the landscape.
finallandscape(deltaWi>0)=1;     % A parcel is assigned a value of 1 if given a
                                 % payment.
finalcost=C.*finallandscape;     % Map of opportunity cost (OC) of conservation.
finalcostsum(iterations,zz)=sum(sum(finalcost));     % Total OC of conservation.
finalcostvar(iterations,zz)=var([C(1,:) C(2,:)]);    % Variance in OC of conservation
                                                     % across parcels.
end; end

% Place simulation results in summary tables.
sumdeltaWiAvg = mean(sumdeltaWi,2);
sumdeltaWiPerc = prctile(sumdeltaWi,[0 5 95 100],2);
finalcostsumAvg = mean(finalcostsum,2);
finalcostsumPerc = prctile(finalcostsum,[0 5 95 100],2);
zzz = 0.02:0.02:1;
finaloutputsummary = [zzz' sumdeltaWiAvg sumdeltaWiPerc finalcostsumAvg
finalcostsumPerc];

clearvars -except finaloutputsummary


% Function that is called by code above.
function [NB,BSumFinal,Pattern,FinalB,CSum] =
findoptimal(C,B1,B2,B3,B4,V,conserveoption)

NB=0; % Initialize NB at 0
Pattern=zeros(2,4); % Initialize landscape at 0

%Finds optimal landscape. (X-star-i). Loops over all possible conservation patterns
given ‘conserveoption’ restrictions.
for a=0:conserveoption(1,1); for b=0:conserveoption(1,2); for c=0:conserveoption(1,3);
for d=0:conserveoption(1,4);
for e=0:conserveoption(2,1); for f=0:conserveoption(2,2); for g=0:conserveoption(2,3);
for h=0:conserveoption(2,4);
    B = B1;

    if b==1 || e==1; B(1,1)=B2(1,1); end;
    if b==1 && e==1; B(1,1)=B3(1,1); end;
    if a==1 || c==1 || f==1; B(1,2)=B2(1,2); end;
    if (a==1 && c==1) || (a==1 && f==1) || (c==1 && f==1); B(1,2)=B3(1,2); end;
```

```
    if (a==1 && c==1 && f==1); B(1,2)=B4(1,2); end;

    if b==1 || d==1 || g==1; B(1,3)=B2(1,3); end;
    if (b==1 && d==1) || (b==1 && g==1) || (d==1 && g==1); B(1,3)=B3(1,3); end;
    if (b==1 && d==1 && g==1); B(1,3)=B4(1,3); end;

    if c==1 || h==1; B(1,4)=B2(1,4); end;
    if c==1 && h==1; B(1,4)=B3(1,4); end;

    if a==1 || f==1; B(2,1)=B2(2,1); end;
    if a==1 && f==1; B(2,1)=B3(2,1); end;

    if b==1 || e==1 || g==1; B(2,2)=B2(2,2); end;
    if (b==1 && e==1) || (b==1 && g==1) || (e==1 && g==1); B(2,2)=B3(2,2); end;
    if (b==1 && e==1 && g==1); B(2,2)=B4(2,2); end;

    if c==1 || f==1 || h==1; B(2,3)=B2(2,3); end;
    if (c==1 && f==1) || (c==1 && h==1) || (f==1 && h==1); B(2,3)=B3(2,3); end;
    if (c==1 && f==1 && h==1); B(2,3)=B4(2,3); end;

    if d==1 || g==1; B(2,4)=B2(2,4); end;
    if d==1 && g==1; B(2,4)=B3(2,4); end;

BSum=sum(sum(B.*[a b c d; e f g h]))*V; % Total conservation benefit on landscape.
CSum=sum(sum(C.*[a b c d; e f g h]));   % Total cost on landscape.

% Retain the landscape that maximizes NB. The landscape that maximizes NB is passed
% back to the main program.
if BSum-CSum>NB
    NB = BSum-CSum; BSumFinal = BSum; Pattern=[a b c d; e f g h]; FinalB = B;
end

end;end;end;end;end;end;end;end;

% If no landscape generates positive NB a null solution is passed back to the main
% program.
if NB==0
    BSumFinal=0; Pattern=zeros(2,4); FinalB = 0; CSum=0;
end

end
```

SI 6. MATLAB code for this simulation graphed in Figure S2

```
% The code is constructed for a 2 x 4 landscape with spatially dependent
% benefits.  The rows are labeled A and B in the paper and the columns are
% labeled 1 through 4 in the paper.  A letter-number combination, for example, A4,
% gives the parcel's address on the map.

% The C matrix gives conservation costs.

% The B1 matrix gives the conservation benefit (b) when no neighboring
% parcel is conserved.

% The B2 matrix gives the conservation benefit (b) when one neighboring
% parcel is conserved.

% The B3 matrix gives the conservation benefit (b) when two neighboring
% parcels are conserved.

% The B4 matrix gives the conservation benefit (b) when three neighboring
% parcels are conserved.
```

```
% To solve the spatially-independent problem define B1 and then set B1=B2=B3=B4.

iterations=0;
for z = 0.02:0.02:1
iterations = iterations + 1;

for zz = 1:1000

    % Ensures that the distribution of costs over landscape for each iteration has a
    % mean between 1.95 and 2.05 where costs are drawn from a uniform distribution on
    % the interval(0,4).
    avgC = 0;
    while avgC > 2.05 || avgC < 1.95
        C = randi([0,4],2,4);
        avgC = sum(sum(C))/8;
    end

B1 = [6 5 4 2; 1 3 5 6];          % User input.
B2 = [9 8 5 5; 2 6 8 9];          % User input.
B3 = [11 10 7 7; 3 8 10 11];      % User input.
B4 = [0 11 9 0; 0 9 11 0];        % User input.

V = z % User input.

% Find optimal landscape. (Find X-star-i) vector, net benefit, etc.  This
% calls the function 'findoptimal.m.'
conserveoption=ones(2,4);
[NB,BSumFinal,Pattern,FinalB,CSum]=findoptimal(C,B1,B2,B3,B4,V,conserveoption);
OptNB=NB; OptBSum=BSumFinal; OptPattern=Pattern; OptB=FinalB;

% OptPattern gives a value of '1' in a cell if the parcel is optimally conserved and
% a 0 otherwise.

% Find W(X-star-i) for each conserved i.
for j=1:2; for k=1:4;
    index=ones(2,4); index(j,k)=0; BV(j,k)=BSumFinal-sum(sum(C.*Pattern.*index));
end; end;
W=BV.*Pattern;  % The matrix 'W' gives the values of "W(X-star-i)".
                % The value for each parcel is given at the parcel's location
                % on the landscape.

%Find X-star-~i for each conserved i.
count = 0;
Wnoti=zeros(2,4);
for j=1:2; for k=1:4;
    if OptPattern(j,k)==1
       count = count + 1;
       conserveoption=ones(2,4);
       conserveoption(j,k)=0;
       [NB,BSumFinal,Pattern,FinalB,CSum]=findoptimal(C,B1,B2,B3,B4,V,conserveoption);
       OptNBnoti(count,1)=NB; OptBSumnoti(count,1)=BSumFinal; OptPatternnoti(((count-
1)*2)+1:count*2,1:4)=Pattern; OptBnoti(((count-1)*2)+1:count*2,1:4)=FinalB;

      %Find W(X-star-~i) for each conserved i.
      Wnoti(j,k)=BSumFinal-sum(sum(C.*Pattern));  % The matrix 'Wnoti' gives the
                                                  % values of "W(X-star-~i)".
                                                  % The value for each parcel is given
                                                  % at the parcel's location on the
                                                  % landscape.
end; end; end
```

```
% Calculate Delta-W(i)and calculate other solution data.
deltaWi = W - Wnoti;              % Payments given out to each parcel owner.
sumdeltaWi(iterations,zz) = sum(sum(deltaWi)); % Sum of payments.
finallandscape=zeros(2,4);        % Initialize the landscape.
finallandscape(deltaWi>0)=1;      % A parcel is assigned a value of 1 if given a
                                  % payment.
finalcost=C.*finallandscape;      % Map of opportunity cost (OC) of conservation.
finalcostsum(iterations,zz)=sum(sum(finalcost));      % Total OC of conservation.
finalcostvar(iterations,zz)=var([C(1,:) C(2,:)]);     % Variance in OC of conservation
                                                      % across parcels.

end; end

% Place simulation results in summary tables.
sumdeltaWiAvg = mean(sumdeltaWi,2);
sumdeltaWiPerc = prctile(sumdeltaWi,[0 5 95 100],2);
finalcostsumAvg = mean(finalcostsum,2);
finalcostsumPerc = prctile(finalcostsum,[0 5 95 100],2);
zzz = 0.02:0.02:1;
finaloutput = [zzz' (sumdeltaWi-finalcostsum)./finalcostsum finalcostvar];
finaloutputsummary = [zzz' sumdeltaWiAvg sumdeltaWiPerc finalcostsumAvg
finalcostsumPerc];

clearvars -except finaloutput finaloutputsummary
```

References

1. Smith R-B-W, Shogren J-F (2002) Voluntary Incentive Design for Endangered Species Protection. *Journal of Environmental Economics and Management* 43(2):169-187.

2. Parkhurst G-M, et al. (2002) Agglomeration bonus: An incentive mechanism to reunite fragmented habitat for biodiversity conservation. *Ecological Economics* 41(2):305-328.

3. Parkhurst G-M, Shogren J-F (2007) Spatial Incentives to Coordinate Contiguous Habitat. *Ecological Economics* 64(2):344–55.

4. Drechsler M, Watzold F, Johst K, Shogren J-F (2010) An Agglomeration Payment for Cost-effective Biodiversity Conservation in Spatially Structured landscapes. *Resource and Energy Economics* 32(2):261-275.

5. Camm J-D, Polasky S, Solow A, Csuti B (1996) A Note on Optimal Algorithms for Reserve Site Selection. *Biological Conservation* 78(3):353-355.

6. Church R-L, Stoms D-M, Davis F-W (1996) Reserve Selection as a Maximal Coverage Problem. *Biological Conservation* 76(2):105-112.

7. Vane-Wright R-I, Humphries C-J, Williams P-H (1991) What to Protect? Systematics and the Agony of Choice. *Biological Conservation* 55(3):235-254.

8. Ando A, Camm J, Polasky S, Solow A (1998) Species Distributions, Land Values, and Efficient Conservation. *Science* 279(5359):2126-2128.

9. Polasky S, Camm J-D, Garber-Yonts B (2001) Selecting Biological Reserves Cost-Effectively: An Application to Terrestrial Vertebrate Conservation in Oregon. *Land Economics* 77(1):68-78.

10. Fischer D-T, Church R-L (2003) Clustering and Compactness in Reserve Site Selection: An Extension of the Biodiversity Management Area Selection Model. *Forest Science* 49(4):555-565.

11. Cabeza M, Moilanen A (2003) Site-Selection Algorithms and Habitat Loss. *Conservation Biology* 17(5):1402-1413.

12. Nalle D-J, Montgomery C-A, Arthur J-L, Polasky S, Schumaker N-H (2004) Modeling Joint Production of Wildlife and Timber. *Journal of Environmental Economics and Management* 48(3): 997-1017.

13. Polasky S, Nelson E, Lonsdorf E, Fackler P, Starfield A (2005) Conserving Species in a Working Landscape: Land Use with Biological and Economic Objectives. *Ecological Applications* 15:1387-1401.

14. Polasky S, et al. (2008) Where to Put Things? Spatial Land Management to Sustain Biodiversity and Economic Production. *Biological Conservation* 141(6):1505-1524.

15. Lewis D-J, Plantinga A-J (2007) Policies for Habitat Fragmentation: Combining Econometrics with GIS-Based Landscape Simulations. *Land Economics* 83(2):109-127.

16. Lewis D-J, Plantinga A-J, Wu J (2009) Targeting Incentives for Habitat Fragmentation. *American Journal of Agricultural Economics* 91(4):1080-1096.

17. Lewis D-J, Plantinga A-J, Nelson E, Polasky S (2011) The Efficiency of Voluntary Incentives Policies for Preventing Biodiversity Loss. *Resource and Energy Economics* 33(1): 192- 211.

18. Latacz-Lohmann U, Van der Hamsvoort C (1997) Auctioning Conservation Contracts: A Theoretical Analysis and an Application. *American Journal of Agricultural Economics* 79(2): 407-418.

19. Stoneham G, Chaudhri V, Ha A, Strappazzon L (2003) Auctions for Conservation Contracts: An Empirical Examination of Victoria's Bush Tender Trial. *Australian Journal of Agricultural and Resource Economics* 47(4):477-500.

20. Cason T-N, Gangadharan L (2004) "Auction Design for Voluntary Conservation Programs. *American Journal of Agricultural Economics* 86(5):1211-1217.

21. Kirwan B, Lubowski R-N, Roberts M-J (2005) How Cost-effective Are Land Retirement Auctions? Estimating the Difference between Payments and Willingness-to-accept in the Conservation Reserve Program. *American Journal of Agricultural Economics* 87(5):1239-1247.

22. Schillizzi S, Latacz-Lohmann U (2007) Assessing the Performance of Conservation Auctions: An Experimental Study. *Land Economics* 83(4):497-515.

23. Vickrey W (1961) Counterspeculation, Auctions, and Competitive Sealed Tenders. *Journal of Finance* 16(1):8-37.

24. Kwerel E (1977) To Tell the Truth: Imperfect Information and Optimal Pollution Control. *Review of Economic Studies* 44(3):595-601.

25. Dasgupta P, Hammond P, and Maskin E (1980) On Imperfect Information and Optimal Pollution Control. *Review of Economic Studies* 47(5):857-860.

26. Kim J-C, Chang K-B (1993) An Optimal Tax/subsidy for Output and Pollution Control under Asymmetric Information in Oligopoly Markets. *Journal of Regulatory Economics* 5(2):183-197.

27. Montero J-P (2008) A Simple Auction Mechanism for the Optimal Allocation of the Commons. *American Economic Review* 98(1):496-518.

SI Figure Legends

Figure S1: Simulated mean and 5^{th} and 95^{th} percentile values of the sum of conservation payments and conservation opportunity cost on the example landscape for various levels of *V*.

Figure S2: Simulated mean ratio of aggregate information rent to conservation opportunity cost generated on the optimal landscape across two landscape dimensions: variance in WTA and *V*.

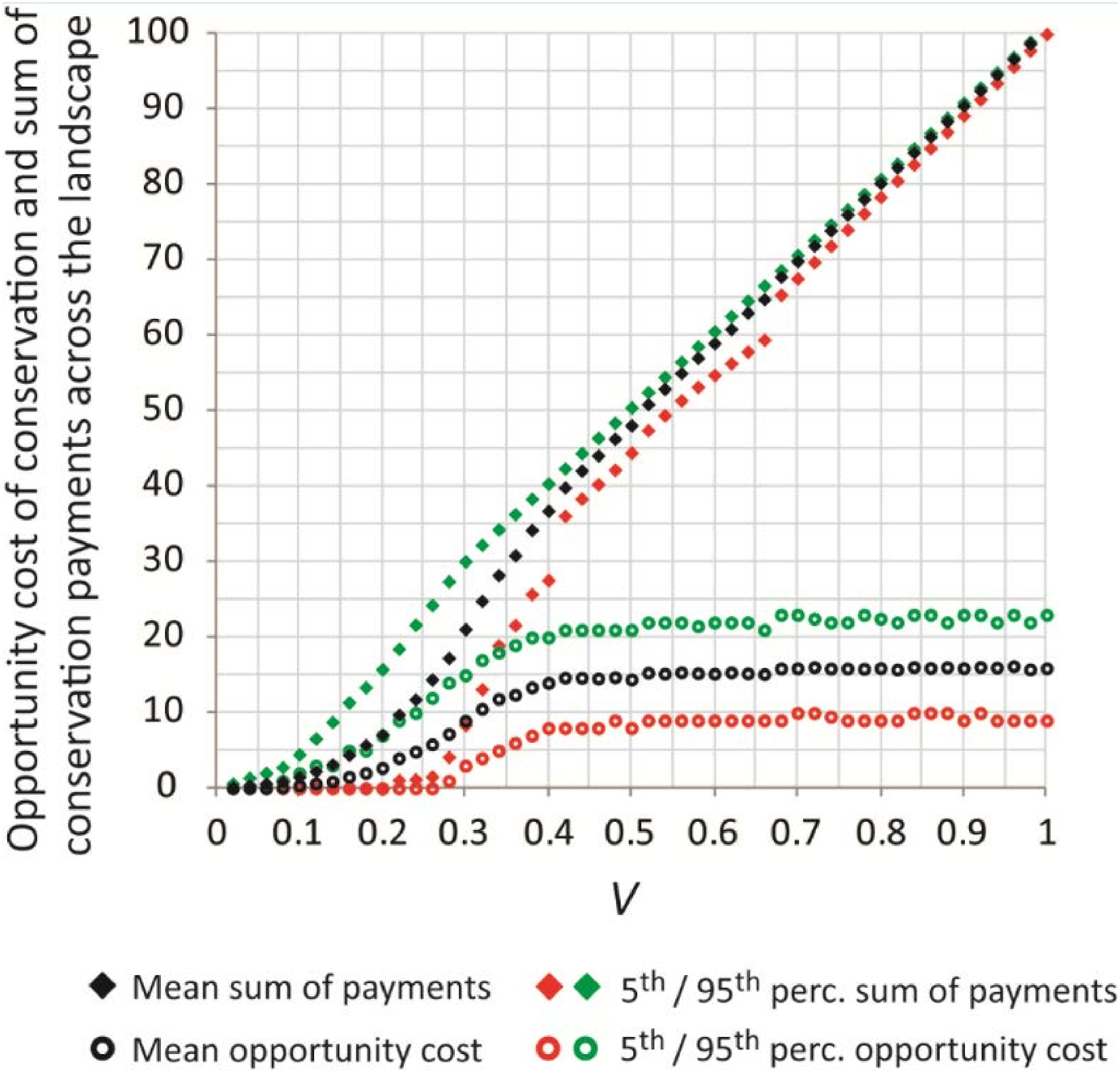
Opportunity cost of conservation and sum of conservation payments across the landscape
100
90
80
70
60
50
40
30
20
10
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
V
Mean sum of payments
5th / 95th perc. sum of payments
Mean opportunity cost
5th / 95th perc. opportunity cost

Figure S1

Figure SI2