Supporting Information

Polasky et al. 10.1073/pnas.1404484111

SI Text

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 (5–9). In some cases, these studies account for spatial dependencies in the objective function (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. Though 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 US Conservation Reserve Program 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 Vickrey–Clarke–Grove auction literature and decouple payment from the landowner's bid.

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 1: $\Delta W_i \geq c_i$. When $\Delta W_i \geq c_i$, then either (*i*) $\Delta W_i \geq s_i$, 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 (*ii*) $\Delta W_i < s_i$, 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 2: $\Delta W_i < c_i$. 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 1: $\Delta W_i \geq c_i$. 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 2: $\Delta W_i < c_i$. 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.

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

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

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

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

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

$$NB\left(X_i^*\right) - NB\left(X_{\sim i}^*\right) \geq 0$$

$$W_i\left(X_i^*\right) - c_i - W\left(X_{\sim i}^*\right) \geq 0$$

$$\Delta W_i \geq c_i.$$

In the auction mechanism, parcel i will be conserved if and only if $\Delta W_i \geq s_i$. Because landowners bid truthfully (proposition 1), 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.

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 2×4 grid of land parcels with arbitrarily chosen parameter values (Fig. 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:

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

In Fig. S1 we graph the simulated mean and fifth 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 in Dataset S1, *SI 5*).

As V increases, parcels receive higher conservation payments. At V values of 0.4 and greater, all parcels on the 2×4 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 in Fig. S1), the aggregate information rent generated on the optimal landscape (the vertical distance between black diamonds and black circles in Fig. S1) 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, we 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 (Fig. S2). (The MATLAB code for this simulation is in Dataset S1, *SI 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, whereas 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.

1. Smith RBW, Shogren JF (2002) Voluntary incentive design for endangered species protection. *J Environ Econ Manage* 43(2):169–187.
2. Parkhurst GM, et al. (2002) Agglomeration bonus: An incentive mechanism to reunite fragmented habitat for biodiversity conservation. *Ecol Econ* 41(2):305–328.
3. Parkhurst GM, Shogren JF (2007) Spatial incentives to coordinate contiguous habitat. *Ecol Econ* 64(2):344–355.
4. 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.
5. Camm JD, Polasky S, Solow A, Csuti B (1996) A note on optimal algorithms for reserve site selection. *Biol Conserv* 78(3):353–355.
6. Church RL, Stoms DM, Davis FW (1996) Reserve selection as a maximal coverage problem. *Biol Conserv* 76(2):105–112.
7. Vane-Wright RI, Humphries CJ, Williams PH (1991) What to protect? Systematics and the agony of choice. *Biol Conserv* 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 JD, Garber-Yonts B (2001) Selecting biological reserves cost-effectively: An application to terrestrial vertebrate conservation in Oregon. *Land Econ* 77(1):68–78.
10. Fischer DT, Church RL (2003) Clustering and compactness in reserve site selection: An extension of the biodiversity management area selection model. *For Sci* 49(4):555–565.
11. Cabeza M, Moilanen A (2003) Site-selection algorithms and habitat loss. *Conserv Biol* 17(5):1402–1413.
12. 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.
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. *Ecol Appl* 15: 1387–1401.
14. Polasky S, et al. (2008) Where to put things? Spatial land management to sustain biodiversity and economic production. *Biol Conserv* 141(6):1505–1524.
15. Lewis DJ, Plantinga AJ (2007) Policies for habitat fragmentation: Combining econometrics with GIS-based landscape simulations. *Land Econ* 83(2):109–127.
16. Lewis DJ, Plantinga AJ, Wu J (2009) Targeting incentives for habitat fragmentation. *Am J Agric Econ* 91(4):1080–1096.
17. 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.
18. Latacz-Lohmann U, Van der Hamsvoort C (1997) Auctioning conservation contracts: A theoretical analysis and an application. *Am J Agric Econ* 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. *Aust J Agric Resour Econ* 47(4):477–500.
20. Cason TN, Gangadharan L (2004) Auction design for voluntary conservation programs. *Am J Agric Econ* 86(5):1211–1217.
21. 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 Agric Econ* 87(5):1239–1247.
22. Schillizzi S, Latacz-Lohmann U (2007) Assessing the performance of conservation auctions: An experimental study. *Land Econ* 83(4):497–515.

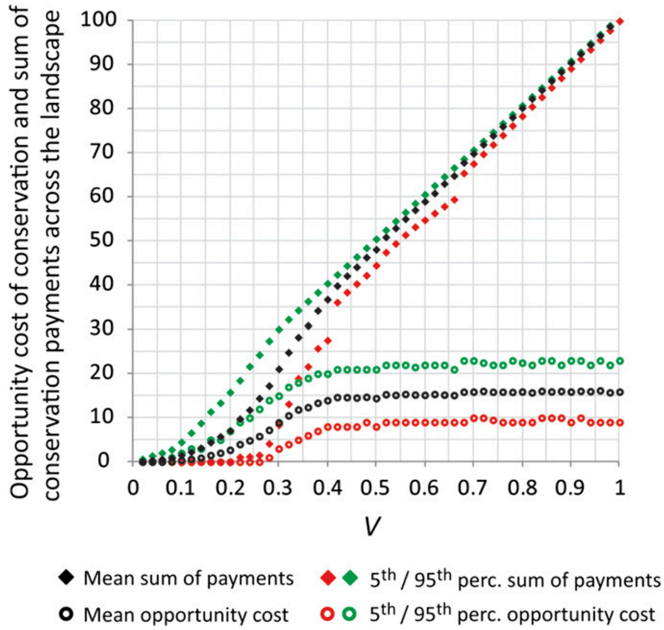

Fig. S1. Simulated mean and 5th and 95th percentile values of the sum of conservation payments and conservation opportunity cost on the example landscape for various levels of *V*.

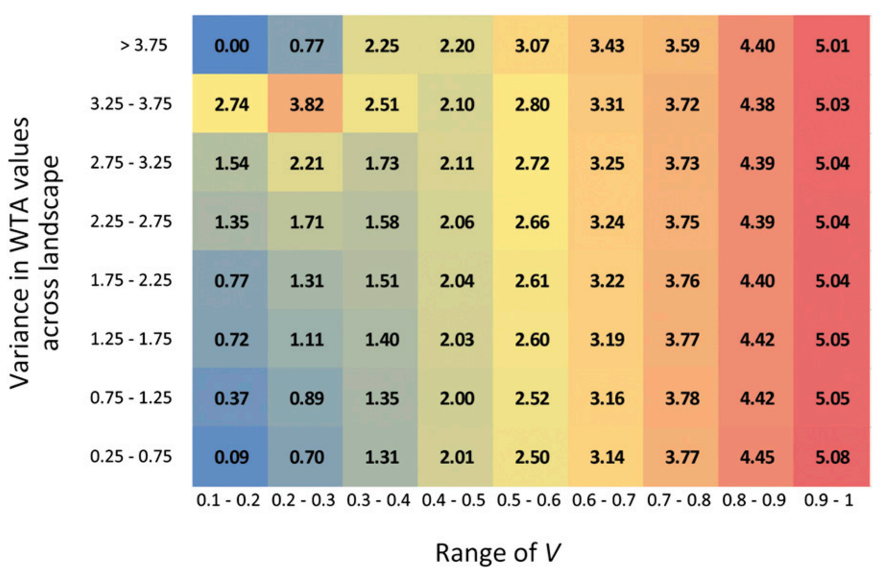

Fig. S2. Simulated mean ratio of aggregate information rent to conservation opportunity cost generated on the optimal landscape across two landscape dimensions: variance in WTA and *V*.

Other Supporting Information Files

Dataset S1 (DOCX)