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An Auction Mechanism for the Optimal Provision of Ecosystem Services under Climate Change

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Abstract: The provision of many ecosystem services depends on the spatial pattern of land use across multiple landowners. Even holding land use constant, ecosystem service provision may change through time due to climate change. This paper develops an auction mechanism that implements an optimal solution for providing ecosystem services through time with multiple landowners who have private information about the net benefits of alternative uses of their land. Under the auction, each landowner has a dominant strategy to truthfully reveal their private information. With this information a regulator can then implement the optimal landscape pattern, which maximizes the present value of net benefits derived from the landscape, following the rules of the auction mechanism. The auction can be designed as a subsidy auction that pays landowners to conserve or a tax auction where landowners pay for the right to develop. Our mechanism optimizes social adaptation of ecosystem management to climate change.

Keywords: ecosystem services, conservation planning, climate change adaptation, spatial modeling, land use, auctions, asymmetric information, truthful mechanism, irreversibility, option value

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1. Introduction

The provision of ecosystem services often depends on the land-use decisions of multiple landowners. Many ecosystem services, such as carbon storage that contributes to climate regulation, filtration of nutrients and pollutants that contribute to water quality, or provision of habitat that supports wildlife, are not traded in markets and landowners generally receive little benefit from managing their land in ways that increase the provision of these services. Therefore, under-provision of ecosystem services occurs in the absence of a policy mechanism to internalize the external benefits to the landowner. The problem of internalizing the provision of ecosystem services benefits is made more complex by dynamics where ecosystem service benefits change through time both as a function of on-going land-use decisions and climate change.

This paper develops an auction mechanism that implements an optimal solution for the provision of ecosystem services in an environment that changes over time. Our mechanism contributes to conservation policy aimed at social adaptation of ecosystem management to climate change. There are five important elements to the problem of internalizing landscape-scale externalities under climate change: i) spatial dependencies, ii) asymmetric information, iii) dynamics that change the net benefit function over time, iv) uncertainty about future net benefits, and v) irreversible decisions. Prior literature has dealt with a subset of these issues, but no prior paper – to the best of our knowledge – has dealt with all five issues.

Knowledge of the ecological production function is necessary to optimally provide ecosystem services (NRC 2005, Barbier 2007, Polasky and Segerson 2009) and many production functions are characterized by spatial dependencies – the contribution of one parcel of land to the provision of an ecosystem service depends on the land use on spatially proximate land (Mitchell et al. 2015a, 2015b). For example, the contribution of a patch of habitat to species conservation depends on fragmentation and connectivity with other patches of habitat (Fahrig 2003, Armsworth et al. 2004). Robinson et al. (1995) provides empirical evidence that the success of breeding birds on a piece of forestland depends on the fragmentation of nearby forestland, and recent global analyses have highlighted that current levels of forest fragmentation may be close to a critical threshold where further forest loss greatly accelerates fragmentation (Taubert et al. 2018). The "Where to Put Things" approach developed in Polasky et al. (2008) illustrates a production possibilities frontier characterizing efficient outcomes for species conservation and market returns to landowners, where species conservation depends on landscape pattern (i.e., spatially-dependent benefits).

Optimal provision of a spatially-dependent ecosystem service relies on a decision-maker, such as a land-use planner (hereafter called the regulator), having complete information about net benefits of land-use alternatives. However, the opportunity cost of conserving a piece of land – a necessary piece of information to implement the "Where to Put Things" approach – is typically private information. The opportunity cost of choosing to conserve a parcel of land depends in part on landowner skills, knowledge, expectations, preferences, attachment to and history with the land. Having a regulator dictate outcomes will likely yield an inefficient outcome if landowner-specific benefits and costs are not incorporated. Voluntary approaches that give decision-making power to landowners can overcome this problem. However, without full information on landowner benefits and costs, landowner decisions under voluntary incentive programs are unlikely to be socially optimal (Lewis et al. 2011).

Polasky, Lewis, Plantinga, and Nelson (2014) – hereafter PLPN – developed an auction mechanism in which landowners have a dominant strategy to truthfully reveal private information, which the regulator can then use to implement an optimal land-use pattern. The auction mechanism in PLPN builds from the work of Vickrey (1961), Clarke (1971), and Groves (1973), and extends it to the case of multiple landowners whose actions jointly determine spatially-dependent net benefits. An important result from PLPN is that spatially-dependent ecosystem service benefits require information across multiple landowners so that internalizing the externality requires a mechanism in which landowners truthfully reveal private information.

This paper's primary contribution is to develop a dynamic extension of the PLPN auction mechanism and apply it to the problem of providing spatially-dependent benefits under climate change. The PLPN mechanism is static and not well-suited to dealing with three key characteristics of internalizing landscape-scale externalities under climate change. First, the spatial dependencies that affect ecosystem service provision from land are likely to change over time. For example, the suitable range of many species is expected to shift under a changing climate (Thomas et al. 2004, Thuiller et al. 2005, Lawler et al. 2009, Staudinger et al. 2013) and there may be significant barriers to species migration to new locations including unsuitable habitat between old and new habitat locations and the speed of movement (Opdam and Wascher 2004, Lawler et al. 2013). Second, future provision of ecosystem services is typically uncertain. Uncertainty arises both because of uncertainty about future climate and how ecological systems will change with climate change (e.g., Millar et al. 2007, Nordhaus 2014). Several papers analyze the optimal solution of spatial-dynamic resource problems (e.g., Sanchirico and Wilen 2005, Costello and Polasky 2008, Smith et al. 2009, Wätzold et al. 2015), but this literature assumes the planner has complete information (i.e., no asymmetric information), and often assumes there is no uncertainty.

Third, many land-use changes (e.g. development to urban uses, cutting old-growth forest, etc.) are irreversible, or only reversible at large cost or with a long time lag. The failure to prevent land-use changes that are costly to reverse reduces the ability to manage adaptively under an uncertain future (Albers 1996). Analysis of the land conservation problem under uncertainty and irreversibility dates back to the seminal article by Arrow and Fisher (1974). Maintaining flexibility and avoiding irreversible decisions gives rise to option value (Arrow and Fisher 1974, Henry 1974). Subsequent studies extended and refined the concept of option value (Hanemann 1989, Dixit and Pindyck 1994, Albers 1996, Traeger 2014), applied the concept to urban development (Mills 1981) and biodiversity conservation (Kassar and Lasserre 2004; Leroux et al. 2009), and more recently have argued for its importance to the problem of conservation planning under climate change (Mezey and Conrad 2010).

This paper develops an auction mechanism that implements an optimal solution to the problem of provision of ecosystem services subject to spatial dependencies, asymmetric information, dynamics, uncertainty, and irreversible decisions. The auction mechanism combines four classic strands of economic literature associated with Pigou, Coase, Arrow-Fisher, and Vickery-Clarke-Groves. The auction mechanism builds off Vickery-Clarke-Groves mechanisms and works as follows. Each landowner simultaneously submits a two-part bid for how much they would need to be paid to forgo development on their land today and in the future (e.g., converting natural habitat for farming or housing). A landowner's bid will be accepted by the regulator if and only if the expected contribution to ecosystem service benefits with conservation is at least as large as the value of development as revealed by the bid. If the bid is not accepted, the landowner can develop the parcel and earn returns from the development. If the bid is accepted, the landowner is prohibited from developing their parcel in the current period and receives a Pigouvian payment from the regulator based on the parcel's contribution to current ecosystem service benefits and option value. In the future period, whether development is prohibited or allowed depends on whether the gain in social net benefits from conserving a parcel under future climate change is positive. If conservation is required in the future period, then an additional Pigouvian payment is made to the landowner based on the land's contribution to ecosystem service benefits in the future period. Otherwise, the landowner is allowed to develop in the future period and earns a return from development.

The truth-revealing property of the auction mechanism arises because payments to the landowner under conservation are independent of their bid and based on the contribution to ecosystem service benefits. We show that it is a dominant strategy for landowners to set their bid equal to their development value, thereby revealing private information to the regulator. By bidding truthfully, the landowner receives Pigouvian payments for conservation whenever conservation benefits exceed development benefits. In effect, the auction payment internalizes the ecosystem service benefit externality. With knowledge of this stream of expected development values over time, the regulator can identify the set of parcels that maximizes the social benefits from the landscape in the current period, accounting for Arrow-Fisher style option values – the value of maintaining the option to conserve or develop parcels in the future depending on the future realization of climate change. With spatially-dependent benefits, the current and option value generated by an individual parcel, and hence the optimal 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. By using the auction to solve for optimal land use with uncertainty and irreversibility in a dynamic setting, our paper extends the literature using VCG-type auctions to address environmental and resource problems (Dasgupta et al. 1980, Montero 2008, PLPN 2014).[1]

We show that an optimal outcome can also be achieved by having the landowners bid for the right to develop. In this auction mechanism, the landowner pays the regulator a Pigouvian tax if they are allowed to develop, rather than being paid by the regulator if required to conserve. As in Coase (1960), an optimal outcome to an externality problem can be achieved regardless of how the initial property rights are defined. This flexibility is important, as a criticism of paying landowners to conserve is the potentially high cost to the regulator who may have a tightly constrained budget (Dreschler 2017; Hellerstein 2017). Defining the property rights differently at the outset disentangles budget or distributional concerns from efficiency concerns. Further, a mechanism designed for the case where the regulator holds the property rights to land is practically important, as the vast majority of the world's forests are government owned (Siry et al. 2009).

Our paper also relates to recent literature that examines conservation planning under climate uncertainty (e.g., Pressey et al. 2007, Heller and Zavaleta 2009, Lawler et al. 2015, Jones et al. 2016). Other analyses have focused on the risk aspect of conservation planning under climate change using portfolio approaches to minimize risk of habitat loss (e.g. Ando and Mallory 2012; Ando et al. 2018, Akter et al. 2015), examining how heterogeneity in threat and conservation value across landowners affects conservation priorities (e.g., Costello and Polasky 2004) and examining how risk aversion affects the prioritization of a budget-constrained conservation planner (Tulloch et al. 2015). None of these conservation planning papers deal with

[1] Jehiel and Modovanu (2005) provide a review of VCG-type mechanisms to find optimal solutions to private value models such as these. All of the prior literature finds optimal solutions in a static context.

asymmetric information regarding conservation costs, nor do they consider the combined problem of uncertainty and irreversible land-use change (with the exception of Costello and Polasky 2004). Arrow and Fisher (1974) show that when applied to a land conservation problem, the option value that arises from uncertainty and irreversibility has a similar effect to risk aversion by generating "a reduction in net benefits of development". (p. 315) Our paper is distinguished from other conservation under uncertainty papers by focusing on the design of an auction mechanism that truthfully reveals asymmetric information at the landowner scale in order to maximize the present value of the stream of social net benefits (as opposed to biophysical goals) from landscape pattern under uncertain climate change impacts and irreversible land-use change.

The rest of the paper is organized as follows. Section 2 introduces the basic setup and notation used in our spatial dynamic model. Section 3 develops a simple example of a three-parcel landscape over two time-periods to set ideas regarding optimal dynamic-spatial conservation. Section 4 introduces the auction mechanism where landowners are paid to conserve and shows that landowners have a dominant strategy to truthfully reveal private information allowing the regulator to implement an optimal solution to the dynamic land use problem. Section 5 revisits the simple example and illustrates how the auction mechanism works to achieve the optimal outcome. Section 6 shows how the auction mechanism can be reframed as a tax on development (tax) rather than a payment for conserving land (subsidy). Section 7 shows how risk aversion affects results. Section 8 offers concluding thoughts.

2. Setup and notation for the spatial dynamic model

There are N parcels in a landscape each owned by a different landowner. Each parcel i = 1 ,2, …, N, can either be developed or conserved. Let x_{it} be a binary variable indicating land-use status: $x_{it} = 0$ if parcel i is conserved in time period t and $x_{it} = 1$ if parcel i is developed in time period t. We consider a simple two period model, t = 1, 2. Development is irreversible so if $x_{i1} = 1$, then $x_{i2} = 1$. The pattern of development and conservation in the landscape at time t is represented by the vector $X_t = (x_{1t}, x_{2t}, \dots, x_{Nt})$ and represents an explicit spatial structure of land-use across a landscape. For example, suppose there are three parcels in a landscape and that in period t parcels 1 and 3 are developed and parcel 2 is conserved, then $X_t = (1, 0, 1)$. The vector X_t represents i) the amount of land allocated to conservation and development, as well as ii) the spatial pattern, including the fragmentation of conservation and development land uses.

Each parcel can contribute to the provision of an ecosystem service that is a public good (e.g., water quality or wildlife habitat) or a private good (e.g., production of agricultural crops). Landowner i earns development value d_{it} in period t from production of the private good if the land is developed, $x_{it} = 1$. The development value for parcel i in each period is known by the landowner of parcel i. We assume that the regulator and other landowners do not know d_{it} but have some prior beliefs about its distribution. If parcel i is conserved, the parcel contributes to the provision of the ecosystem service but does not earn the landowner any private return. The provision of the ecosystem service depends upon the pattern of conservation and development across the whole landscape, X_t. Let $B_1(X_1)$ represent the public value of the ecosystem service in period 1 and $B_2^s(X_2)$ represent the public value of the ecosystem service in period 2, where climate state $s \in S$ is the realization of the climate state in period 2 and S is the set of possible climate states. We assume that each land parcel makes a non-negative contribution to the ecosystem service if it is conserved. We assume the regulator knows the functions $B_1(X_1)$ and

$B_2^s(X_2)$, and knows the probability density function over possible climate states. The climate state for period 1 is assumed to be known when land-use decisions for period 1 are made. The climate state in period 2 is not known in period 1 but is revealed prior to when period 2 land-use decisions are made. We assume that landowners do not know $B_1(X_1)$ and $B_2^s(X_2)$ but have some prior beliefs about these functions. In the auction mechanism we describe below the equilibrium outcome is independent of the prior beliefs of the regulator and other landowners about the distribution of d_{it} for each *i*, and of the prior beliefs of landowners over the distribution of $B_1(X_1)$ and $B_2^s(X_2)$.

We assume that the objective of each risk-neutral landowner is to maximize the expected returns from their parcel, which consist of the private returns and net payments from the regulator. Alternatively, we could assume that some fraction of the public good accrues to the landowner but doing so adds notational complexity without changing the nature of the results. We assume the objective of the risk-neutral regulator is to maximize expected net social returns, which is equal to the sum of the value of public and private goods. The assumption that both the regulator and landowners are risk-neutral provides a simple and tractable approach to developing our mechanism. We recognize the possibility that either the regulator or the landowners could be risk-averse and we further discuss the issue of risk aversion in Section 7.

If the regulator knew the development value of each landowner, the regulator could solve for the optimal land-use pattern that maximizes expected net social returns. With full information about development values, the regulator could find the optimal land-use pattern over periods 1 and 2 by solving a stochastic dynamic programming problem. In period 2, the optimal land-use pattern for a given climate state *s* is given by:

$$X_2^{s*} = argmax\,[B^s(X_2) + \sum_{i=1}^{N} x_{i2} d_{i2}] \qquad (1)$$

$$s.t.\, x_{i2} \geq x_{i1} \text{ for all } i$$

where developed parcels contribute a social value of ($\sum_{i=1}^{N} x_{i2} d_{i2}$) to the landscape, while the pattern of conserved and developed parcels contribute a social value of $B^s(X_2)$ to the landscape. Let $V_2^s(X_1)$ represent the value of social benefits (conservation plus development benefits) in period 2 given the optimal period 2 land-use pattern for climate state s and the choice of X_1 in period 1. Note that period 1 choices only show up in the period 2 problem via the constraint that development is irreversible. Without this constraint, the period 2 problem can be solved independently of the period 1 problem. Note that we use an "*" throughout the paper to indicate an optimized landscape. The optimal land use choice in period 1 can then be found by solving

$$X_1^* = argmax[B(X_1) + \sum_{i=1}^{N} x_{i1} d_{i1}] + \delta E[V_2^s(X_1)]] \qquad (2)$$

where δ is the discount factor between periods and the expectation is taken over potential climate states in period 2.

We discuss how to solve this problem optimally given decentralized decision-making among N landowners who have private information about development value (d_{it}) in Section 4 below. First, however, we provide a simple example to illustrate ideas and demonstrate the challenge of finding the dynamically optimal landscape pattern with changing climate, spatial dependencies, and asymmetric information.

3. A simple example

Consider the example landscape shown in Figure 1 with three adjacent parcels and two time periods. The landscape is meant to represent a spatial grid, whereby parcel (1) is a neighbor to parcel (2), and parcel (2) is a neighbor to parcel (3). Benefits of development (top line) and conservation (bottom line) in period 1 are shown in figure 1a. The ecosystem service production function incorporates spatial dependency so that the conservation value for a parcel increases with more neighboring parcels conserved. The present value of the benefits of development for period 2 are identical to development benefits in period 1. The benefits of conservation in period 2 are uncertain and will take one of two values: a low value where the present value of conservation remains the same as in period 1, and a high value where the present value of ecosystem services from conserving parcels (1) and (3) are much greater when each parcel is adjacent to a conserved parcel (shown in figure 1b). The probability of the high value climate state is q, and the probability of the low value climate state is 1-q. In this example, a "high value climate state" could occur if climate change induces range shifts of wildlife species into this region that are sensitive to habitat fragmentation, and thus, there is greater future social value in having spatially contiguous habitat. A low value climate state could occur if the composition of wildlife species sensitive to habitat fragmentation are not greatly affected by climate change induced range shifts. For an empirical example of the uncertainty in projected wildlife range shifts under climate change scenarios, see Lawler et al. (2009).

Consider first the static version of the problem with period 1 values. Note that parcel (1) is always optimally conserved regardless of the conservation status of neighboring parcel (2) because the benefit of conserving the parcel with no neighboring conserved parcels (12) outweighs the benefits of development (10). Next, note that it is not optimal to conserve parcel (2) because the high value of development (25) outweighs the maximum possible benefit from conservation. The maximum benefit from conserving parcel (2) is 24 (15 for conserving parcel 2 with both neighbors conserved, an additional value of 3 on parcel 1 and 6 on parcel 3 for having a conserved neighboring parcel). Given that it is not optimal to conserve parcel (2), it is not optimal to conserve parcel (3) as the benefits of development (10) outweigh the benefits of conservation (9). The benefits for conserving parcel 1 and developing parcels 2 and 3 is: 12 + 25 + 10 = 47. Note that this value is higher than the value of conserving all three parcels: 15 + 15 + 15 = 45. Solving for the optimal choice requires information about both the benefits of conservation and development. Without both of these pieces of information it is not, in general, possible to solve for an optimal solution, a point to which we return below when we consider the problem of finding an optimal solution given asymmetric information.

Now consider the dynamic version of the problem and the solution to the stochastic dynamic programming problem. An important aspect of the dynamic problem is irreversible development – if a parcel is developed in period 1, it is not eligible for conservation in period 2. Following the backward induction logic of stochastic dynamic programming, consider the conservation decision in period 2 if all parcels are eligible for conservation. Under the low climate state ($s = s^l$), all benefits and costs are identical to period 1 and so the conservation decision is the same as described in the static case above: it is optimal to conserve parcel 1 and develop parcels 2 and 3. Under the high climate state ($s = s^h$), conservation benefits are higher than in the low climate state and we can check whether it is optimal to conserve parcels (2) and (3) versus developing them by comparing the value with all three parcels conserved with the value of conserving parcel (1) and developing parcels (2) and (3). Since the value of conserving all three parcels (20 + 15 + 20 = 55) is greater than the value of conserving parcel (1) while developing parcels (2) and (3) (12 + 25 + 10 = 47), it is optimal to conserve all three parcels in the high climate state.

Given that it is optimal to conserve all three parcels in period 2 in the high climate state but not the low climate state, should parcels (2) and (3) be conserved in period 1? Conserving all three parcels in period 1 generates a value of 45 (15 + 15 + 15). Conditional on all parcels being conserved in period 1, all parcels should be conserved in period 2 if $s = s^h$ and parcels 2 and 3 should be developed in period 2 if $s = s^l$. Therefore, the present value of conserving all parcels in period 1 is 45 + 55*q* + 47(1-*q*). On the other hand, developing parcels (2) and (3) in period 1 forecloses the option of conserving these parcels in period 2 so the present value of this alternative is 47 + 47. It is optimal to conserve all parcels in period 1 if 45 + 55*q* + 47(1-*q*) ≥ 47 + 47, which holds for *q* ≥ ¼.

There are several important take-away messages from this simple example. First, optimal choice requires information about the benefits of both conservation and development. Without both of these pieces of information one cannot compare the net benefits of conservation across alternatives. Since neither the regulator nor the landowners have all relevant information, no party can solve for the optimal solution given only their own information. Second, as in PLPN, the spatial dependencies in the ecosystem service benefits function mean that solving for the optimal landscape pattern requires information about the benefits of development and conservation *across multiple parcels*. The problem cannot, in general, be solved independently parcel by parcel. Even in this simple example the optimal decision of what to do on parcel (3) depends upon the decision of what to do on parcel (2). Third, while the static optimal conservation problem of PLPN only requires knowledge of current benefits of development and conservation, solving the stochastic dynamic programming problem for optimal conservation under climate change requires information regarding current and expected future benefits of development and conservation.

We now turn to the description of the auction mechanism that allows the regulator to gain information about the benefits of development and then to implement the optimal solution even with asymmetric information, spatial dependency, and climate change that causes uncertain changes in the benefits of conservation.

4. The Dynamic Subsidy Auction Mechanism

In this section, we describe an auction mechanism that generates an optimal solution, i.e., one that maximizes net social benefits. We assume the regulator commits to carrying out the auction mechanism. We also assume there is no collusion among landowners in the bidding process.

In period 1, each landowner i submits a bid with two parts, b_{it}, for t = 1, 2. Upon receiving the bids from landowners, the regulator chooses which bids to accept. If the bid is not accepted, the landowner is allowed to develop and earns d_{it} for t = 1, 2.[2] If the bid for parcel i is accepted, the landowner is required to conserve the parcel in period 1 and the regulator gives the landowner a payment based on the contribution of the parcel to the value of the ecosystem service. Upon learning the climate state in period 2, the regulator then either allows the landowner to develop or requires the landowner to continue to conserve. If development is allowed the landowner will develop and receive d_{i2}. With continued conservation in period 2, the

[2] Note that if the landowner prefers conservation to development then $d_{it} < 0$. As long as the marginal contribution to conservation from a parcel is positive, the landowner can bid 0 and the bid will always be accepted.

landowner receives an additional payment based on the contribution of the parcel to the value of the ecosystem service.

The payments to landowners whose parcels are conserved are set using the marginal social benefits of conserving the parcel. We define the marginal social benefits of conserving parcel *i* in period *t*, net of the parcel's development value, using the following steps.

Step 1: Define the period 1 and period 2 social benefits when parcel *i* is conserved as:

$$W_{i1}(X_{i1}^{*}) = B_1(X_{i1}^{*}) + \sum_{j\neq i} x_{ij1}^{*} d_{j1} \tag{3a}$$

$$W_{i2}^{s}(X_{i2}^{*s}) = B_2^{s}(X_{i2}^{*s}) + \sum_{j\neq i} x_{ij2}^{*s} d_{j2} \tag{3b}$$

where X_{i1}^{*} and X_{i2}^{*s} are the optimal landscape patterns in periods 1 and 2 (consistent with equations 1 and 2), x_{ij1}^{*} and x_{ij2}^{*s} are the optimal choice for parcel *j* for all $j \neq i$ in periods 1 and 2, when choice is constrained to have parcel *i* conserved. Note that for parcel *i* to be conserved in period 2 it must be conserved in period 1.

Step 2: Define the period 1 and 2 social benefits when parcel *i* is developed net of the private development benefits of parcel *i* as:

$$W_{\sim i1}(X_{\sim i1}^{*}) = B_1(X_{\sim i1}^{*}) + \sum_{j\neq i} x_{\sim ij1}^{*} d_{j1} \tag{4a}$$

$$W_{\sim i2}^{s}\left(X_{\sim i2}^{*s}|_{x_{i1}}\right) = B_2^{s}\left(X_{\sim i2}^{*s}|_{x_{i1}}\right) + \sum_{j\neq i}(x_{\sim ij2}^{*s}|_{x_{i1}}) d_{j2} \tag{4b}$$

where $X_{\sim i1}^{*}$ is the optimal landscape pattern and $x_{\sim ij1}^{*}$ is the optimal choice for parcel *j* for all $j \neq i$ in period 1 when choice is constrained to have parcel *i* developed in period 1; $X_{\sim i2}^{*s}|_{x_{i1}}$ is the optimal landscape pattern and $x_{\sim ij2}^{*s}|_{x_{i1}}$ is the optimal choice for parcel *j* for all $j \neq i$ in period 2 conditional on the choice of x_{i1}, for $x_{i1} = 0$ or 1. We use the "~i" notation to indicate that parcel *i* is not conserved, i.e., *i*'s land-use status is held fixed at developed ($x_{it} = 1$).

Step 3: The period 1 and 2 marginal social benefits of conserving parcel *i* are defined as the difference between the social benefits defined in steps 1 and 2:

$$\Delta W_{i1} = W_{i1}(X_{i1}^{*}) - W_{\sim i1}(X_{\sim i1}^{*}) \tag{5a}$$

$$\Delta W_{i2}^{s}|_{x_{i1}} = W_{i2}^{s}(X_{i2}^{*s}) - W_{\sim i2}^{s}\left(X_{\sim i2}^{*s}|_{x_{i1}}\right). \tag{5b}$$

The optimal landscape pattern in steps 1 and 2 can differ by more than just adding or dropping conservation from parcel *i* as doing so may change the conservation value of other parcels and therefore the optimal choice of conservation on other parcels -- $X_{\sim i2}^{*s}|_{x_{i1}=0}$ is not necessarily the same landscape pattern as $X_{\sim i2}^{*s}|_{x_{i1=1}}$. The period 2 marginal benefits of conserving parcel *i* must therefore be conditioned on whether parcel *i* is conserved or developed in period 1, $\Delta W_{i2}^{s}|_{x_{i1}}$.

To define the auction, we specify the rules used by the regulator for deciding which parcels to enroll in conservation and the payment to landowners who have enrolled parcels. Because achieving an optimal solution that maximizes net social benefits requires the regulator to know the development value, the auction mechanism is designed to induce each landowner to truthfully reveal their development value in each period. Assuming the regulator knows the development value for each parcel, the regulator can solve the stochastic dynamic programming problem described in Section 2. Using the definitions in equations (3) and (4), the dynamic optimality condition for enrolling parcel *i* in conservation in period 1 is

$$W_{i1}(X_{i1}^{*}) + \delta E_S\left\{max\left[W_{i2}^{s}(X_{i2}^{*s}), W_{\sim i2}^{s}\left(X_{\sim i2}^{*s}|_{x_{i1}=0}\right) + d_{i2}\right]\right\} \geq$$

$$W_{\sim i1}\left(X^{*}_{\sim i,t}\right) + d_{i1} + \delta\left(E_S W^{s}_{\sim i2}\left(X^{*s}_{\sim i2}|_{x_{i1}=1}\right) + d_{i2}\right) \tag{6}$$

where E_S is the expectation operator over the set of all possible climate states *s* in *S*. The first term on the left side of equation (6), $W_{i1}(X^{*}_{i1})$, is the period 1 optimal social benefits given that parcel *i* is conserved, while the second term on the left side of equation (6), $\delta E_S\left\{max\left[W^{s}_{i2}(X^{*s}_{i2}), W^{s}_{\sim i2}\left(X^{*s}_{\sim i2}|_{x_{i1}=0}\right) + d_{i2}\right]\right\}$, is the expected optimal social benefits in period 2 given that parcel *i* was conserved in period 1. When conservation is chosen in period 1, the regulator can flexibly alter the conservation decision in period 2 in response to future climate information (Arrow and Fisher 1974, Albers 1996). If parcel *i* is optimally conserved under climate state *s*, the future landscape optimal social benefits are $W^{s}_{i2}(X^{*s}_{i2})$; if parcel *i* is optimally developed under climate state *s*, the future landscape optimal social benefits are $W^{s}_{\sim i2}\left(X^{*s}_{\sim i2}|_{x_{i1}=0}\right) + d_{i2}$. The right side of equation (6) is the period 1 optimal social benefits given that parcel *i* is developed, $W_{\sim i1}\left(X^{*}_{\sim i,t}\right) + d_{i1}$, plus the expected social benefits in period 2 given that parcel *i* is developed in period 1, $\delta\left(E_S W^{s}_{\sim i2}\left(X^{*s}_{\sim i2}|_{x_{i1}=1}\right) + d_{i2}\right)$.

Define S^{*} as the set of climate states where parcel *i* is optimally conserved in period 2 given that it was conserved in period 1, and define S' as the set of climate states where parcel *i* is optimally developed in period 2 given that it was conserved in period 1. Further, define the change in period 2 benefits when parcel *i* is developed in period 2 that arise from different choices on other parcels when parcel *i* is conserved versus developed in period 1: $\Delta W^{s}_{\sim i2} = W^{s}_{\sim i2}\left(X^{*s}_{\sim i2}|_{x_{i1}=0}\right) - W^{s}_{\sim i2}\left(X^{*s}_{\sim i2}|_{x_{i1}=1}\right)$. With these definitions, equation (6) can be re-arranged:

$$\Delta W_{i1} + \delta q E_{s\in S^{*}}\left\{\Delta W^{s}_{i2}|_{x_{i1}=1} - d_{i2}\right\} + \delta(1-q)E_{s\in S'}\{\Delta W^{s}_{\sim i2}\} \geq d_{i1} \tag{7}$$

where q is the probability that it is optimal to conserve parcel i in period 2 given that it was conserved in period 1. The middle term, $\delta q E_{s\in S^*}\left\{\Delta W_{i2}^s|_{x_{i_1}=1} - d_{i2}\right\}$, represents the discounted option value of being able to conserve parcel i in period 2 should climate conditions warrant it (Arrow and Fisher 1974). This term is zero if parcel i is never optimally conserved in period 2. As defined in equation (5b), $\Delta W_{i2}^s|_{x_{i1=1}}$ is the marginal benefit of conserving parcel i in period 2: $\Delta W_{i2}^s|_{x_{i1=1}} = W_{i2}^s(X_{i2}^{*s}) - W_{\sim i2}^s\left(X_{\sim i2}^{*s}|_{x_{i_1}=1}\right)$. The third term, $\delta(1-q)E_{s\in S'}\{\Delta W_{\sim i2}^s\}$ represents the expected potential change in discounted period 2 social benefits arising from potentially different conservation choices on other parcels in period 2 when parcel i is conserved versus developed in period 1. Equation (7) can be slightly rearranged to be more convenient for the discussion that follows:

$$\Delta W_{i1} + \delta q E_{s\in S^*}\left\{\Delta W_{i2}^s|_{x_{i_1}=1}\right\} + \delta(1-q)E_{s\in S'}\{\Delta W_{\sim i2}^s\} \geq d_{i1} + \delta q d_{i2} \quad (8)$$

With this groundwork in place we now formally define the auction mechanism.

Subsidy Auction Mechanism:

- At the beginning of period 1, each landowner i =1, 2, …, N, submits a two-part bid, b_{i1} and b_{i2}.
- In period 1, the regulator accepts the bid from landowner i if and only if

$$\Delta W_{i1} + \delta q E_{s\in S^*}\left\{\Delta W_{i2}^s|_{x_{i_1}=1}\right\} + \delta(1-q)E_{s\in S'}\{\Delta W_{\sim i2}^s\} \geq b_{i1} + \delta q b_{i2} \quad (9)$$

  where the calculation of the optimal landscapes is done assuming that $b_{jt} = d_{jt}$ for all j =1, 2, …, N, and t = 1, 2.

- If the bid from landowner i is accepted, the landowner receives

$\Delta W_{i1} + \delta(1-q)E_{s\in S'}\{\Delta W^{s}_{\sim i2}\}$ in period 1.

- With enrollment in the conservation program, the landowner also agrees to allow the regulator to decide the conservation status of the parcel in period 2. In period 2, the regulator observes climate state *s* for period 2 and then decides whether to continue conservation on the parcel in period 2 or allow development.
  - If parcel *i* is optimally conserved in period 2 ($s \in S^*$), the regulator then pays the landowner $\Delta W^{s}_{i2}|_{x_{i1}=1}$.
  - If parcel *i* is not optimally conserved in period 2 ($s \in S'$), the landowner is paid zero but is allowed to develop and earns d_{i2}.

Showing that the auction mechanism will achieve an optimal solution involves proving two claims. First, it must be the case that all landowners truthfully reveal development value in their bids ($b_{it} = d_{it}$, *i* = 1, 2, …, *N*, and *t* = 1, 2). Second, given this information the regulator optimally chooses which parcels to conserve and which to allow to develop. In the following propositions we show that the auction mechanism satisfies both claims.

Proposition 1. Under the subsidy auction mechanism described above, each landowner *i*, *i* = 1, 2,…, *N*, has a dominant strategy to bid $b_{it} = d_{it}$ for *t* = 1, 2.

Proof. See Appendix A.

The intuition for the proof of proposition 1 is as follows. First, consider the intuition for why truthful bidding in period 2 is a dominant strategy. Figure 2 depicts the potential losses from overbidding and from underbidding. By not bidding truthfully, the landowner alters the future climate states in which the regulator accepts the bid such that they deviate from having bids accepted for the set of $s \in S^*$.[3] However, since truthful bidding under the auction mechanism ensures the landowner always maximizes their payoffs for any given climate state – seen with the bold line in figure 2 – then any deviations from truthful bidding will alter their payoffs such that the landowner is worse off than with truthful bidding of the period 2 development value. Similarly in period 1, the landowner can change whether the bid is accepted by changing the bid, but not the payment if the bid is accepted. By not bidding truthfully, the landowner will cause a deviation from the acceptance set that maximizes the landowner's expected payoffs. Hence, bidding truthfully is a dominant strategy and a landowner will maximize their expected returns by bidding truthfully.

Using the result that landowners will bid truthfully, we now prove the main result of the paper that the auction mechanism will generate an optimal dynamic landscape that maximizes the sum of the values of ecosystem services plus private goods.

Proposition 2. The subsidy auction mechanism generates an optimal dynamic landscape that maximizes the sum of ecosystem service value plus private goods value.

Proof. See Appendix B.

The subsidy auction mechanism generates an optimal outcome because it provides incentives for landowners to truthfully reveal their private information, which then allows the regulator to choose the outcome with the highest social net benefits. Another interpretation of the subsidy auction mechanism is that it is a form of a Pigouvian subsidy that promises to pay the landowner an amount equal to their contribution to the public good provided by the ecosystem service, thereby internalizing positive externalities from conserving the landowner's parcel.

[3] If the landowner overbids (underbids), then the regulator accepts the bid in fewer (more) climate states than S^*.

5. Simple Example Revisited

We revisit the simple example from Section 3 to illustrate the subsidy auction mechanism. Table 1 shows the calculation of each component necessary to form the optimal payment for each parcel of land. In this example, note that the term $\Delta W^{s}_{\sim i2} = W^{s}_{\sim i2}\left(X^{*s}_{\sim i2}|_{x_{i1}=0}\right) - W^{s}_{\sim i2}\left(X^{*s}_{\sim i2}|_{x_{i1}=1}\right)$ is zero for all three parcels since the period t = 2 social benefits when parcel i is developed net of the private development benefits of parcel i are the same whether parcel i is initially conserved in t = 1 or not: $W^{S}_{\sim i2}(X^{*}_{\sim i2})|_{x_{i1}=0} = W^{S}_{\sim i2}(X^{*}_{\sim i2})|_{x_{i1}=1}$ for all i. Consider the incentives offered to the landowner of parcel 2 in the auction. In period 1, ΔW_{21} = 23, which is less than the period 1 development value d_{21} = 25. However, by conserving in t = 1, the landowner preserves the period 2 option to be paid marginal benefits of conservation $\Delta W^{s^h}_{22}$ = 33 if climate state s^h occurs, or to develop and earn d_{22} = 25 if climate state s^l occurs. By developing in period 1, landowner 2 would earn d_{22} = 25 with certainty in period 2. Landowner 2 gains an expected value of 8q in period 2 by conserving in period 1, where q is the probability of the high climate state. So, conserving parcel 2 in period 1 is optimal for the landowner of parcel 2 if 8q ≥ 2, or q ≥ ¼, which is the socially optimal solution as shown in Section 3. Further, the components of their payment (ΔW_{i1}, $\Delta W^{s^h}_{22}, q$) are exogenous to their bid, and a landowner cannot increase their returns by under-or over-bidding as in the original Vickrey auction.

6. The Dynamic Auction Tax Mechanism

This section defines a dynamic auction tax mechanism which is most appropriately used when the government owns land and must therefore be paid by individuals who want to develop.

Significant shares of many landscapes are owned by governments rather than private individuals. For example, it has been estimated that 86% of the world's forests are owned by governments (Siry et al. 2009). Sweden and the United States have a relatively low amount of public forestland ownership at 20 and 42% respectively, while other countries like China and Russia have 100% of forest land government owned. Rangelands – including grasslands – also tend to have significant government ownership, as close to half of U.S. rangelands are government owned (federal, state, local)[4] and all of China's grasslands – comprising 40% of the country's land area (Kang et al. 2007) – are government owned. Further, many governments auction the development or use rights of some of their publicly-owned forest and grasslands to the highest bidder, e.g. U.S. Forest Service timber auctions, U.S. Bureau of Land Management grazing auctions, etc. Auctions are often used to allocate development or use of public lands. While most contemporary auctions are designed to maximize the government's rents from developing public lands, we show how a simple modification of the subsidy auction mechanism discussed in the prior section can be made into a tax auction mechanism that can be used to implement the dynamically optimal provision of ecosystem services under climate change.

In the tax auction, the landowner submits a bid b_{it} for the right to develop parcel *i* in *t* = 1, 2. The previously defined marginal benefits of conserving parcel *i* today (ΔW_{i1}) and in the future under climate state *s* ($\Delta W_{i2}^{s}|_{x_{i1}=1}$) are now interpreted as environmental damages from developing parcel *i*. The bid to allow development is accepted and development occurs in period 1, which then allows developed use in both periods 1 and 2, if and only if

$$\Delta W_{i1} + \delta q E_{s\in S^*}\left\{\Delta W_{i2}^{s}|_{x_{i1}=1}\right\} + \delta(1-q)E_{s\in S'}\{\Delta W_{\sim i2}^{s}\} < b_{i1} + \delta q b_{i2}. \qquad (10)$$

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[4] See the U.S. Forest Service, https://www.fs.fed.us/rangeland-management/aboutus/index.shtml (accessed 6/24/17).

Development should be approved in period 1 if the value of development over the two periods is greater than the expected loss in the value of ecosystem services in period 1 plus the loss in option value from not being able to optimally choose between conservation and development in period 2, plus the loss (or gain) in the expected value of ecosystem services in period 2 due to the development of parcel *i* in period 1. Since development is irreversible, a landowner who is granted development rights in period 1 will pay a tax in period 1 of $\Delta W_{i1} + \delta(1-q)\, E_{s\in S'}\{\Delta W^{s}_{\sim i2}\}$, and in the second period once the climate state has been realized, the landowner will pay an additional tax of $\Delta W^{s}_{i2}|_{x_{i1}=1}$ if the parcel *would have been* optimally conserved were it not irreversibly developed in the first period ($s \in S^*$ occurs). The tax requires the regulator to calculate $\Delta W^{s}_{i2}|_{x_{i1}=1}$ in period 1 for all *s*, and then commit to taxing the landowner the appropriate amount depending on the realization of *s*. From the perspective of period 1, the landowner who develops expects to pay a tax in period 2 of $\delta q E_{s\in S^*}\{\Delta W^{s}_{i2}|_{x_{i1}=1}\}$. Note that the tax includes both the change in the value of period 1 ecosystem services and the change in the discounted expected period 2 benefits had the parcel been conserved in period 1. If the bid is not accepted in period 1, then the landowner's development request is reconsidered in period 2 once the climate state *s* has been realized. The landowner is allowed to develop in period 2 if $\Delta W^{s}_{i2}|_{x_{i1}=1} < b_{i2}$, and is required to pay a tax of $\Delta W^{s}_{i2}|_{x_{i1}=1}$. If $\Delta W^{s}_{i2}|_{x_{i1}=1} > b_{i2}$, the landowner is not allowed to develop in period 2 and the parcel remains conserved.

The dynamic auction tax mechanism generates the same incentives for the landowner to set their bid equal to their development value d_{it} because their tax payment in each period is independent of their bid. This dynamic tax mechanism also generates the same dynamically-optimal land-use outcome as the subsidy in that development occurs in $t = 1$ if equation (10) holds. Similar to Coase (1960), the main difference between the auction tax and the auction subsidy mechanism is who pays whom: the landowners pay the regulator under the tax, while the regulator pays the landowners under the subsidy. The optimal land-use pattern can be implemented with either mechanism.

7. Risk Aversion

To this point, we have assumed that the regulator and landowners are risk neutral. Here we show how risk aversion affects the main results of the paper. As the general analysis with risk aversion is quite messy, we use the simple example developed in Sections 3 and 5 to illustrate results.

Here we assume that the regulator has a concave utility function that exhibits constant absolute risk aversion: $U(SR) = 1 - e^{-\alpha SR}$, where SR represents net social returns and we set the constant $\alpha = 0.05$. In the simple example from Section 3 conserving parcel (1) dominates developing parcel (1), and it never makes sense to conserve either parcel (2) or parcel (3) without conserving the other, so we can find the optimal solution by comparing results when all parcels are conserved versus conserving only parcel (1) in period 1. Conserving all three parcels in period 1 generates a period one return of 45 (15+15+15; Fig. 1). Conditional on all parcels being conserved in period 1, all parcels should be conserved in period 2 if $s = s^h$ with a return of 55 (20+15+20; Fig. 1), and parcels 2 and 3 should be developed in period 2 if $s = s^l$ with a return of 47 (12+25+10; Fig. 1). Therefore, the present value of expected utility of conserving all parcels in period 1 is

$$U(45) + q\,U(55) + (1\text{-}q)U(47) = 0.8946 + 0.9361q + 0.9046(1\text{-}q) = 1.7992 + 0.0315q.$$

On the other hand, developing parcels (2) and (3) in period 1 forecloses the option of conserving these parcels in period 2 so the present value of expected utility in this case is

$U(47) + U(47) = 0.9046 + 0.9046 = 1.8092.$

It is optimal to conserve all three parcels in period 1 when

$$1.7992 + 0.0315q \geq 1.8092; \quad q \geq 0.319.$$

Note that the range of probabilities for the high climate state (q) for which it is optimal to conserve all parcels in period 1 is reduced in the case with risk aversion as compared to the risk neutral case ($q \geq 0.25$). In our model, the value of development is constant while the value of conservation varies with the climate state. Therefore, conservation is less desirable relative to development when the regulator is risk averse.

Though risk aversion changes what is viewed as optimal, it is still possible to implement the optimal outcome using the auction mechanism. Consider the case where each landowner has the same constant absolute risk aversion utility function as the regulator: $U(SR) = 1 - e^{-\alpha SR}$. As shown in Section 5, the key landowner is the owner of parcel (2). With conservation of all parcels in period 1, landowner 2 receives a payment of 23, and in period 2 receives a payment of 33 if climate state s^h occurs, which happens with probability q, or is allowed to develop and earn a payoff of 25 if climate state s^l occurs. If landowner 2 develops in period 1, they earn a payoff of 25 in each period. Landowner 2 is better off with conservation (assuming parcels 1 and 3 also conserve) when

$$U(23) + q\,U(33) + (1-q)U(25) \geq U(25) + U(25)$$

$$0.6834 + 0.8080q + (1-q)0.7135 \geq 0.7135 + 0.7135$$

$$q \geq 0.319.$$

As in Section 5, the incentives for the landowner align with the incentives of the regulator. The landowner wants to conserve if and only if the regulator does, which is the key condition for the proof of Proposition 2 in section 4. As with risk neutrality, the auction mechanism can implement the optimal land use pattern.

With non-constant absolute risk averse utility, however, risk aversion will introduce slight differences between conditions when the regulator views it optimal to conserve and when the landowner will find that conservation maximizes their expected utility. For example when utility of both regulators and private landowners takes the form $U(SR) = ln(SR)$, the regulator will find it optimal to conserve all parcels in period 1 when $q \geq 0.277$. The landowner of parcel (2), however, will find it optimal to conserve when $q \geq 0.300$. Therefore, there is a small range of potential outcomes ($0.277 \leq q \leq 0.300$) for which truthful bidding by the landowner will result in a bid being accepted by the regulator but for which the landowner is worse off with conservation. The landowner now has an incentive to overbid to dissuade the regulator from accepting bids that are socially desirable but privately undesirable.

Risk aversion can affect outcomes in a couple of important ways. First, risk aversion affects the optimal land-use pattern. A risk averse regulator will tend to conserve less land and allow more development relative to a risk neutral regulator because the value of development is constant while the value of conservation is uncertain and varies with the climate state. Second, risk aversion may interfere with the ability of the regulator to implement the first best solution via the auction mechanism. The intuition for this result is that with non-constant absolute risk aversion it is no longer possible to match up the desirability of private and public returns, as is possible with risk neutrality or with constant absolute risk aversion.

8. Discussion

In this paper we defined an auction mechanism that implements an optimal dynamic landscape pattern where net benefits include an ecosystem service that is a public good whose benefits change through time depending on the landscape pattern and climate change, and a private good whose value is private information to the landowner. The auction is designed so that individual landowners truthfully reveal private information about returns to development. With this information, the regulator can then implement the optimal dynamic landscape pattern. The auction can be designed as a subsidy auction that pays landowners to conserve or a tax auction where landowners have to pay for the right to develop.

The dynamic auction mechanism developed in this paper, along with that of the static PLPN paper, differs from most prior work on conservation auctions in one simple but fundamental way. Here we are interested in using an auction mechanism to find an optimal solution that maximizes social net benefits. Much of the prior literature on conservation auctions focuses on minimizing the government's costs of achieving a conservation target or maximizing a conservation goal given a fixed budget (Latacz-Lohman and van der Hamsvoort 1997, Arnold et al. 2013, Drechsler 2017). Other papers focus on the performance of mechanisms such as the agglomeration bonus (Parkhurst et al. 2002, Parkhurst and Shogren 2007, Drechsler et al. 2010, Banerjee et al. 2014) or other voluntary incentive programs (Lewis et al. 2011). See de Vries and Hanley (2016) for a recent review of this literature. But solving these problems does not ensure achieving an optimal outcome. Government payments to landowners are transfer payments. Absent distributional concerns, transfer payments net to zero in social net benefit calculations.

With asymmetric information, reducing payments to landowners to guard against paying more than is necessary will lead to not paying enough to some landowners for whom conservation is efficient. A focus on minimizing government expenditures rather than maximizing social net benefits results in an efficiency loss. Our approach using auctions to achieve optimal dynamic conservation fits conservation planning squarely into the realm of classical environmental economics, which involves devising policy mechanisms to internalize externalities and achieve a socially optimal solution.

In our approach, concerns over the distribution of benefits and costs can be addressed by the appropriate use of subsidy or tax auctions. As in Coase (1960), we show that an optimal solution can be achieved regardless of how initial property rights are defined. While some landscapes are dominated by privately owned land (e.g. the U.S. Midwest), much of the world's environmentally important forests and grasslands are government owned, making the tax auction an important practical policy mechanism for many landscapes.

This paper uses a two-period framework to develop insights into the dynamic auction mechanism. This two-period framework could be thought of as representing a more general dynamic framework where uncertainty about the benefits function is reduced at a future time t^*, where $t < t^*$ is "period 1" and $t \geq t^*$ is "period 2." With this view, costs and benefits in period 1 include the present discounted value of the stream of costs and benefits for $t < t^*$, while period 2 include the present value of costs and benefits for $t \geq t^*$. The model could be extended to multiple periods with multiple resolutions of uncertainty or to a continuous time approach (Dixit and Pindyck 1994).

The auction mechanism requires landowners to bid current and future development values. This is akin to landowners simply bidding the sale price of land, since the sale price capitalizes the discounted stream of annualized rents that the land is expected to produce. Properly decomposing a capitalized price into a stream of rents requires information on the discount rate and the expected time path of rents. In the simplest case of constant annual rents, the annual rent simply equals the discount rate multiplied by the capitalized price. In the more complex case where the price of undeveloped land capitalizes future development rents that would occur at some future date, there has been econometric work on how to decompose current prices into rents from undeveloped land and expected future rents (e.g. Plantinga et al. 2002).

The mechanism in this paper assumes that future development values are known with certainty and not a function of the future climate state or other uncertainties. This assumption is useful for clarifying the key elements of a mechanism to implement optimal dynamic conservation. Our mechanism can accommodate uncertain future development values as long as the uncertainty is symmetric and landowners are risk neutral. For example, the auction mechanism implements an optimal outcome for the case where the development value in period 2 is given by $d_{i2} = \bar{d}_{i2} + \varepsilon_{i2}^{S}$, where $\bar{d}_{i2}$ is the development value that the landowner expects to receive in period 2 given information available in period 1, and ε_{i2}^{S} is a random variable with mean zero, and whose realization in *t* = 2 is observed by the government and the landowner once the climate state is revealed. In this case, a risk-neutral landowner makes a bid in period 1 based on expected value and in period 2 whether conservation is required or not depends on the realization of climate variable. However, if ε_{i2}^{S} is private information that the landowner will learn but that the regulator will not, then another truth-revealing auction mechanism would need to be developed for *t* = 2. Analysis of such a model is beyond the scope of this paper.

There are two other conditions needed to ensure that the auction mechanism generates an optimal outcome. First, the regulator must commit to carrying out the auction in both periods and not change the rules once bids are revealed. In particular, the government cannot reduce payments to match revealed costs as this would destroy the truth-telling properties of the auction. Second, we have assumed that landowners cannot collude. Although it is theoretically possible for landowners to game the auction by colluding, doing so in practice would be quite difficult. As noted in PLPN, successful collusion requires that a set of landowners have information about the benefits of conservation as well as development values for other landowners, and can then manipulate their bids, here by underbidding costs, to try to win conservation opportunities at the expense of other landowners. Underbidding is risky, however, and may result in "winning" a conservation payment that is worth less than the value of development. See Montero (2008) for analysis of an optimal solution with potential collusion within a VCG-type auction.

It is not always necessary to have a dynamic mechanism even with a dynamically changing environment. There are two types of dynamic problems where the static auction mechanism developed in PLPN is sufficient for obtaining an optimal outcome. First, if all future costs and benefits are known with certainty, then the PLPN mechanism can accommodate a dynamic problem by treating all costs and benefits in terms of present values of the stream of future costs and benefits. Even when optimal landscape patterns change through time, the dynamic landscape pattern can be determined from the first period (e.g., an optimal control solution to a dynamic problem). Second, if development is reversible at no cost, then the conservation problem can be revisited every period with the PLPN mechanism. In contrast, the static PLPN auction mechanism is insufficient when i) development is irreversible, or reversible at some cost, and ii) the benefits of the future landscape are uncertain. As in Arrow and Fisher

(1974) it is the combination of uncertainty and irreversibility that gives rise to option value. The dynamic auction mechanism developed in this paper is most applicable to problems of managing development decisions that are to some degree irreversible in the face of climate change induced shifts in ecosystem service production functions.

Conservation and land-use planning for provision of ecosystem services under climate change is an important and practical policy problem with implications for the ability of society to adapt to climate change and make ecosystems and human society more resilient. This paper provides a direct method for internalizing dynamic-spatial externalities, which is an important part of improving adaptation outcomes for society under climate change.

Figure 1. Benefits of development and conservation for a three parcel example. The top number in each cell represents the value to developing the parcel. The bottom numbers indicate the value of ecosystem services when the parcel is conserved. The first number in the bottom row indicates the value of ecosystem services when no neighboring parcel is conserved. The second number in the bottom row indicates the value of ecosystem services with one neighboring parcel conserved. For parcel 2, the third number in the bottom row indicates the value of ecosystem services with two neighboring parcel conserved. The probability of the high value climate state is q and the probability of the low value climate state is $1 - q$.

1a Benefits of development and conservation in period 1. The present value of the benefits of development and conservation in time period t=2 remain the same with the low value climate state.

Parcel	Parcel 1	Parcel 2	Parcel 3
Development value	10	25	10
Conservation value	12 15	12 13 15	9 15

1b The present value of benefits of development and conservation in period 2 with the high value climate state.

Parcel	Parcel 1	Parcel 2	Parcel 3
Development value	10	25	10
Conservation value	12 20	12 13 15	9 20

Figure 2. Potential losses from over-bidding or under-bidding future (t=2) costs.

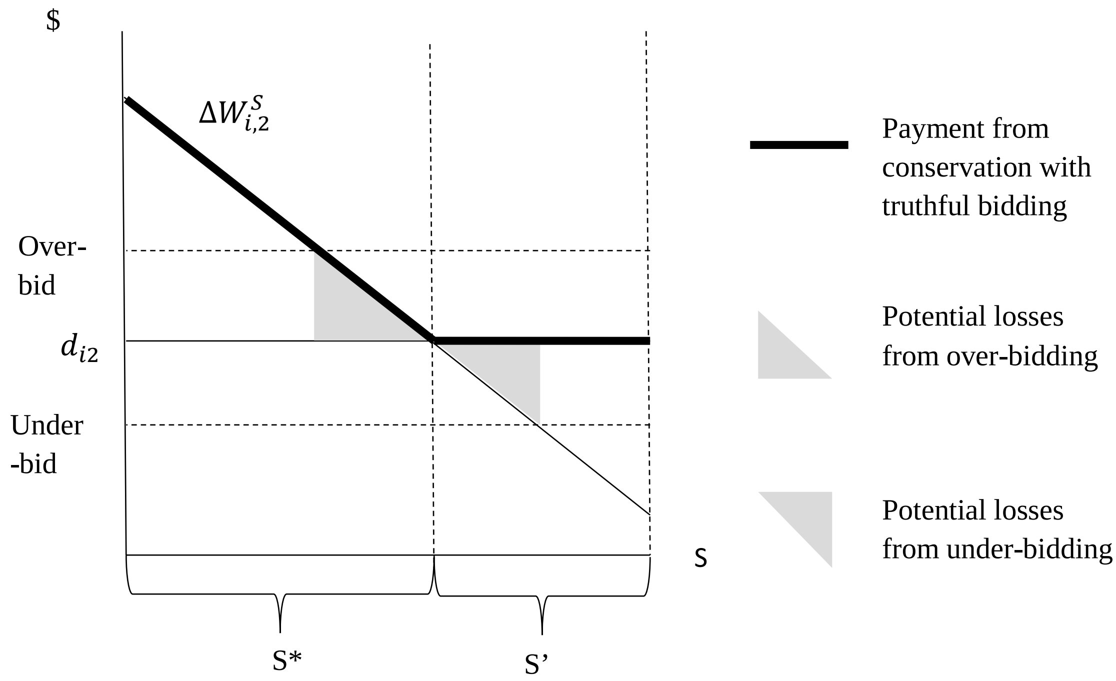

Table 1. Optimal payments in the simple example

1.a Period *t*=1 and in *t*=2 under low climate state s^l

Parcel	d_{it}	X^*_{it}	$W_{it}(X^*_{it})$	$X^*_{\sim it}$	$W_{\sim it}(X^*_{\sim it})$	ΔW_{it}
1	10	(1)	47	-	35	12
2	25	(1), (2), (3)	45	(1)	22	23
3	10	(1), (3)	46	(1)	37	9

1.b Period *t*=2 under high climate state s^h

Parcel	d_{i2}	X^*_{i2} if s^h	$W_{i2}(X^*_{i2})$	$X^*_{\sim i2}$	$W_{\sim i2}(X^*_{\sim i2})$	ΔW_{i2}
1	10	(1), (2), (3)	55	-	35	20
2	25	(1), (2), (3)	55	(1)	22	33
3	10	(1), (2), (3)	55	(1)	37	18

References

Akter, S., T. Compas, and M.B. Ward. 2015. Application of portfolio theory to asset-based biosecurity decision analysis. *Ecological Economics* 117: 73-85.

Albers, H.J. 1996. "Modeling ecological constrains on tropical forest management: Spatial interdependence, irreversibility, and uncertainty." *Journal of Environmental Economics and Management*, 30: 73-94.

Ando, A.W. and M.L. Mallory. 2012. "Optimal portfolio design to reduce climate-related conservation uncertainty in the Prairie Pothole Region." *Proceedings of the National Academy of Sciences*, *109*(17), 6484-6489.

Ando, A., A. Howlader, and M. Mallory. 2018. "Diversifying to reduce conservation outcome uncertainty in multiple environmental objectives." *Agricultural and Resource Economics Review*. https://doi.org/10.1017/age.2018.7

Armsworth, P.R., B.E. Kendall, and F.W. Davis. 2004. "An introduction to biodiversity concepts for environmental economists." *Resource and Energy Economics*, 26(2), 115-136.

Arnold, M.A., J.M. Duke, and K.D. Messer. 2013. "Adverse selection in reverse auctions for ecosystem services." *Land Economics,* 89: 387-412.

Arrow, K., and A. Fisher. 1974. "Environmental preservation, uncertainty, and irreversibility." *Quarterly Journal of Economics*, 88: 312-319.

Barbier, E. 2007. "Valuing ecosystem services as productive inputs." *Economic Policy* 22: 177-209.

Banerjee, S., F.P. de Vries, N. Hanley, and D.P. van Soest. 2014. "The impact of information provision on agglomeration bonus performance: An experimental study on local networks." *American Journal of Agricultural Economics*, 96: 1009-1029.

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

Coase, R.H. 1960. "The problem of social cost." *Journal of Law and Economics*, 3(1): 1-44.

Costello, C. and S. Polasky. 2004. "Dynamic reserve site selection.**"** *Resource and Energy Economics* 26(2): 157-174.

Costello, C. and S. Polasky. 2008. "Optimal harvesting of stochastic spatial resources." *Journal of Environmental Economics and Management*, 56(1): 1-18.

Dasgupta, P., P. Hammond, and E. Maskin. 1980. "On imperfect information and optimal pollution control." *Review of Economic Studies*, 47(5): 857–60.

de Vries, F.P., and N. Hanley. 2016. “Incentive-based policy design for pollution control and biodiversity conservation: A review.” *Environmental and Resource Economics*, 63(4): 687-702.

Dixit, A.K., and R.S. Pindyck. 1994. *Investment Under Uncertainty*. Princeton University Press, Princeton, NJ.

Drechsler, M. 2017. “Generating spatially optimized habitat in a trade-off between social optimality and budget efficiency.” *Conservation* Biology, 31(1): 221-225.

Dreschsler, M., F. Wätzold, K. Johst, and J.F. Shogren. 2010. “An agglomeration payment for cost-effective biodiversity conservation in spatially structured landscapes.” *Resource and Energy Economics*, 32(2): 261-275.

Fahrig, L. 2003. “Effects of habitat fragmentation on biodiversity.” *Annual Review of Ecology, Evolution, and Systematics*, 34: 487-515.

Groves, T. 1973. “Incentives in teams.” *Econometrica*, 41: 617-631.

Hanemann, W.M. 1989. “Information and the concept of option value.” *Journal of Environmental Economics and Management*, 16(1): 23-37.

Henry, C. 1974. “Investment decisions under uncertainty: the ‘irreversibility effect.’” *American Economic Review*, 64(6): 1006-1012.

Heller, N.E. and E.S. Zavaleta. 2009. “Biodiversity management in the face of climate change: A review of 22 years of recommendations.” *Biological Conservation* 142: 14–32.

Hellerstein, D.M. 2017. “The U.S. Conservation Reserve Program: The evolution of an enrollment mechanism.” *Land Use Policy*, 63: 601-610.

Jehiel, P. and Moldovanu, B., 2005. “Allocative and informational externalities in auctions and related mechanisms.” Discussion Paper Series of SFB/TR 15 Governance and the Efficiency of Economic Systems 142, Free University of Berlin. Available at https://ideas.repec.org/p/trf/wpaper/142.html.

Jones, K.R., J.E. Watson, H.P. Possingham, and C.J. Klein. 2016. “Incorporating climate change into spatial conservation prioritisation: A review.” *Biological Conservation, 194*, 121-130.

Kang, L., X. Han, Z. Zhang, Z. and O.J. Sun. 2007. “Grassland ecosystems in China: Review of current knowledge and research advancement.” *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, *362*(1482): 997-1008.

Kassar, I. and Lasserre, P., 2004. “Species preservation and biodiversity value: a real options approach.” *Journal of Environmental Economics and Management*, *48*(2), pp.857-879.

Latacz-Lohmann, U., and C. Van der Hamsvoort. 1997. “Auctioning conservation contracts: A theoretical analysis and an application.” *American Journal of Agricultural Economics*, 79(2): 407-418.

Lawler, J.J., S.L. Shafer, D. White, P. Kareiva, E.P. Maurer, A.R. Blaustein, and P.J. Bartlein. 2009. “Projected climate-induced faunal change in the western hemisphere.” *Ecology*, 90: 588-597.

Lawler, J.J., A.S. Ruesch, J.D. Olden, and B.H. McRae. 2013. “Projected climate-driven faunal movement routes.” *Ecology Letters*, 16: 1014-1022.

Lawler, J.J., D.D. Ackerly, C.M. Albano, M.G. Anderson, S.Z. Dobrowski, J.L. Gill, N.E. Heller, R.L. Pressey, E.W. Sanderson, and S.B. Weiss. 2015. “The theory behind, and the challenges of, conserving nature's stage in a time of rapid change.” *Conservation Biology* 29: 618–629.

Leroux, A.D., Martin, V.L. and Goeschl, T., 2009. “Optimal conservation, extinction debt, and the augmented quasi-option value.” *Journal of Environmental Economics and Management*, *58*(1), pp.43-57.

Lewis, D.J., A.J. Plantinga, E. Nelson, and S. Polasky. 2011. “The efficiency of voluntary incentives policies for preventing biodiversity loss.” *Resource and Energy Economics*, 33(1): 192- 211.

Mezey, E.W., and J.M. Conrad. 2010. “Real options in resource economics.” *Annual Review of Resource Economics*, 2: 33-52.

Millar, C., N.L. Stephenson, and S.L. Stephens. 2007. “Climate change and forests of the future: Managing in the face of uncertainty.” *Ecological Applications*, 17: 2145–2151.

Mills, D.E., 1981. “Growth, speculation and sprawl in a monocentric city.” *Journal of Urban Economics*, *10*(2), pp.201-226.

Mitchell, M.G.E., E.M. Bennett, and A. Gonzalez. 2015a. “Strong and nonlinear effects of fragmentation on ecosystem service provision at multiple scales.” *Environmental Research Letters*, *10*(9): 094014.

Mitchell, M.G.E., A.F. Suarez-Castro, M. Martinez-Harms, M. Maron, C. McAlpine, K.J. Gaston, K. Johansen, and J.R. Rhodes. 2015b. “Reframing landscape fragmentation's effects on ecosystem services.” *Trends in Ecology & Evolution*, 30(4): 190-198.

Montero, J.P. 2008. “A simple auction mechanism for the optimal allocation of the commons.” *American Economic Review*, 98(1): 496-518.

National Research Council (NRC) . 2005. *Valuing Ecosystem Services: Towards Better Environmental Decision-making*. National Academies Press, Washington, DC.

Nordhaus, W.D. 2014. *The Climate Casino: Risk, Uncertainty, and Economics for a Warming World*. Yale University Press, New Haven, CT.

Opdam, P., and D. Wascher. 2004. "Climate change meets habitat fragmentation: linking landscape biogeographical scale levels in research and conservation." *Biological Conservation*, 117: 285-297.

Parkhurst, G.M., and J. Shogren. 2007. "Spatial incentives to coordinate contiguous habitat." *Ecological Economics*, 64(2): 344-355.

Parkhurst, G.M., J.F. Shogren, C. Bastian, P. Kivi, J. Donner, and R.B.W. Smith. 2002. "Agglomeration bonus: an incentive mechanism to reunite fragmented habitat for biodiversity conservation." *Ecological Economics*, 41: 305–328.

Plantinga, A.J., R.N. Lubowski, and R.N. Stavins. 2002. "The effects of potential land development on agricultural land prices." *Journal of Urban Economics*, 52(3): 561-581.

Polasky, S., D.J. Lewis, A.J. Plantinga, and E. Nelson. 2014. "Implementing the optimal provision of ecosystem services." *Proceedings of the National Academy of Sciences*, 111(17): 6248-6253.

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

Polasky, S., and K. Segerson. 2009. "Integrating ecology and economics in the study of ecosystem services: some lessons learned." *Annual Review of Resource Economics*, 1: 409-434.

Pressey R.L., M. Cabeza, W.E. Watts, R.M. Cowling, and K.A. Wilson. 2007. "Conservation planning in a changing world." *Trends in Ecology & Evolution* 22: 583–592.

Robinson, S. K., F.R. Thompson III, T.M. Donovan, D.R. Whitehead, and J. Faaborg. 1995. "Regional forest fragmentation and the nesting success of migratory birds." *Science*, 267: 1987-1990.

Sanchirico, J.N. and J.E. Wilen. 1999. "Bioeconomics of spatial exploitation in a patchy environment." *Journal of Environmental Economics and Management*, 37: 129-150.

Sanchirico, J.N. and Wilen, J.E., 2005. "Optimal spatial management of renewable resources: matching policy scope to ecosystem scale." *Journal of Environmental Economics and Management*, *50*(1): 23-46.

Siry, J.P., F.W. Cubbage, and D.H. Newman. 2009. "Global forest ownership: implications for forest production, management, and protection." In *XIII World Forestry Congress, FAO, Buenos Aires*.

Smith, M.D., J. Sanchirico, and J. Wilen. 2009. "The economics of spatial-dynamic processes: Applications to renewable resources." *Journal of Environmental Economics and Management*, 57: 104-121.

Staudinger, M.D., S.L. Carter, M.S. Cross, N.S. Dubois, J.E. Duffy, C. Enquist, R. Griffis, J.J. Hellmann, J.J. Lawler, J. O'Leary, and S.A. Morrison. 2013. "Biodiversity in a changing climate: a synthesis of current and projected trends in the US." *Frontiers of Ecology and the Environment*, 11(9): 465-473.

Taubert, F., Fischer, R., Groeneveld, J., Lehmann, S., Müller, M.S., Rödig, E., Wiegand, T. and Huth, A., 2018. "Global patterns of tropical forest fragmentation." *Nature*, *554*(7693), p.519.

Thomas, C.D., A. Cameron, R.E. Green, M. Bakkenes, L.J. Beaumont, Y.C. Collingham, B.F.N. Erasmus, M. Ferreira de Siqueira, A. Grainger, L. Hannah, L. Hughes, B. Huntley, A.S. van Jaarsveld, G.F. Midgley, L. Miles, M.A. Ortega-Huerta, A.T. Peterson, O.L. Phillips, and S.E. Williams. 2004. "Extinction risk from climate change." *Nature*, 427: 145–148.

Thuiller, W., S. Lavorel, M.B. Araujo, M.T. Sykes, and I.C. Prentice. 2005. "Climate change threats to plant diversity in Europe." *Proceedings of the National Academy of Sciences*, 102: 8245-8250.

Traeger, C.P. 2014. "On option values in environmental and resource economics." *Resource and Energy Economics*, 37: 242-252.

Tulloch, A.I., R.F. Maloney, L.N. Joseph, J.R. Bennett, M.M. Fonzo, W.J. Probert, S.M. O'Connor, J.P. Densem, and H.P. Possingham. 2015. "Effect of risk aversion on prioritizing conservation projects." *Conservation Biology*, *29*(2), 513-524.

Vickrey, W. 1961. "Counterspeculation, auctions, and competitive sealed tenders." *Journal of Finance*, 16(1): 8-37.

Wätzold, F., M. Drechsler, K. Johst, M. Mewes, and A. Sturm. 2015 "A novel, spatiotemporally explicit ecological-economic modeling procedure for the design of cost-effective agri-environment schemes to conserve biodiversity." *American Journal of Agricultural Economics*, 98(2): 489-512.

Appendix A: Proof of Proposition 1

We show that truthful bidding, $b_{it} = d_{it}$, leads to payoffs that are equal to or greater than over bidding ($b_{it} > d_{it}$) or under-bidding ($b_{it} < d_{it}$), with strict inequality in payoffs for some potential outcomes. We begin by considering the bid for the second period, b_{i2}. We first show that, conditional on parcel *i* being conserved in period 1, it is a dominant strategy to set $b_{i2} = d_{i2}$. After proving this, we then show that it is a dominant strategy to set $b_{i1} = d_{i1}$.

Part 1: $b_{i2} = d_{i2}$. Suppose landowner *i*'s bid has been accepted and parcel *i* was conserved in period 1. In period 2, if $b_{i2} \leq \Delta W_{i2}^{s}|_{x_{i1}=1}$ then the regulator will require the landowner to conserve and the landowner will receive a payment of $\Delta W_{i2}^{s}|_{x_{i1}=1}$. If $b_{i2} > \Delta W_{i2}^{s}|_{x_{i1}=1}$, the landowner will be allowed to develop and will receive d_{i2}.

Suppose the landowner over-bids: $b_{i2} > d_{i2}$. There is some set of climate states $s \in S_O$ for which $b_{i2} > \Delta W_{i2}^{s}|_{x_{i1}=1} > d_{i2}$. In this case, the regulator would allow parcel *i* to be developed and give no payment to the landowner since $b_{i2} > \Delta W_{i2}^{s}|_{x_{i1}=1}$. However, since $\Delta W_{i2}^{s}|_{x_{i1}=1} > d_{i2}$, the landowner would be better off bidding truthfully, having the parcel be conserved and receive a payment of $\Delta W_{i2}^{s}|_{x_{i1}=1}$. For other climate states $s \notin S_O$, $\Delta W_{i2}^{s}|_{x_{i1}=1} \geq b_{i2}$ or $\Delta W_{i2}^{s}|_{x_{i1}=1} \leq d_{i2}$, overbidding will yield the same outcome as truthful bidding. When $\Delta W_{i2}^{s}|_{x_{i1}=1} < d_{i2}$, overbidding is harmless since the bid will be rejected both under truthful bidding and overbidding. When $\Delta W_{i2}^{s}|_{x_{i1}=1} = d_{i2}$, the landowner is indifferent between development and conservation so any bid generates the same payoff. When $\Delta W_{i2}^{s}|_{x_{i1}=1} \geq b_{i2}$, the bid will be accepted regardless of overbidding so that payoffs are equal for overbidding and for truthful bidding. Therefore, overbidding, $b_{i2} > d_{i2}$, is dominated by truthful bidding, $b_{i2} = d_{i2}$.

Suppose that the landowner under-bids: $b_{i2} < d_{i2}$. There is some set of climate states $s \in S_U$ for which $b_{i2} \leq \Delta W_{i2}^s|_{x_{i1}=1} < d_{i2}$. In this case, the regulator would conserve parcel *i* since $b_{i2} \leq \Delta W_{i2}^s|_{x_{i1}=1}$. However, given that $\Delta W_{i2}^s|_{x_{i1}=1} < d_{i2}$ the landowner would be better off with truthful bidding and developing the parcel. For other climate states $s \notin S_O$, $\Delta W_{i2}^s|_{x_{i1}=1} < b_{i2}$ or $\Delta W_{i2}^s|_{x_{i1}=1} \geq d_{i2}$, underbidding will yield the same outcome as truthful bidding. When $\Delta W_{i2}^s|_{x_{i1}=1} \geq d_{i2}$, underbidding is harmless since the bid will be accepted both under truthful bidding and underbidding. When $\Delta W_{i2}^s(X_{i2}^{*s}) < b_{i2}$ the bid will be accepted regardless of underbidding so that payoffs are equal for underbidding and for truthful bidding. Therefore underbidding, $b_{i2} < d_{i2}$, is dominated by truthful bidding: $b_{i2} = d_{i2}$.

Part 2: $b_{i1} = d_{i1}$. Part 1 of the proof established that the landowner has a dominant strategy to truthfully bid their second period development value, $b_{i2} = d_{i2}$, conditional on the bid being accepted. Given that $b_{i2} = d_{i2}$, if $b_{i1} \leq \Delta W_{i1} + \delta(1-q)E_{s\in S'}\{\Delta W_{\sim i2}^s\}$ then equation (9) will be satisfied and the landowner's bid will be accepted. The landowner will receive a payment of $\Delta W_{i1} + \delta(1-q)E_{s\in S'}\{\Delta W_{\sim i2}^s\}$ in period 1 with continuation payoffs of either conservation or development as described above in period 2. Now we show that setting $b_{i1} = d_{i1}$ dominates overbidding ($b_{i1} > d_{i1}$) or underbidding ($b_{i1} < d_{i1}$).

Suppose the landowner overbids: $b_{i1} > d_{i1}$. There is some set of climate states $s \in S_\theta$ for which $b_{i1} + \delta q b_{i2} > \Delta W_{i1} + \delta q E_{s\in S^*}\left\{\Delta W_{i2}^s|_{x_{i1}=1}\right\} + \delta(1-q)E_{s\in S'}\{\Delta W_{\sim i2}^s\} > d_{i1} + \delta q d_{i2}$. In this case, the regulator would allow parcel *i* to be developed and give no payment to the landowner since $b_{i1} + \delta q b_{i2} > \Delta W_{i1} + \delta q E_{s\in S^*}\left\{\Delta W_{i2}^s|_{x_{i1}=1}\right\} + \delta(1-q)E_{s\in S'}\{\Delta W_{\sim i2}^s\}$. However, since $\Delta W_{i1} + \delta q E_{s\in S^*}\left\{\Delta W_{i2}^s|_{x_{i1}=1}\right\} + \delta(1-q)E_{s\in S'}\{\Delta W_{\sim i2}^s\} > d_{i1} + \delta q d_{i2}$, the landowner would be better off bidding truthfully, having the parcel be conserved and receive a payment of $\Delta W_{i1} + \delta(1-q)E_{s\in S'}\{\Delta W_{\sim i2}^{s}\}$ in period 1 and receiving the maximum of $\Delta W_{i2}^{s}|_{x_{i1}=1}$ or d_{i2} in period 2. For other climate states $s \notin S_{\theta}$, $\Delta W_{i1} + \delta q E_{s\in S^*}\left\{\Delta W_{i2}^{s}|_{x_{i1}=1}\right\} + \delta(1-q)E_{s\in S'}\{\Delta W_{\sim i2}^{s}\} \geq b_{i1} + \delta q b_{i2}$ or $\Delta W_{i1} + \delta q E_{s\in S^*}\left\{\Delta W_{i2}^{s}|_{x_{i1}=1}\right\} + \delta(1-q)E_{s\in S'}\{\Delta W_{\sim i2}^{s}\} \leq d_{i1} + \delta q d_{i2}$, overbidding will yield the same outcome as truthful bidding. When $\Delta W_{i1} + \delta q E_{s\in S^*}\left\{\Delta W_{i2}^{s}|_{x_{i1}=1}\right\} + \delta(1-q)E_{s\in S'}\{\Delta W_{\sim i2}^{s}\} < d_{i1} + \delta q d_{i2}$, overbidding is harmless since the bid will be rejected both under truthful bidding and overbidding. When $\Delta W_{i1} + \delta q E_{s\in S^*}\left\{\Delta W_{i2}^{s}|_{x_{i1}=1}\right\} + \delta(1-q)E_{s\in S'}\{\Delta W_{\sim i2}^{s}\} = d_{i1} + \delta q d_{i2}$, the landowner is indifferent between development and conservation so any bid generates the same payoff. When $\Delta W_{i1} + \delta q E_{s\in S^*}\left\{\Delta W_{i2}^{s}|_{x_{i1}=1}\right\} + \delta(1-q)E_{s\in S'}\{\Delta W_{\sim i2}^{s}\} \geq b_{i1} + \delta q b_{i2}$, the bid will be accepted regardless of overbidding so that payoffs are equal for overbidding and for truthful bidding. Therefore, overbidding, $b_{i1} > d_{i1}$, is dominated by truthful bidding, $b_{i1} = d_{i1}$, given that $b_{i2} = d_{i2}$, as shown in part 1.

Suppose that the landowner underbids: $b_{i1} < d_{i1}$. There is some set of climate states $s \in S_{\varphi}$ for which $b_{i1} + \delta q b_{i2} \leq \Delta W_{i1} + \delta q E_{s\in S^*}\left\{\Delta W_{i2}^{s}|_{x_{i1}=1}\right\} + \delta(1-q)E_{s\in S'}\{\Delta W_{\sim i2}^{s}\} < d_{i1} + \delta q d_{i2}$. In this case, the regulator would conserve parcel *i* since $b_{i1} + \delta q b_{i2} \leq \Delta W_{i1} + \delta q E_{s\in S^*}\left\{\Delta W_{i2}^{s}|_{x_{i1}=1}\right\} + \delta(1-q)E_{s\in S'}\{\Delta W_{\sim i2}^{s}\}$. However, given that $\Delta W_{i1} + \delta q E_{s\in S^*}\left\{\Delta W_{i2}^{s}|_{x_{i1}=1}\right\} + \delta(1-q)E_{s\in S'}\{\Delta W_{\sim i2}^{s}\} < d_{i1} + \delta q d_{i2}$, the landowner would be better off with truthful bidding and developing the parcel. For other climate states $s \notin S_{\varphi}$, $\Delta W_{i1} + \delta q E_{s\in S^*}\left\{\Delta W_{i2}^{s}|_{x_{i1}=1}\right\} + \delta(1-q)E_{s\in S'}\{\Delta W_{\sim i2}^{s}\} < b_{i1} + \delta q b_{i2}$ or $\Delta W_{i1} + \delta q E_{s\in S^*}\left\{\Delta W_{i2}^{s}|_{x_{i1}=1}\right\} + \delta(1-q)E_{s\in S'}\{\Delta W_{\sim i2}^{s}\} \geq d_{i1} + \delta q d_{i2}$, underbidding will yield the same outcome as truthful bidding. When $\Delta W_{i1} + \delta q E_{s\in S^*}\left\{\Delta W_{i2}^{s}|_{x_{i1}=1}\right\} + \delta(1-q)E_{s\in S'}\{\Delta W_{\sim i2}^{s}\} \geq d_{i1} + \delta q d_{i2}$, underbidding is harmless since the bid will be accepted both under truthful bidding and underbidding. When $\Delta W_{i1} + \delta q E_{s\in S^*}\{\Delta W_{i2}^{s}|_{x_{i1}=1}\} + \delta(1 - q)E_{s\in S'}\{\Delta W_{\sim i2}^{s}\} < b_{i1} + \delta q b_{i2}$ the bid will be rejected regardless of underbidding so that payoffs are equal for underbidding and for truthful bidding. Therefore underbidding, $b_{i1} < d_{i1}$, is dominated by truthful bidding: $b_{i1} = d_{i1}$, given that $b_{i2} = d_{i2}$, as shown in part 1.

Combining parts (1) and (2), we have shown that both overbidding and underbidding are dominated by the truthful bidding strategy $b_{i1} = d_{i1}$ and $b_{i2} = d_{i2.}$ QED.

Appendix B. Proof of Proposition 2.

First, proposition 1 established that landowners bid truthfully ($b_{i1} = d_{i1}$ and $b_{i2} = d_{i2}$) so that the regulator knows all development values in period 1 and 2. Therefore, the regulator can solve for the set of parcels to conserve in period 1 that maximizes expected social benefits. In the auction, parcel *i* is conserved in period 1 if and only if

$$\Delta W_{i1} + \delta q E_{s\in S^*}\left\{\Delta W_{i2}^{s}|_{x_{i1}=1}\right\} + \delta(1-q)E_{s\in S'}\{\Delta W_{\sim i2}^{s}\} \geq b_{i1} + \delta q b_{i2}.$$

But since landowners are bidding truthfully this expression is equivalent to

$$\Delta W_{i1} + \delta q E_{s\in S^*}\left\{\Delta W_{i2}^{s}|_{x_{i1}=1}\right\} + \delta(1-q)E_{s\in S'}\{\Delta W_{\sim i2}^{s}\} \geq d_{i1} + \delta q d_{i2}$$

which is the same as equation (8) that characterizes what must be true in an optimal solution. Therefore, the auction mechanism correctly solves the social benefits optimization problem in period 1. Further, in period 2, under the auction mechanism the regulator will continue to conserve parcels if and only if $\Delta W_{i2}^{s}|_{x_{i1}=1} \geq b_{i2} = d_{i2}$, which again is the optimal rule for conservation in period 2. Therefore, the auction mechanism achieves the optimal solution. QED