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Implementing the Optimal Provision of Ecosystem Services

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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 pays a landowner for the increased value of ecosystem services generated by the landowner's actions 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.

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 (Daily 1997, MA 2005). 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.

A potential solution to the under-provision of ecosystem services is to provide landowners with payments for ecosystem services (PES). A PES program is a voluntary incentive-based program that pays landowners for their contribution to the provision of ecosystem services. A prominent example of a PES program is Costa Rica's 1996 National Forest Law that pays landowners to conserve forests for carbon sequestration, water quality improvement, habitat, and scenic beauty. Though not originally designed as a PES program, the U.S. Conservation Reserve Program fulfills much the same purpose by paying landowners to retire land from active crop production, which contributes to provision of a number of ecosystem services (e.g., water quality improvement carbon sequestration, habitat provision).

An optimal PES program 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 PES 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 (e.g., Fahrig 2003). 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 the decisions of all 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 (e.g., land productivity or skills, knowledge, and preferences of landowners) that 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 fail 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 that pay each landowner according to their actions alone will also fail 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 simple regulatory or PES schemes can be used to maximize 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 and 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 PES programs (though it does prevent optimal implementation via top-down regulation). When the contribution of a parcel to the value of ecosystem services depends only on the characteristics of the land parcel itself (i.e., there are no spatial dependencies), the regulator can implement an optimal solution by simply offering a payment equal to the parcel's contribution to benefits. Only landowners with private costs below their parcel's incremental value will want to participate, accept the payment and take actions to increase provision of ecosystem services. In this case, the optimal solution is obtained despite asymmetric information. Neither regulation nor simple PES mechanisms, however, achieve an optimal solution with the combination of assymetric information and spatially-dependent benefits.

In this paper, we present a PES scheme that achieves optimal provision of ecosystem services with spatially-dependent benefits and asymmetric information. Our approach builds from the mechanism design literature in economics on the optimal provision of public goods (Groves 1973, Groves and Ledyard 1977), combining elements of a Vickrey auction that induces auction participants to truthfully reveal private information (Vickrey 1961), with Pigouvian

subsidies that provide optimal incentives by paying landowners for their incremental contribution to the value of ecosystem services. Under our mechanism, landowners simultaneously submit bids specifying the minimum price they would accept to undertake an action to increase provision of ecosystem services on their land. A landowner's bid is accepted if and only if doing so increases the value of ecosystem services from the landscape as a whole by at least as much as the bid. If the bid is accepted, the landowner is paid 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 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 enrollment, and pay landowners accordingly. With spatially-dependent benefits, the value generated by an individual parcel, and hence the payment to each landowner, is a function of land uses on all parcels and so can only be determined once all bids are submitted.

Economists and others have recognized that implementing optimal land use with spatially-dependent benefits and private information is a challenging but important task (e.g., Drechsler et al. 2010), which we briefly summarize here (see Supplementary Information Text S1 for a more in-depth literature review). One strand of literature investigates the ability of incentive policies to affect the spatial pattern of land use and associated levels of ecosystems services (e.g., Parkhurst et al. 2002, Lewis et al. 2011), 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 (e.g., Church et al. 1996, Polasky et al. 2008). Several prior papers study auctions for land conservation mostly with an emphasis on how auctions can

be used to reduce government expenditures (e.g., Stoneham et al. 2003, Kirwan et al. 2005). Our study is most closely related to papers in the economics literature on information-revealing mechanisms for optimal pollution control (Kwerel 1977, Dasgupta et al. 2000, Montero 2008). However, none of these papers consider spatially-dependent benefits.

2. A Simple Example

We start with a simple example of a landscape composed of a 2×4 grid of land parcels (Fig. 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 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 (Fig. 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 neighbors. 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 for other parcels. If $V=0.33$, then 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 $(11+10+3+9+8)*0.25$, and a cost of $(3+1+1+1+1)$, 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 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 to 2.25 from 3.25 under the optimal solution.

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 solves this problem in the next section.

3. The 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 so we stick to binary choice representation here.

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 that the benefits function $B(X)$ is common knowledge.

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 (Montero 2008).

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 (e.g., Polasky et al. 2008). However, without knowledge of costs, the auction is needed to reveal costs in order to determine the optimal solution..

In the 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 $W_i(X_i^*)$:

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

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 which other landowners bids will be accepted.

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 auction mechanism (Proposition 1) and then that the auction mechanism yields an optimal solution (Proposition 2).

Proposition 1: Under the 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 2). When the landowner overbids ($s_i > c_i$), there is the 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 the possibility that the bid will be accepted ($s_i \leq p_i$) 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 $p_i \geq c_i$ 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 auction mechanism generates the

optimal solution when the regulator 1) accepts bids if and only if $s_i \leq \Delta W_i$ 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 ΔW_i is greater

than c_i, then it is optimal to conserve parcel i, as it implies the net benefits of conserving parcel i

are positive. 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 simple example revisited

To illustrate the auction mechanism, 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 1 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 1 we can see that the optimal payment, $p_i = \Delta W_i$, 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.

6. Discussion

This paper examines the implementation of a PES program 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 (e.g., landowner skills and preferences), asymmetric information is an important feature of most voluntary PES 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 PES program for spatially-dependent ecosystem services cannot be implemented without first addressing the problem of asymmetric information.

The auction mechanism proposed in this paper provides a surprisingly simple solution to the optimal provision of ecosystem services. The mechanism differs from traditional PES schemes 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 to the owners of parcels that make up the optimal solution. By paying each landowner an amount equal to the increase in social benefits with conservation of their parcel, an amount that is independent of their bid, the auction mechanism applies the fundamental insight of Vickrey auctions 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 pay landowners the increase in social benefits of conservation even when bids come in far lower than benefits, 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 payments the group receives from the regulator. 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 in this case:

$$\Delta W_i = W_i(X_i^*) - W_i(X_{\sim i}^*) = (8 - 2) - 0 = 6.$$

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 (Montero 2008).

Truthfully bidding cost is a dominant strategy for each landowner when the regulator commits ex-ante to paying landowners the social value of their increase in services. However, if landowners believe the regulator will renegotiate after bids have been submitted, then truth-telling is no longer necessarily a dominant strategy. In this case, 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 enforcement of the payment plan.

Under our 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. Paying 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).

Economists have studied mechanisms designed to reduce information rents associated with environmental policies (see Lewis, 1996, for a survey and Mason and Plantinga, 2013, 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. 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 (Walker 1980). 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.

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 (e.g., Nalle et al. 2004, Nelson et al. 2008, Polasky et al. 2008). Lewis et al. (2011) 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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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.
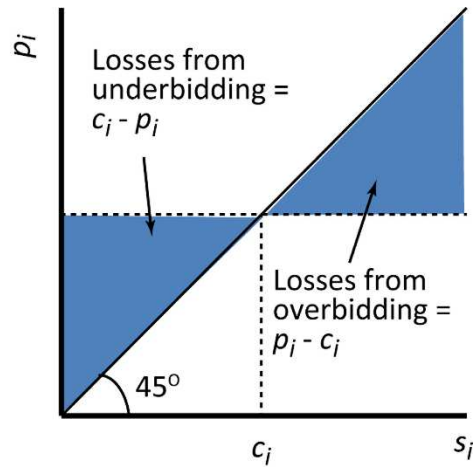
Table 1. Optimal Payments in the Simple Example

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

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 Vickery (23) and decouple payment from the landowner's bid. As such, our study is most closely related to the literature on information-revealing mechanisms. Kwerel (24) develops a tradable permit and subsidy scheme in which it is a Bayesian-Nash equilibrium for competitive firms to truthfully reveal private information about pollution control costs and implement an optimal pollution abatement solution. Dasgupta et al. (25) and Kim and Chang (26) develop mechanisms that implement an optimal solution even with imperfect competition. Montero (27) develops a uniform-price auction that achieves an optimal solution in which firms submit a demand schedule, and based on this, the regulator sets the number of permits for sale and a partial rebate of auction revenues. These mechanisms achieve an optimal solution in the context of pollution reduction because they induce firms to correctly reveal information about cost of emissions reductions and provide incentives so that firms choose the efficient emissions level. Our mechanism works similarly to Montero's

mechanism but in the context of providing ecosystem services. However, the benefit function in our problem is more complex than in the pollution control problem because the provision of conservation benefits can be spatially-dependent, i.e., the net benefits of conservation on one land parcel depend on whether or not specific neighboring parcels are conserved. The benefits of emissions control considered in the papers mentioned above, though they can depend on aggregate pollution, are not spatially dependent as in our problem.

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:

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

where $X_i\ast$ 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:

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

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
```

```matlab
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.
```

```matlab
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
```

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SI Figure Legends

Figure S1: Simulated mean and 5th and 95th 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*.

SI Figure Legends

Figure S1: Simulated mean and 5th and 95th 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*.
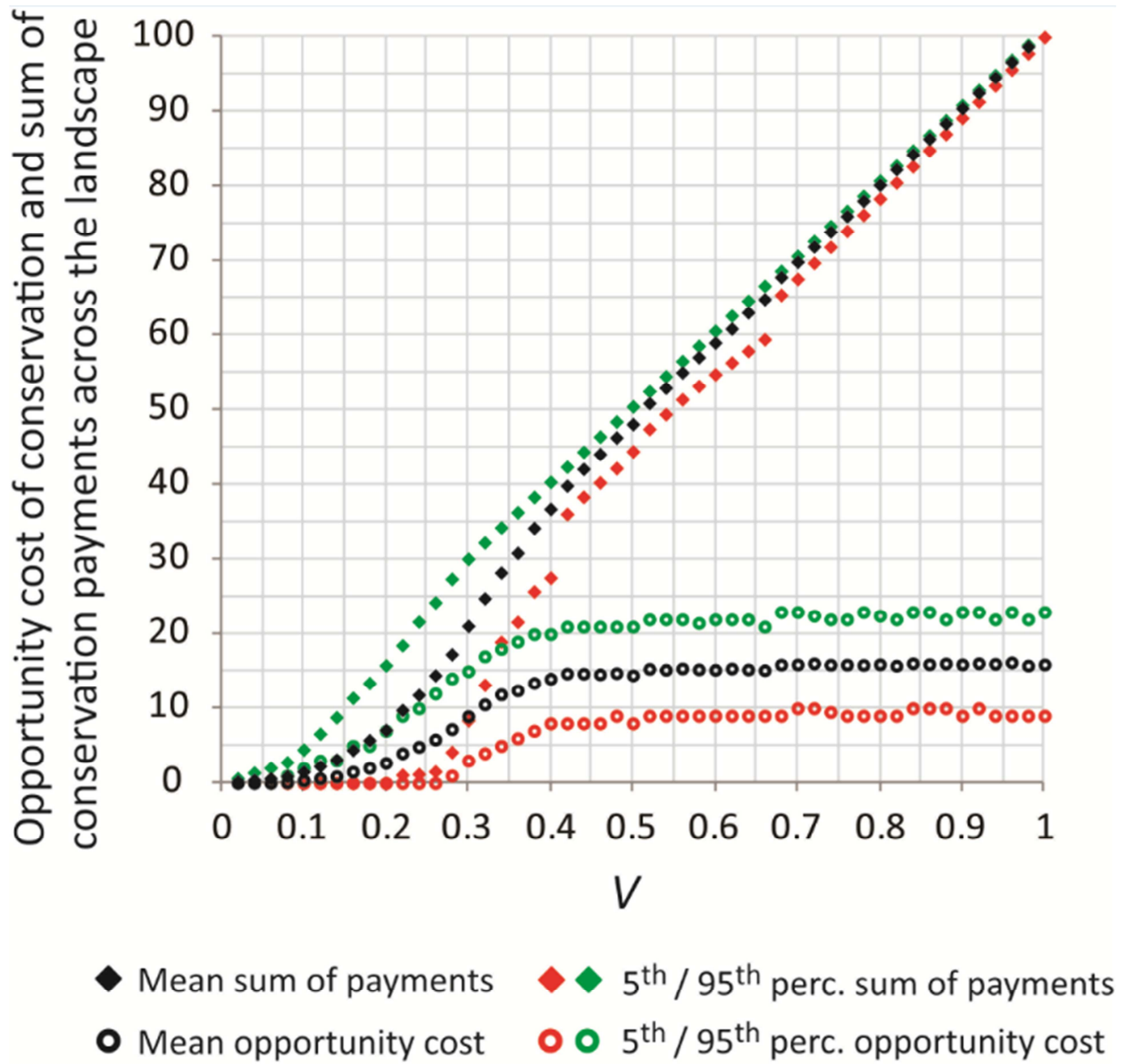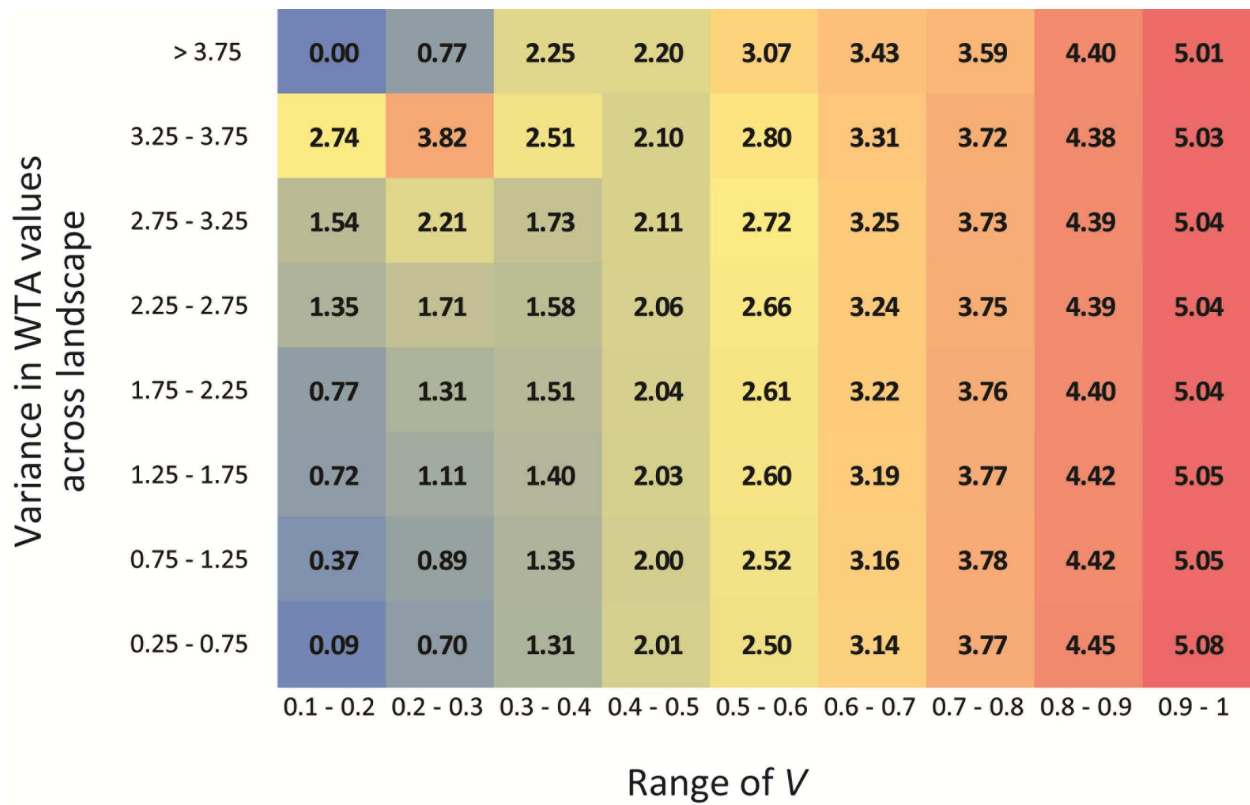
Figure S1

Figure SI2