Optimal Preservation of Agricultural and Environmental Land within a Municipality under Irreversibility and Uncertainty

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Abstract

This paper analyzes the optimal policy choice for the conservation of privately owned open space when future land cover types are uncertain. Policymakers must use land use policies to make conservation decisions under uncertainty over the social benefits of future vegetation, due to the uncertain effects of climate change on suitable habitat ranges. If policymakers fail to account for future information gains when designing land use policies, expected social welfare may not be maximized. To examine this situation, I consider three policy instruments: urban growth boundaries (UGB), location-independent development fees (LIF), and location-dependent development fees (LDF). I analyze them in a spatial-dynamic model in which climate change is treated as a land use externality with an uncertain future value. I derive the privately and socially optimal land allocations under open-loop and closed-loop control. By comparing the privately and socially optimal land allocations for each control problem, I identify the optimal trajectory of each instrument over time. Results depend on whether or not there is a cumulative externality from urban development. When no cumulative externality exists, welfare-maximizing UGB and LIF depend on the control problem. In contrast, LDF are identical in expectation across the two control problems. As a consequence, LDF are the first best policy when landowners do and policymakers do not anticipate (or cannot respond to) the future availability of climatic information. When a cumulative externality exists, none of the policies are robust to the type of control problem, including LDF, and only UGB are time consistent. Therefore, UGB are the first best policy when policymakers anticipate future climatic information and there is a cumulative externality. This work implies that conservation programs should amend current methods for ranking conservation choices to account for future ecosystem movement, and return lands to other uses if climate change causes conservation goals to not be achieved.

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I. Introduction

Many vegetation types are currently under threat from agricultural and residential development and the potential effects of climate change. Scientists predict that many vegetation types will shrink and shift in extent due to global warming (Kueppers et al., 2005; Hannah et al., 2008). However, the predicted future locations of these vegetation types vary depending on the climate model, the future scenario, and the species distribution model. As a result, policymakers must make conservation decisions under substantial scientific uncertainty. Because in many areas certain vegetation types are primarily privately owned and states do not always have regulatory authority over the removal of non-commercial plant species (WCB, 2007; Ineich, 2007), it falls to local governments to adjust existing land use policies to account for the uncertainty surrounding any benefits from privately owned open space not obtained by the landowner, such as amenity benefits obtained by nearby residents (Ineich, 2007; Campos-Palacin et al., 2002).

The primary objective of this research is to show how uncertainty over future amenities affects a local government's social welfare-maximizing land use policies. I develop a spatial-dynamic model in order to analyze three alternative land use policies: urban growth boundaries (UGBs), location-independent development fees (LIFs), and location-dependent development fees (LDFs). A modified open-city model, which consists of a municipality and its "sphere of influence," represents the spatial component of the problem. Two time periods, uncertainty, and irreversibility, represents the dynamic components. Using this model, I derive the privately and socially optimal land allocations under open-loop and closed-loop control assumptions. In the open-loop control problem, policymakers cannot or do not respond to new information, while in a closed-loop control problem they can. By comparing the privately and socially optimal land allocations in each control problem, I identify the optimal trajectory of each policy instrument over time. By comparing the socially optimal land allocations in the two control problems, I identify the value of information that policymakers can obtain by responding to new information.

In the context of privately owned open space, the closed-loop control problem represents informational conditions in the real world: policymakers and other economic agents will learn over time about the effects of climate change on vegetation types and the value of their non-market services. The open-loop control problem represents the certainty-equivalent problem in which policymakers cannot or do not respond to new information. The reduction of the existing uncertainty over the effects of climate change on vegetation over time, and the irreversibility of urban development result in an additional conservation value, known as option value. If, as many observers believe, current land use policies do not take the potential effects of climate change on vegetation into account, then an implication of my analysis is that existing land-use policies should be adjusted to preserve more open space than they aim to achieve in the absence of this consideration.

I obtain four major results. First, the socially optimal land use policies prevent more development in the first period under closed-loop control than under open-loop control when there is no cumulative environmental externality from urban development and the marginal external cost of development increases in the amount of urban land at a non-decreasing rate. Second, the socially optimal UGBs and LIFs differ between the two control problems; both socially optimal open-loop policies under-conserve privately owned open space relative to the corresponding socially optimal closed-loop policies when there is no cumulative environmental externality from development. Third, the socially optimal LDFs are the same at each location for the two control problems when there is no cumulative environmental externality from development. Because many policymakers ignore the uncertainty over future open space amenities and uncertainty is likely to decline gradually and at an unknown rate, this indicates that LDFs are likely to be a better suited policy for ensuring a socially optimal level of open space conservation when there is no cumulative environmental externality from development. For example, LDFs achieve the socially optimal land use allocation when there is no cumulative environmental externality from development and the policymaker gains unexpected information about the effect of climate change after making her first period land use decision, i.e. an open-loop feedback control problem, while UGBs under-conserve open space. Last, when there is a cumulative environmental externality from development, under some conditions the socially optimal land use policies continue to prevent more open space development in the first period under closed-loop control than under open-loop control. However, the socially optimal LDFs are no longer independent of the type of control problem and, of the three policies analyzed in this paper, only the socially optimal UGBs are time consistent.

These results apply to any spatial-temporal problem in which private landowners choose between land uses that produce externalities with uncertain future values and irreversible land uses. The results extend to all local conservation programs, including agricultural preservation programs, which aim to preserve particular land-uses on private lands with uncertain future social values due to the potential effects of climate change, disease, and/or regeneration problems. The results also apply to the discouragement of land-uses that produce negative externalities. For instance, policymakers who aim to reduce mining by replacing it with residential development or permanent nature reserves may restrict this activity excessively if they do not take into account uncertainty regarding the creation and use of future alternative technologies.

The paper is structured as follows. Section II reviews the key literature. Section III introduces the general model. Section IV specifies the various landlord and social planner problems that are to be solved. Section V derives the conditions defining equilibrium for each of these problems. Section VI derives the sufficient conditions for a unique global maximum for each of these problems. Section VII derives the key results of the paper and discusses their implication. Section VIII concludes with a discussion of the greater implications of these results and the direction of future work.

II. Literature Review

To the author's knowledge, no previous work has addressed how a local government's social welfare-maximizing land use policies are affected by uncertainty over future amenities. Three strands of literature form a sound starting point: farmland preservation, non-market valuation, and irreversible investment. Beginning with Gardner (1977), the agricultural preservation literature has recognized that open space, environmental amenities and other rural amenities provided by farmland are public goods, and thus constitute an argument for agricultural preservation. The non-market valuation literature provides empirical justification for extending this public support to other privately owned ecosystems. However, the agricultural preservation literature and the non-market valuation studies fail to capture the full benefit of conservation due to their implicit assumption that the benefits of conservation are known. The irreversible investment literature addresses this shortcoming by developing the modeling framework for irreversible decision making under uncertainty, upon which this paper will expand.

In practice, the non-market benefits of privately owned open space are often uncertain. This uncertainty arises from various sources, as noted earlier. Such uncertainty may decrease over time, for example, as scientists learn more about the regional effects of global climate change.

Because learning allows decision makers to make more informed decisions, there is a value to this information conditional on preservation. This value is known as Dixit-Pindyck (D-P) option value in discrete development problems, or quasi-option value when in addition there is no cost to development; quasi-option value is equivalent to the optimal development tax necessary to induce the socially optimal discrete development decision if a social welfare maximizing policymaker ignores the reduction over time of the uncertainty surrounding the net benefits to preservation (Arrow and Fisher 1976). In continuous development problems, these option values do not exist, although there is still a value of information conditional on the first period land use decision (Hanemann 1989). Unlike discrete development problems, the irreversibility effect, which in my context corresponds to first period development declining as more information becomes available in the future, does not always hold (Epstein 1980). Epstein (1980), Ulph and Ulph (1997) and Freixas and Laffont (1984) define sufficient conditions for the irreversibility effect to hold in two-period development problems.

A landowner does not fully account for her land's amenity value or the corresponding value of information that arises from preserving open space when making her land use decision due to the public good nature of open space amenities. As a consequence, I define two values of information in this paper: the social value of information and the private value of information. The social value of information is the value of information that arises in the closed-loop Pareto efficient equilibrium, while the private value of information is the value of information that arises in the closed-loop competitive equilibrium. Because information has no value in open-loop problems, the social (private) value of information is calculated as the difference between the total value of welfare in the closed-loop and open-loop Pareto efficient (competitive) equilibria (Hanemann, 1989). The private value of information is the portion of the social value of information that landlords as a group take into account when making their land use decisions. Because the public good nature of some amenities implies that the private and social values of information may differ if the irreversibility effect holds, social welfare-maximizing land use policies must account for any such difference.

The irreversible development literature focuses on public lands. As a consequence, the effect of uncertainty on irreversible private land-use decisions and the land use policies that regulate these decisions has not been explored. Nor has the irreversible investment framework been integrated into a continuous spatial model, such as the Muth-Mills model. My paper fills these two niches by integrating the irreversible investment decision making framework into an open-city model to explore the effects of uncertainty on social welfare maximizing land-use policies.

The most similar works in the literature are Albers (1996) and Albers and Robison (2007). These papers integrate the irreversible investment framework into a discrete spatial model in order to explore temporal-spatial aspects of park management. As in the case here, these papers: use a spatial-temporal land-use choice model, include irreversibility and land use externalities with uncertain future values, address two types of government represented by open-loop and closed-loop control, and assume that property size is fixed and that each property has two adjacent properties. The primary difference between this analysis and Albers (1996) is that she models a centrally planned forest, whereas I model privately owned open space covered by vegetation; this difference is driven by the difference in our research questions. My paper solves for open-loop and closed-loop competitive and Pareto optimal land-use configurations, whereas Albers (1996) only solves for open and closed-loop Pareto optimal land-use configurations. While Albers (1996) and Albers and Robinson (2007) demonstrate that uncertain spatial externalities give rise to an additional option value unaccounted for by Arrow and Fisher (1976) and the authors recognize that this result indicates a possible difference between private and socially optimal land-use configurations, they do not solve for competitive equilibria. In addition Albers (1996) recognizes the need to account for quasi-option values when developing spatial-temporal land use policies under uncertainty, but neither paper models market instruments, as is done here.

III. Analytical Model

This paper models a municipality over two time periods, $t \in \{1,2\}$, when urban development is irreversible and a net land use externality exists and is uncertain in the second time period. In the context of the class of policy problem that I examine, the municipality can be conceptualized as a small city and its undeveloped area of influence (i.e. private rural open space). The vegetation type of interest either degenerates and is replaced by a less desirable type of vegetation or thrives over time due to climate change, represented as the second period net land use externality taking one of two possible states, $k \in \{L, H\}$, which correspond to the services in period 2 produced by a given amount of open space being less than or greater than the services it provided in period 1 assuming that there is no cumulative environmental externality. States H and L occur with probability $0 < p_H < 1$ and $p_L = 1 - p_H$ respectively.

The municipality is a one-dimensional space of exogenous size A. Each point on the $[0, A]$ interval represents a property X_i owned by an absentee landlord i and rented by a tenant j. Properties are infinitely small, and as a consequence there are an infinite number of landlords and tenants in the municipality.[1] By definition, the landlord cannot change the density of

[1] An alternative interpretation of this assumption is that each tenant chooses to live on one unit of land where one unit of land is small enough that each landlord's land use choice has an insignificant effect on the net land use externality experienced by her tenant. Like Brueckner (1990), integration is used as a simplification under the assumption that A is large enough for it to be approximately true.

residents on her property. The Central Business District (CBD) is located at $X = 0$ where all tenants who rent urban land work.

Tenants. Tenants live on either urban or rural land. If tenant *j* is located in an urban area, he commutes to the CBD at a financial cost of $\mathrm{T}_{j,t,k} = T(X_j)$ in period *t* and state *k*, earns a salary y_t, and pays rent $R_{j,t,k}$. Commuting cost increases with distance, i.e. $\frac{\partial T(X_j)}{\partial X_j} > 0$, and $T(X_j)$ is a twice continuously differentiable function. If tenant *j* is located on rural land, he earns profits $\Pi_{j,t,k} = \Pi(X_j)$ in period *t* and state *k* from farming the land and pays rent $r_{j,t,k}$. All rural tenants have access to the same agricultural technologies, so that land quality is the only source of difference in agricultural profits by location; the quality of land is non-decreasing in distance from the CBD, i.e. $\frac{\partial \Pi(X_j)}{\partial X_j} \geq 0$. Agricultural profit is a twice continuously differentiable function, which is unaffected by climate change. All agricultural output is sold in a perfectly competitive market and potential producers in the municipality are sufficiently small relative to the market for the price to be unaffected. Rural tenants do not travel to work, so $\mathrm{T}_{j,t,k} = 0$ for all rural tenants.

Tenants have homogenous, time invariant preferences represented by a time-additive, von Neumann-Morgenstern expected utility function. Each tenant has a utility function $V_{j,t,k} = V(c_{j,t,k}, g_{j,t,k}, S_{j,t,k})$, which is twice continuously differentiable in all its arguments. Tenants gain utility from consuming housing $g_{j,t,k}$ $\left(\frac{\partial V}{\partial g_{j,t,k}} > 0\right)$, the numeraire good $c_{j,t,k}$ $\left(\frac{\partial V}{\partial c_{j,t,k}} > 0\right)$, and the net land use externality $S_{j,t,k}$ $\left(\frac{\partial \mathrm{V}}{\partial \mathrm{S}_{\mathrm{j,t,k}}} > 0\right)$. Housing differs from the other two goods in that tenants are restricted to one unit of housing consumption.

In each period t and state k, tenant j chooses to live or not live within the municipality at location X_j, represented by $g_{j,t,k} = 1$ or $g_{j,t,k} = 0$ respectively, and the quantity of the numeraire good, $c_{j,t,k}$, to consume in order to maximize his utility subject to his budget constraint. His budget constraint depends on the land use at X_j. It is $c_{j,t,k} + R_{j,t,k}g_{j,t,k} = y_t - T(X_j)$ when he lives on urban land and $c_{j,t,k} + r_{j,t,k}g_{j,t,k} = \Pi(X_j)$ when he lives on agricultural land. The tenant makes his consumption choice knowing that there is a net land use externality equal to $S_{j,1}$ in period 1 at location j and a net land use externality equal to $S_{j,2,k}$ in period 2 and state k. Tenant j experiences a positive net land use externality in period t when $S_{j,t,k} > 0$. Because the tenant can move freely and costly into and out of the municipality, he must receive at least his exogenous level of utility, which he could obtain outside of the municipality in period t, $\bar{\bar{V}}_t$.[2] Exogenous utility, urban salaries, and net land use externalities are the only three parameters that vary over time, and, as a result, drive the growth of urban land over time.

Tenant j's decision problem in period t and state k when he lives on urban land is

$$\max_{c_{j,t,k},\, g_{j,t,k}} g_{j,t,k}V(c_{j,t,k}, g_{j,t,k}S_{j,t,k}) + (1 - g_{j,t,k})\bar{\bar{V}}_t \text{ subject to}$$
$$c_{j,t,k} + R_{j,t,k} = y_t - T(X_j)$$
$$g_{j,t,k} = 0 \text{ or } 1.$$

Tenant j's decision problem in period t and state k when he lives on agricultural land is

$$\max_{c_{j,t,k},\, g_{j,t,k}} g_{j,t,k}V(c_{j,t,k}, g_{j,t,k}S_{j,t,k}) + (1 - g_{j,t,k})\bar{\bar{V}}_t \text{ subject to}$$
$$c_{j,t,k} + r_{j,t,k} = \Pi(X_j)$$
$$g_{j,t,k} = 0 \text{ or } 1.$$

Landlords. All landlords are identical except for the location of their properties. Landlords do not live within the municipality and they are price takers. The i^{th} landlord's profit in period t and

[2] It is standard to assume that there is a cost of daily commuting within the municipality, but no cost to relocating into, out of, and within the municipality. See Brueckner (1990).

state k, $Y_{i,t,k}$, equals $Y_{i,t,k} = w_{i,t,k}R_{i,t,k} + \left(1 - w_{i,t,k}\right)r_{i,t,k}$ where $w_{i,t,k} = 1$ if she chooses to rent her land for urban use and $w_{i,t,k} = 0$ if she chooses to rent her land for agricultural use. Renting land for urban purposes requires development. Development is costless to the landlord and subject to an irreversibility constraint: $w_{i,2,k} \geq w_{i,1}$. Each landlord makes her land use decisions in periods $t \in \{1,2\}$ and states $k \in \{L, H\}$, i.e. chooses $w_{i,t,k}$, to maximize the present value of her expected profits subject to the irreversibility constraint. I assume that all land is initially rural, i.e. in agricultural use, so that the first period development decision is unconstrained by an earlier development choice.

A key concept in this paper is the marginal landlord, defined as the landlord who is indifferent between the urban and agricultural use of her land. The marginal landlord in period t and state k, denoted $\tilde{X}_{t,k}$, is endogenously determined. Because $\tilde{X}_{t,k}$ represents the urban-agricultural boundary and I impose assumptions in Section VI that guarantee $\tilde{X}_{t,k}$ is unique, urban space covers $X \in [0, \tilde{X}_{t,k}\ ]$ and private open space covers $X \in \left(\tilde{X}_{t,k}, \mathrm{A}\right]$.

<u>The net land use externality.</u> A net land use externality at a specific location is the sum of urban and open space location-independent and location-dependent externalities. Location-independent externalities are externalities that all tenants experience equally. Location-dependent externalities are externalities that all tenants experience differently based on their location within the municipality. I limit attention to the scenario in which a natural resource may be under conserved. In my specific policy application, this corresponds to assuming that urban land produce negative location-independent and location-dependent externalities, such as smog and noise pollution, while open space produces positive location-independent and location-dependent externalities, such as carbon sequestration and aesthetics. Both open space location-

independent and location-dependent externalities have uncertain values in the second period due to the effect of climate change on vegetation.

The net land use externality experienced by tenant j in period t in state k is a function of the amount of urban space, $\tilde{X}_{t,k}$, and his location, X_j. The net location-independent externality is non-increasing in $\tilde{X}_{t,k}$ and is unaffected by a change in X_j. For a given X_j, the net location-dependent externality is non-increasing in $\tilde{X}_{t,k}$. In the case of an urban tenant, he is farther from the urban-agricultural boundary, strictly speaking, as the amount of urban space expands, which implies that he experiences less of the positive location-dependent externalities from open space. In the case of a rural tenant, he is closer to the urban-rural boundary as the amount of urban space expands, which means that he is nearer to the negative location-dependent externalities of urban space. For a given $\tilde{X}_{t,k}$, the net location-dependent externality is non-decreasing in X_j for both the urban and rural tenants.

Formally, $S_{j,1} = S_1(X_j, \tilde{X}_1)$ is the net externality experienced by tenant j in period 1. It is a twice continuously differentiable function in X_j and $\tilde{X}_1$, and $\frac{\partial S_1(X_j,\tilde{X}_1)}{\partial X_j} \geq 0$ and $\frac{\partial S_1(X_j,\tilde{X}_1)}{\partial \tilde{X}_1} \leq 0$. The net externality experienced by tenant j in period 2, $S_{j,2,k} = S_{2,k}(X_j, \tilde{X}_1, \tilde{X}_2)$, is dependent on state $k \in \{L, H\}$:

$$\textbf{(1)} \quad S_{2,L}(X_j, 0, \tilde{X}) < S_1(X_j, \tilde{X}) < S_{2,H}(X_j, 0, \tilde{X}) \; \forall X_j, \tilde{X} < A.$$

$S_{2,k}(X_j, \tilde{X}_1, \tilde{X}_2)$ is a twice continuously differentiable function in X, $\tilde{X}_1$, and $\tilde{X}_2$.[3] As was the case for the first period net externality, $\frac{\partial S_{2,k}(X_j,\tilde{X}_1,\tilde{X}_2)}{\partial X_j} \geq 0$ and $\frac{\partial S_{2,k}(X_j,\tilde{X}_1,\tilde{X}_2)}{\partial \tilde{X}_2} \leq 0$ for all $k \in \{L, H\}$.

[3] In the traditional irreversibility literature, the second period net land use externality function is written as $S_{j,2,k} = S_2(X_j, \tilde{X}_1, \tilde{X}_2 | Z = z_k)$ where Z is a random variable, which has 2 possible events, z_L and z_H, corresponding to states L and H. The probability that the random variable Z will take the value z_L is p_L and z_H is p_H. This traditional notation makes explicit that climate change affects only the parameters of the net land use externality function, and

Because the amount of urban land can have negative cumulative environmental effects, the net land use externality in period 2 and state k is a function of the amount of urban land in period 1. Therefore, $\frac{\partial S_{2,k}(X_j,\tilde{X}_1,\tilde{X}_2)}{\partial \tilde{X}_1} \leq 0$ where $\frac{\partial S_{2,k}(X_j,\tilde{X}_1,\tilde{X}_2)}{\partial \tilde{X}_1} < 0$ and $\frac{\partial S_{2,k}(X_j,\tilde{X}_1,\tilde{X}_2)}{\partial \tilde{X}_1} = 0$ imply that there is and is not a cumulative environmental externality from development, respectively. Therefore, expression **(1)** does not necessarily hold when there is development in the first period.

IV. The Maximization Problems

The goal of this paper is to demonstrate that a local government's social welfare-maximizing land use policies are affected by whether it takes into account the uncertainty over future open space amenities due to climate change. I address this research question in two steps. First, I find the amount of urban land, $\tilde{X}_{t,k}$, in each period $\forall t \in \{1,2\}$ and future state $\forall k \in \{L,H\}$ chosen by a profit-maximizing landlord and a welfare-maximizing social planner in open-loop and closed-loop contexts. Second, I calculate the socially optimal magnitudes of three land-use policies: urban growth boundaries (UGBs), location-independent development fees (LIFs), and location-dependent development fees (LDFs).

In terms of notation, superscript $m \in \{M,P\}$ indicates the decision maker: M indicates the landlord and P the social planner. Superscript $n \in \{O,C\}$ indicates the type of control problem: O is an open-loop control problem and C is a closed-loop control problem. Superscript * indicates that the corresponding variable is at its optimal value, e.g. $\tilde{X}_{t,k}^{nm^*}$, or the corresponding function is evaluated at the optimal amount of urban land, e.g. $S_{i,t,k}^{nm^*} = S_{t,k}\big(X_i, \tilde{X}_1^{nm^*}, \tilde{X}_{2,k}^{nm^*}\big)$. Table 1 summarizes the four problems I analyze, including notation.

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not the functional form itself. For simplicity, I utilize the alternative specification in **(1)**. This simplification is used throughout the paper for multiple functional forms.

Table 1. Optimization Problems

Control Problem	Optimizer: Landlord (m=M)	Optimizer: Social Planner (m=P)
Open-Loop (n=O)	Solve W^{OM} to find $\tilde{X}_1^{OM*}$ and $\tilde{X}_2^{OM*}$ when facing net land use externalities $S_{i,t,k}^{OM}$, rental rate functions $R_{i,t,k}^{OM}$ and $r_{i,t,k}^{OM}$, numeraire good consumption $c_{j,t,k}^{OM}$, and housing consumption $g_{j,t,k}^{OM}$	Solve W^{OP} to find $\tilde{X}_1^{OP*}$ and $\tilde{X}_2^{OP*}$ when facing net land use externalities $S_{i,t,k}^{OP}$, rental rate functions $R_{i,t,k}^{OP}$ and $r_{i,t,k}^{OP}$, numeraire good consumption $c_{j,t,k}^{OP}$, and housing consumption $g_{j,t,k}^{OP}$
Closed-Loop (n=C)	Solve W^{CM} to find $\tilde{X}_1^{CM*}$ and $\tilde{X}_{2,k}^{CM*}$ when facing net land use externalities $S_{i,t,k}^{CM}$, rental rate functions $R_{i,t,k}^{CM}$ and $r_{i,t,k}^{CM}$, numeraire good consumption $c_{j,t,k}^{CM}$, and housing consumption $g_{j,t,k}^{CM}$	Solve W^{CP} to find $\tilde{X}_1^{CP*}$ and $\tilde{X}_{2,k}^{CP*}$ when facing net land use externalities $S_{i,t,k}^{CP}$, rental rate functions $R_{i,t,k}^{CP}$ and $r_{i,t,k}^{CP}$, numeraire good consumption $c_{j,t,k}^{CP}$, and housing consumption $g_{j,t,k}^{CP}$

The Optimizers. The landlords and the social planner have the same information regarding the effects of climate change on open space's vegetation in state k and the probabilities of each future state occurring. Only their objective functions differ. As discussed earlier, each landowner maximizes the present value of expected profits by choosing whether to develop her land for urban use in each period subject to an irreversibility constraint. She does not consider the effect of her land use decisions on surrounding tenants and landlords and takes other landlords' land use decisions as given. In contrast, the social planner chooses the optimal amount of urban land in each period subject to an irreversibility constraint in order to maximize the present value of expected social utility within the municipality. Because tenants' reservation utility is exogenous, this is equivalent to maximizing the present value of expected landlord profits, taking into consideration the effect of developing each piece of land on other tenants and landlords.

The only difference between the landlord profit-maximization problem and the social planner problem is in the treatment of externalities. Because landlord *i* takes the land use decisions of other landlords as given, modeling the profit-maximizing decisions of all I landlords is equivalent to modeling the decisions of a single landlord who maximizes the present value of expected municipality-wide profits by choosing the amount of urban land in each period *t* and state *k* assuming that the level of the externality varies only with the location of the property: $S_{i,1}^{nM} = \bar{S}_1(X_i)$ and $S_{i,2,k}^{nM} = \bar{S}_{2,k}(X_i)\ \forall n \in \{O, C\}$. In equilibrium, the net land use externality at location X_i in the *n*-type control problem equals $S_{i,1}^{nM^*} = S_1\left(X_i, \tilde{X}_1^{nM^*}\right)$ in the first period and $S_{i,2,k}^{nM\ *} = S_{2,k}\left(X_i, \tilde{X}_1^{nM^*}, \tilde{X}_{2,k}^{nM^*}\right)$ in the second period if state *k* occurs where $\tilde{X}_{t,k}^{nM^*}$ is the Nash equilibrium amount of urban land in period *t* and state *k* in the *n* type control problem. The social planner, in contrast, maximizes the present value of expected municipality-wide profits by choosing the amount of urban land in each period *t* and state *k* recognizing that externalities vary with tenant location and the amount of urban space: $S_{i,1}^{nP} = S_1\left(X_i, \tilde{X}_1^{nP}\right)$ and $S_{i,2,k}^{nP} = S_{2,k}\left(X_i, \tilde{X}_1^{nP}, \tilde{X}_{2,k}^{nP}\right)\ \forall n \in \{O, C\}$. In equilibrium, the net land use externality at location X_i in the *n*-type control problem is evaluated at $\tilde{X}_{t,k}^{nP} = \tilde{X}_{t,k}^{nP^*}$ where $\tilde{X}_{t,k}^{nP^*}$ is the Pareto optimal amount of urban land in period *t* and state *k* in the *n* type control problem.

<u>The type of control problem</u>. Over time, new information about the effects of climate change becomes available. The optimizer in the closed-loop problem recognizes that new information will emerge, while the optimizer in the open-loop problem ignores or is unable to react to this

information. Formally, the optimizer *m* learns the true state of nature either before (n=C) or after (n=O) she makes her second period land use decision.

In the closed-loop problem, the order of events is as follows: the decision maker makes her first period land use decision, the rental rates for period one are determined for all locations within the municipality, the true state of nature is revealed, the decision maker makes her second period land use decision, and, finally, rental rates for period two are determined. Consequently, the closed-loop problem for decision maker *m* has the following specification:

$$(\mathbf{2})\quad W^{Cm} = \max_{\tilde{X}_1^{Cm}} \left\{ \int_0^{\tilde{X}_1^{Cm}} R_{i,1}^{Cm}\, dX_i + \int_{\tilde{X}_1^{Cm}}^{A} r_{i,1}^{Cm}\, dX_i + B \sum_{k\in\{L,H\}} p_k \max_{\tilde{X}_{2,k}^{Cm}} \left(\int_0^{\tilde{X}_{2,k}^{Cm}} R_{i,2,k}^{Cm}\, dX_i + \int_{\tilde{X}_{2,k}^{Cm}}^{A} r_{i,2,k}^{Cm} dX_i \right) \right\}$$

$$s.t. \tilde{X}_{2,k}^{Cm} \geq \tilde{X}_1^{Cm} \quad \forall m \in \{M, P\}.$$

In the open-loop problem, the order of events is as follows: the decision maker makes her first period land use decision, the rental rates for period one are determined for all locations within the municipality, the decision maker makes her second period land use decision, the true state of nature is revealed, and, finally, the rental rates in period two are determined. Thus, the open-loop problem for decision maker *m* has the following specification:

$$(\mathbf{3}) W^{Om} = \max_{\tilde{X}_1^{Om}, \tilde{X}_2^{Om}} \left\{ \int_0^{\tilde{X}_1^{Om}} R_{i,1}^{Om}\, dX_i + \int_{\tilde{X}_1^{Om}}^{A} r_{i,1}^{Om}\, dX_i + B \sum_{k\in\{L,H\}} p_k \left(\int_0^{\tilde{X}_2^{Om}} R_{i,2,k}^{Om}\, dX_i + \int_{\tilde{X}_2^{Om}}^{A} r_{i,2,k}^{Om}\, dX_i \right) \right\}$$

$$s.t. \tilde{X}_2^{Om} \geq \tilde{X}_1^{Om} \quad \forall m \in \{M, P\}.$$

<u>Land use policies.</u> This paper analyzes three land use policies: urban growth boundaries (UGBs), location-dependent development fees (LDFs), and location-independent development fees (LIFs). The first period closed-loop UGB is denoted $\bar{\bar{X}}_1^C$, and the state-dependent second period closed-loop UGBs are $\bar{\bar{X}}_{2,k}^C$. The UGBs enter the closed-loop problem as constraints on the amount of urban land: $\tilde{X}_1^{CM} \leq \bar{\bar{X}}_1^C$ in the first period problem and $\tilde{X}_{2,k}^{CM} \leq \bar{\bar{X}}_{2,k}^C$ in the second

period problem in state k. The first and second period open-loop UGBs are denoted as $\bar{\bar{X}}_1^O$ and $\bar{\bar{X}}_2^O$, and enter the open-loop problem as the following constraints: $\tilde{X}_1^{OM} \leq \bar{\bar{X}}_1^O$ and $\tilde{X}_2^{OM} \leq \bar{\bar{X}}_2^O$.

The first period closed-loop LDF at location X_i is denoted $D_{i,1}^C = D_1^C(X_i)$, and the state-dependent second period closed-loop LDFs at location X_i are $D_{i,2,k}^C = D_{2,k}^C(X_i)$. The terms $\int_0^{\tilde{X}_1^{CM}} D_1^C(X_i)dX_i$ and $\int_{\tilde{X}_1^{CM}}^{\tilde{X}_{2,k}^{CM}} D_{2,k}^C(X_i)\ dX_i$, representing the total value of LDFs assessed in the first and second periods if state k occurs, are included in the first period and second period-state k closed-loop optimization problems. The first and second period open-loop LDFs at location X_i are denoted $D_{i,1}^O = D_1^O(X_i)$ and $D_{i,2}^O = D_2^O(X_i)$ and enter the open-loop problem as additional terms in the open-loop objective function: $\int_0^{\tilde{X}_1^{OM}} D_1^O(X_i)dX_i$ and $B\sum_{k\in\{L,H\}} p_k \int_{\tilde{X}_1^{OM}}^{\tilde{X}_2^{OM}} D_2^O(X_i)\,dX_i$.

The first period closed-loop LIF is denoted F_1^C and the second period closed-loop LIF in state k is $F_{2,k}^C$. The total value of the LIFs assessed in each period and state are included in the appropriate objective function. The term $\int_0^{\tilde{X}_1^{CM}} F_1^C dX_i$ is included in the first period closed-loop optimization problem and $B\sum_{k\in\{L,H\}} p_k \int_{\tilde{X}_1^{CM}}^{\tilde{X}_{2,k}^{CM}} F_{2,k}^C\,dX_i$ is included in the second period closed-loop optimization problem in state k. The first and second period open-loop LIFs are denoted F_1^O and F_2^O, and enter the open-loop problem as additional terms in the objective function: $\int_0^{\tilde{X}_1^{OM}} F_1^O dX_i$ and $B\sum_{k\in\{L,H\}} p_k \int_{\tilde{X}_1^{OM}}^{\tilde{X}_2^{OM}} F_2^O\,dX_i$.

V. Solution Method

I solve for the expressions that define $\tilde{X}_{t,k}^{nm*}$ in the maximization problems specified in the previous section using three steps. First, I solve for the equilibrium rental rates for decision maker m as a function of X_j, y_t, $\bar{\bar{V}}_t$, and $\tilde{X}_{t,k}^{nm}$; these equilibrium rental rates apply to both the open-loop and closed-loop forms. Second, I solve for each problem's two-period Euler conditions. From this set of Euler conditions, I determine the expression for each problem's optimal amount of urban land. Finally, I derive the social welfare-maximizing land-use policies under each type of control problem by comparing Euler conditions between problems.[4]

Determining equilibrium rental rates. All tenants receive their exogenous reservation utility, $\bar{\bar{V}}_t$, in equilibrium, which implies that one of the following two conditions applies to every X_j in equilibrium: $V\left(y_t - T(X_j) - R_{j,t,k}^{nm}, 1, S_{j,t,k}^{nm}\right) = \bar{\bar{V}}_t$ when X_j is urbanized and $V\left(\Pi(X_j) - r_{j,t,k}^{nm}, 1, S_{j,t,k}^{nm}\right) = \bar{\bar{V}}_t$ when X_j is in agriculture. Invoking the implicit function theorem, there exists some function $\hat{h}$ such that $c_{j,t,k}^{nm} = \hat{h}\left(g_{j,t,k}^{nm}, S_{j,t,k}^{nm}, \bar{\bar{V}}_t\right)$. Therefore, $R_{j,t,k}^{nm} = y_t - T(X_j) - \hat{h}\left(g_{j,t,k}^{nm}, S_{j,t,k}^{nm}, \bar{\bar{V}}_t\right)$ and $r_{j,t,k}^{nm} = \Pi(X_j) - \hat{h}\left(g_{j,t,k}^{nm}, S_{j,t,k}^{nm}, \bar{\bar{V}}_t\right)$ by the tenant budget constraints. The equilibrium rental rate for each landlord and social planner problem are obtained by substituting the appropriate definition of $S_{j,t,k}^{nm}$.

Determining the Euler Conditions. In order to obtain each problem's Euler conditions, I rewrite each problem as a Lagrangian function. The Euler conditions for the open-loop problems are found by solving the Lagrangian in the traditional manner. Because the irreversibility constraint is conditional on the realized second period state in the closed-loop problem, the Lagrange multiplier is state dependent in each close-loop problem and the corresponding Euler conditions are found recursively. In the landlord problems, $R_{j,t,k}^{nM}$ and $r_{j,t,k}^{nM}$ are replaced by $R_{j,t,k}^{nP}$ and $r_{j,t,k}^{nP}$ after taking the first order conditions in order to solve for their Euler conditions because the landlord does not consider the effect of the amount of urban land on the net land use externality at each X_j. The four maximization problems are presented below.

[4] I assume in this solution that the government can credibly bind its hands when determining land use policy. In section VII, I demonstrate that all three policies are time consistent if there is no cumulative environmental externality.

The closed-loop landowner profit-maximization problem with LDFs becomes

$$\mathbf{W^{CM}} = \max_{\tilde{X}_1^{CM}} \left\{ \begin{array}{c} \int_0^{\tilde{X}_1^{CM}} \bar{R}_1\left(y_1, \bar{\bar{V}}_1, X\right) \, dX + \int_0^{\tilde{X}_1^{CM}} D_1^C(X_i) dX_i + \int_{\tilde{X}_1^{CM}}^{A} \bar{r}_1\left(\bar{\bar{V}}_1, \mathrm{X}\right) dX + \\ B \sum_{k \in \{L,H\}} p_k \max_{\tilde{X}_{2,k}^{CM}} \left(\int_0^{\tilde{X}_{2,k}^{CM}} \bar{R}_{2,k}\left(y_2, \bar{\bar{V}}_2, X\right) dX + \int_{\tilde{X}_1^{CM}}^{\tilde{X}_{2,k}^{CM}} D_{2,k}^C(X_i) \, dX_i + \int_{\tilde{X}_{2,k}^{CM}}^{A} \bar{r}_{2,k}\left(\bar{\bar{V}}_2, X\right) dX \right) \end{array} \right\}$$

$$s.t. \tilde{X}_{2,k}^{CM} \geq \tilde{X}_1^{CM} \; \forall k \in \{L, H\}.$$

The open-loop landowner profit-maximization problem becomes

$$\mathbf{W^{OM}} = \max_{\tilde{X}_1^{OM}, \tilde{X}_2^{OM}} \left\{ \begin{array}{c} \int_0^{\tilde{X}_1^{OM}} \bar{R}_1\left(y_1, \bar{\bar{V}}_1, X\right) \, dX + \int_0^{\tilde{X}_1^{OM}} D_1^O(X_i) dX_i + \int_{\tilde{X}_1^{OM}}^{A} \bar{r}_1\left(\bar{\bar{V}}_1, X\right) dX + \\ B \sum_{k \in \{L,H\}} p_k \left(\int_0^{\tilde{X}_2^{OM}} \bar{R}_{2,k}\left(y_2, \bar{\bar{V}}_2, X\right) dX + \int_{\tilde{X}_1^{OM}}^{\tilde{X}_2^{OM}} D_2^O(X_i) \, dX_i + \int_{\tilde{X}_2^{OM}}^{A} \bar{r}_{2,k}\left(\bar{\bar{V}}_2, X\right) dX \right) \end{array} \right\}$$

$$s.t. \tilde{X}_2^{OM} \geq \tilde{X}_1^{OM}.$$

By setting $D_1^n(X_i) = F_1^n$, $D_2^O(X_i) = F_2^O$, and $D_{2,k}^C(X_i) = F_{2,k}^C$, the landlord profit maximization problems with LIFs are derived. By setting $D_1^n(X_i) = D_2^O(X_i) = D_{2,k}^C(X_i) = 0$, the landlord profit maximization problems are derived. By setting $D_1^n(X_i) = D_2^O(X_i) = D_{2,k}^C(X_i) = 0$ and imposing $\tilde{X}_1^{nM} \leq \bar{\bar{X}}_1^n$, $\tilde{X}_2^{OM} \leq \bar{\bar{X}}_2^O$, $\tilde{X}_{2,k}^{CM} \leq \bar{\bar{X}}_{2,k}^C \; \forall k \in \{L, H\}$ in the corresponding problem, the landlord profit maximization problems with UGBs are derived. The closed-loop social planner problem becomes

$$\mathbf{W^{CP}} = \max_{\tilde{X}_1^{CP}} \left\{ \begin{array}{c} \int_0^{\tilde{X}_1^{CP}} R_1\left(y_1, \bar{\bar{V}}_1, X, \tilde{X}_1^{CP}\right) \, dX + \int_{\tilde{X}_1^{CP}}^{A} r_1\left(\bar{\bar{V}}_1, X, \tilde{X}_1^{CP}\right) dX + \\ B \sum_{k \in \{L,H\}} p_k \max_{\tilde{X}_{2,k}^{CP}} \left(\int_0^{\tilde{X}_{2,k}^{CP}} R_{2,k}\left(y_2, \bar{\bar{V}}_2, X, \tilde{X}_1^{CP}, \tilde{X}_{2,k}^{CP}\right) dX + \int_{\tilde{X}_{2,k}^{CP}}^{A} r_{2,k}\left(\bar{\bar{V}}_2, X, \tilde{X}_1^{CP}, \tilde{X}_{2,k}^{CP}\right) dX \right) \end{array} \right\}$$

$$s.t. \tilde{X}_{2,k}^{CP} \geq \tilde{X}_1^{CP} \; \forall k \in \{L, H\}.$$

The open-loop social planner problem becomes

$$\mathbf{W^{OP}} = \max_{\tilde{X}_1^{OP},\tilde{X}_2^{OP}} \left\{ \begin{array}{c} \int_0^{\tilde{X}_1^{OP}} R_1\left(y_1, \bar{\bar{V}}_1, X, \tilde{X}_1^{OP}\right)\, dX + \int_{\tilde{X}_1^{OP}}^{A} r_1\left(\bar{\bar{V}}_1, X, \tilde{X}_1^{OP}\right) dX + \\ B \sum_{k \in \{L,H\}} p_k \left(\int_0^{\tilde{X}_2^{OP}} R_{2,k}\left(y_2, \bar{\bar{V}}_2, X, \tilde{X}_1^{OP}, \tilde{X}_2^{OP}\right) dX + \int_{\tilde{X}_2^{OP}}^{A} r_{2,k}\left(\bar{\bar{V}}_2, X, \tilde{X}_1^{OP}, \tilde{X}_2^{OP}\right) dX \right) \end{array} \right\}$$

$$s.t. \tilde{X}_2^{OP} \geq \tilde{X}_1^{OP}.$$

Because the policy question that I address is of little relevance in cases where corner solutions are optimal, I restrict attention to internal solutions in all cases.

VI. Privately and Socially Optimal Equilibria

This section discusses the competitive equilibria and social optima obtained using the procedure detailed in the previous section. First, it discusses the Euler conditions for the open-loop and closed-loop social planner and landlord problems without land-use policies; these are displayed in the appendix. Second, this section derives the sufficient second-order conditions for a unique global maximum, and discusses their implications.

First Order Conditions. The first-order conditions differ across the four models without land use policies. As a consequence, the location of the landlord who is indifferent between renting for agricultural or urban purposes differs across the four models. These differences occur for two reasons. First, unlike the landlord problems, the social cost of development is included in the social planner problems. Second, while there are two potential solution regimes for the open-loop problems, there are four potential solution regimes in the closed-loop landlord problems; the open-loop and closed-loop problems' solution regimes are differentiated by whether or not the irreversibility constraint or irreversibility constraints bind, i.e. $\tilde{X}_2^{Om^*} \genfrac{}{}{0pt}{}{=}{>} \tilde{X}_1^{Om^*}$ or $\tilde{X}_1^{Cm^*} \genfrac{}{}{0pt}{}{=}{>} \tilde{X}_{2,k}^{Cm^*}$, respectively.

Landlord versus social planner.

The Euler conditions for the open-loop and closed-loop landlord problems imply that the amount of urban land should increase until the expected value of the marginal unit of urban land equals the expected value of the marginal unit of open space. The Euler conditions for the open-loop and closed-loop social planner problems differ from the Euler conditions for the corresponding landlord problem due to the inclusion of the marginal external cost of urban development. The marginal external cost of urban development has three components in the social planner problems:

$$C_1^{nP} = C_1\left(\tilde{X}_1^{nP^*}\right) = \int_0^{\tilde{X}_1} \frac{\partial R_1\left(y_1,\overline{\overline{V}}_1,X_i,\tilde{X}_1\right)}{\partial \tilde{X}_1} dX_i + \int_{\tilde{X}_1}^{A} \frac{\partial r_1\left(\overline{\overline{V}}_1,X_i,\tilde{X}_1\right)}{\partial \tilde{X}_1} dX_i =$$

$$\int_0^A \frac{\frac{\partial V}{\partial S_1}\left(h_1\left(X_i,\tilde{X}_1,\overline{\overline{V}}_1\right),1,S_1\left(X_i,\tilde{X}_1\right)\right)}{\frac{\partial V}{\partial c_1}\left(h_1\left(X_i,\tilde{X}_1,\overline{\overline{V}}_1\right),1,S_1\left(X_i,\tilde{X}_1\right)\right)} \frac{\partial S_1}{\partial \tilde{X}_1} dX_i;$$

$$G_k^{nP} = G_k\left(\tilde{X}_1^{nP^*},\tilde{X}_2^{nP^*}\right) = \int_0^{\tilde{X}_2} \frac{\partial R_{2,k}\left(y_2,\overline{\overline{\overline{V}}}_2,X_i,\tilde{X}_1,\tilde{X}_2\right)}{\partial \tilde{X}_1} dX_i + \int_{\tilde{X}_2}^{A} \frac{\partial r_{2,k2}\left(\overline{\overline{\overline{V}}}_2,X_i,\tilde{X}_1,\tilde{X}_2\right)}{\partial \tilde{X}_1} dX_i =$$

$$\int_0^A \frac{\frac{\partial V}{\partial S_{2,k}}\left(h_{2,k}\left(X_i,\tilde{X}_1,\tilde{X}_{2,k},\overline{\overline{\overline{V}}}_2\right),1,S_{2,k}\left(X_i,\tilde{X}_1,\tilde{X}_2\right)\right)}{\frac{\partial V}{\partial C_{2,k}}\left(h_{2,k}\left(X_i,\tilde{X}_1,\tilde{X}_{2,k},\overline{\overline{\overline{V}}}_2\right),1,S_{2,k}\left(X_i,\tilde{X}_1,\tilde{X}_2\right)\right)} \frac{\partial S_{2,k}}{\partial \tilde{X}_1} dX_i;$$

$$C_{2,k}^{nP} = C_{2,k}\left(\tilde{X}_1^{nP^*},\tilde{X}_2^{nP^*}\right) = \int_0^{\tilde{X}_2} \frac{\partial R_{2,k}\left(y_2,\overline{\overline{\overline{V}}}_2,X_i,\tilde{X}_1,\tilde{X}_2\right)}{\partial \tilde{X}_2} dX_i + \int_{\tilde{X}_2}^{A} \frac{\partial r_{2,k}\left(\overline{\overline{\overline{V}}}_2,X_i,\tilde{X}_1,\tilde{X}_2\right)}{\partial \tilde{X}_2} dX_i =$$

$$\int_0^A \frac{\frac{\partial V}{\partial S_{2,k}}\left(h_{2,k}\left(X_i,\tilde{X}_1,\tilde{X}_{2,k},\overline{\overline{\overline{V}}}_2\right),1,S_{2,k}\left(X_i,\tilde{X}_1,\tilde{X}_2\right)\right)}{\frac{\partial V}{\partial c_{2,k}}\left(h_{2,k}\left(X_i,\tilde{X}_1,\tilde{X}_{2,k},\overline{\overline{\overline{V}}}_2\right),1,S_{2,k}\left(X_iX,\tilde{X}_1,\tilde{X}_2\right)\right)} \frac{\partial S_{2,k}}{\partial \tilde{X}_2} dX_i.$$

The first term $C_1\left(\tilde{X}_1^{nP^*}\right)$ is the marginal external cost of first period urban development on total (municipality-wide) first period rents, or the sum of the marginal changes in rent $\forall X_i \in [O,A]$ due to the change in the net land use externality in period 1 if the amount of urban area expands by one unit in period 1. $G_k\left(\tilde{X}_1^{nP^*},\tilde{X}_2^{nP^*}\right)$ is the marginal external cost of first period urban development on total second period rents in state k resulting from the cumulative environmental effect of development, or the sum of the marginal changes in rent $\forall X_i \in [O,A]$ due to the change in the net land use externality in period 2 through the cumulative effect of development if the amount of urban area expands by one unit in period 1 and state k occurs. Unlike the other two components, the interpretation of $C_{2,k}\left(\tilde{X}_1^{nP^*}, \tilde{X}_2^{nP^*}\right)$ depends on whether the irreversibility constraint or constraints bind because $C_{2,k}\left(\tilde{X}_1^{nP^*}, \tilde{X}_2^{nP^*}\right)$ is captured in the Lagrange multipliers. If the corresponding irreversibility constraint is non-binding then $C_{2,k}^{nP}$ is the marginal external cost of second period urban development on total second period rents in state k, or the sum of the marginal changes in rent $\forall X_i \in [O, A]$ due to the change in the net land use externality in period 2 if the amount of urban area expands by one unit in period 2 and state k occurs. If the corresponding irreversibility constraint is binding, $C_{2,k}^{nP}$ is the marginal external cost of first period urban development on total second period rents if state k occurs resulting from the irreversibility of urban development, or the sum of the marginal changes in rent $\forall X_i \in [O, A]$ due to the change in the net land use externality in period 2 through the irreversibility of development if the amount of urban area expands by one unit in period 1 and state k occurs. In the appendix, I prove that each component is non-positive and that they differ in magnitude across the open-loop and closed-loop social planner problems; the two exceptions to this latter rule are when the socially optimal amounts of urban land are equal across the two problems, i.e. $\tilde{X}_1^{OP^*} = \tilde{X}_1^{CP^*}$ and $\tilde{X}_2^{OP^*} = \tilde{X}_{2,H}^{CP^*} = \tilde{X}_{2,L}^{CP^*}$, or when all three components of the marginal external cost of urban development are constant with respect to the amount of urban land.

Open-loop versus closed-loop.

The key difference between the open-loop and closed-loop problems is the number of irreversibility constraints. Because the interpretation of $C_{2,k}^{nP}$ depends on whether the corresponding irreversibility constraint binds, the expected marginal external cost of first period and second period urban development can differ between the open-loop and closed-loop social planner problems. If the irreversibility constraint is non-binding in the open-loop social planner problem, the expected marginal external cost of first period urban development is $C_1^{nP} + B\sum_{k\in[L,H]} p_k G_k^{nP}$ and the expected marginal external cost of second period urban development is $\sum_{k\in[L,H]} p_k\, C_{2,k}^{nP}$; this is also holds in the closed-loop social planner problem if both irreversibility constraints do not bind. If the irreversibility constraint is binding in the open-loop social planner problem, the expected marginal external cost of first period urban development is $C_1^{nP} + B\sum_{k\in[L,H]} p_k G_k^{nP} + B\sum_{k\in[L,H]} p_k\, C_{2,k}^{nP}$ and there is no marginal external cost of second period urban development; this is also case in the closed-loop social planner problem if both irreversibility constraints bind. Unlike the open-loop social planner problem, the closed-loop social planner problem can simultaneously have binding and non-binding irreversibility constraints. If only the irreversibility constraint in state *H* binds then there is no development in period 2 if state H is realized, the expected marginal external cost of first period urban development is $C_1^{CP} + B\sum_{k\in[L,H]} p_k G_k^{CP} + Bp_H C_{2,H}^{CP}$ and the marginal external cost of second period urban development in state L is $C_{2,L}^{CP}$. Expected marginal external costs have a similar form if only the irreversibility constraint in state *L* binds.

This discussion leads to the following remarks.

Remark 1: *Regardless of which state is realized in the second period, the competitive equilibrium amounts of urban land are identical under open-loop and closed-loop control in each period.*

Remark 2: *In each period, the socially optimal amount of urban land is always less than or equal to the privately optimal amount under open-loop and closed-loop control.*

The intuition behind the first remark is that landowners do not face uncertainty in their decision-making process because agricultural profits are unaffected by climate change, landowners do not account for the effect of their land use decisions on other landowners' welfare or land use decisions, and agricultural and urban tenants are equally affected by the net land use externality.

As a consequence, landowners do not gain information relevant to their decision making process under closed-loop versus open-loop control. The second remark follows from landlords' failure to consider the external cost of their development decisions on surrounding tenants.

Second order conditions. Given that I restrict attention to interior solution and the irreversibility constraints are convex, there is a unique global maximum for each model if the value function is concave. An objective functions is strictly concave (and hence concave) if its Hessian matrix is negative definite. In the open-loop and closed-loop landlord problems, the objective functions are strictly concave because the necessary and sufficient conditions for their Hessian matrices to be negative definite, i.e. $\frac{\partial T(X)}{\partial X}+\frac{\partial \Pi(X)}{\partial X}>0\ \ \forall X_j$ and $0<p_H<1$, hold by earlier assumptions. In the open-loop social planner problem, the necessary and sufficient conditions for a strictly concave objective function are that the marginal change in the expected present value of total rent with respect to the amount of urban land in the first period must decline in the amount of urban land in the first period, i.e. $\frac{\partial C_1}{\partial \tilde{X}_1}+B\sum_{k\in\{L,H\}}p_k\frac{\partial G_k}{\partial \tilde{X}_1}-\frac{\partial T}{\partial X}-\frac{\partial \Pi}{\partial X}<0$, and that the product of the expected within period effects of development must be greater than the product of the expected between period effects of development, i.e. $\left(\frac{\partial C_1}{\partial \tilde{X}_1}+B\sum_{k\in\{L,H\}}p_k\frac{\partial G_k}{\partial \tilde{X}_1}-\frac{\partial T}{\partial X}-\frac{\partial \Pi}{\partial X}\right)\left(\sum_{k\in\{L,H\}}p_k\frac{\partial C_{2,k}}{\partial \tilde{X}_2}-\frac{\partial T}{\partial X}-\frac{\partial \Pi}{\partial X}\right)>B\left(\sum_{k\in\{L,H\}}p_k\frac{\partial C_{2,k}}{\partial \tilde{X}_1}\right)^2$.

In the closed-loop social planner problem, the necessary and sufficient conditions for a strictly concave objective function are that: the marginal change in the expected present value of total rent with respect to the amount of urban land in the first period must decline in the amount of urban land in the first period, i.e. $\frac{\partial C_1}{\partial \tilde{X}_1}+B\sum_{k\in\{L,H\}}p_k\frac{\partial G_k}{\partial \tilde{X}_1}-\frac{\partial T}{\partial X}-\frac{\partial \Pi}{\partial X}<0$; the product of the rate of change described in the first condition and the change in the marginal change in the expected present value of total rent with respect to the amount of urban land in the second period when state H occurs resulting from an increase in the amount of urban land in the second period when state H occurs must be greater than the square of the change in the marginal change in the expected present value of total rent with respect to the amount of urban land in the second period when state H occurs resulting from an increase in the amount of urban land in the first period, i.e. $\left(\frac{\partial C_1}{\partial \tilde{X}_1} + B\sum_{k\in\{L,H\}} p_k \frac{\partial G_k}{\partial \tilde{X}_1} - \frac{\partial T}{\partial X} - \frac{\partial \Pi}{\partial X}\right)\left(\frac{\partial C_{2,H}}{\partial \tilde{X}_{2,H}} - \frac{\partial T}{\partial X} - \frac{\partial \Pi}{\partial X}\right) > Bp_H\left(\frac{\partial C_{2,H}}{\partial \tilde{X}_1}\right)^2$; and a difficult to interpret third condition, $\frac{\partial C_1}{\partial \tilde{X}_1} + B\sum_{k\in\{L,H\}} p_k \frac{\partial G_k}{\partial \tilde{X}_1} - \frac{\partial T}{\partial X} - \frac{\partial \Pi}{\partial X} < \frac{Bp_H \frac{\partial C_{2,H}}{\partial \tilde{X}_1}\frac{\partial G_H}{\partial \tilde{X}_{2,H}}}{\frac{\partial C_{2,H}}{\partial \tilde{X}_{2,H}} - \left(\frac{\partial T}{\partial X} + \frac{\partial \Pi}{\partial X}\right)} + \frac{Bp_L \frac{\partial C_{2,L}}{\partial \tilde{X}_1}\frac{\partial G_L}{\partial \tilde{X}_{2,L}}}{\frac{\partial C_{2,L}}{\partial \tilde{X}_{2,L}} - \left(\frac{\partial T}{\partial X} + \frac{\partial \Pi}{\partial X}\right)}$.

Given the complexity of the sets of necessary and sufficient conditions for the closed-loop problems, I derive and use sufficient conditions for the remainder of my analysis. Doing so provides results that can be explained intuitively. Because many of my key results depend on whether or not there are cumulative environmental externalities from urban development, I define two sets of sufficient conditions that guarantee that the objective function is strictly concave in all four problems. Only the strong sufficient conditions guarantee that there are zero cumulative environmental externalities. Though cumulative environmental externalities and the irreversibility of urban development are separate land use issues, the former affects the cost of the latter in two ways. First, it changes the magnitude of the cost of irreversibility by decreasing second period rents. Second, this decrease in second period rents affects whether or not the irreversibility constraints bind and, hence, whether or not a cost of irreversibility is realized.

The strong conditions are the more restrictive of the two sets of conditions. The strong sufficient conditions for a unique global maximum are:

(i) $\frac{\partial^2 S_1}{\partial \tilde{X}_1{}^2} \leq 0$ **(ii)** $\frac{\partial^2 S_{2,k}}{\partial \tilde{X}_{2,k}{}^2} \leq 0$ and **(iii)** $\frac{\partial S_{2,k}}{\partial \tilde{X}_1} = 0$.

These three conditions state that the first period net land use externality decreases at an increasing rate in the amount of urban land in the first period, the second period net land use externality in state k decreases at an increasing rate in the amount of urban land in the second period, and there is no cumulative environmental externality from development in the first period. The final condition implies that the marginal external cost of first period urban development on total second period rents in state k resulting from the cumulative environmental effect of development equals zero, i.e. $G_k\left(\tilde{X}_1^{nm}, \tilde{X}_{2,k}^{nm}\right) = 0$, and that the marginal external cost of second period urban development on total second period rents in state k is not a function of the amount of urban land in the first period, i.e. there exists a function, $\hat{C}_{2,k}$, such that $C_{2,k}\left(\tilde{X}_1^{nm}, \tilde{X}_{2,k}^{nm}\right) = \hat{C}_{2,k}\left(\tilde{X}_{2,k}^{nm}\right)$.

While the assumption of no cumulative environmental externality is analytically tractable, this assumption may not hold in the real world. Therefore, I define a weaker set of five sufficient conditions that allow for non-zero cumulative environmental externalities. The weak sufficient conditions for a unique global maximum are:

(i′) $\frac{\partial^2 S_1}{\partial \tilde{X}_1{}^2} \leq 0$ **(ii′)** $\frac{\partial^2 S_{2,k}}{\partial \tilde{X}_{2,k}{}^2} \leq 0$ **(iii′)** $\frac{\partial^2 S_{2,k}}{\partial \tilde{X}_1{}^2} \leq 0$ **(iv′)** $\frac{\partial S_{2,k}}{\partial \tilde{X}_1 \partial \tilde{X}_{2,k}} \leq 0$

$$\textbf{(v′)} \left\{ \begin{array}{c} \frac{\partial C_1}{\partial \tilde{X}_1} + B \sum_{k \in \{L,H\}} p_k \frac{\partial G_k}{\partial \tilde{X}_1} - \frac{\partial T}{\partial X} - \frac{\partial \Pi}{\partial X} \\ < \min \left[\frac{B \sum_{k \in \{L,H\}} p_k \frac{\partial G_k}{\partial \tilde{X}_2} \sum_{k \in \{L,H\}} p_k \frac{\partial C_{2,k}}{\partial \tilde{X}_1}}{\sum_{k \in \{L,H\}} p_k \frac{\partial C_{2,k}}{\partial \tilde{X}_2} - \frac{\partial T}{\partial X} - \frac{\partial \Pi}{\partial X}}, \frac{B p_H \frac{\partial C_{2,H}}{\partial \tilde{X}_1} \frac{\partial G_H}{\partial \tilde{X}_{2,H}}}{-\left(\frac{\partial T}{\partial X} + \frac{\partial \Pi}{\partial X}\right) + \frac{\partial C_{2,H}}{\partial \tilde{X}_{2,H}}} + \frac{B p_L \frac{\partial C_{2,L}}{\partial \tilde{X}_1} \frac{\partial G_L}{\partial \tilde{X}_{2,L}}}{-\left(\frac{\partial T}{\partial X} + \frac{\partial \Pi}{\partial X}\right) + \frac{\partial C_{2,L}}{\partial \tilde{X}_{2,L}}} \right] \end{array} \right\}.$$

Conditions **(i′) - (iv′)** state that the net land use externality functions are decreasing at a non-decreasing rate in the amounts of urban land in each period and future state. Condition **(v’)** is a combination of the second necessary and sufficient condition in the open-loop social planner problem and the third necessary and sufficient condition in the closed-loop social planner problem.

VII. Key Results

The results of this paper depend on which set of sufficient conditions for a unique global maximum holds. Under the strong sufficient conditions, the net benefit functions are separable in their decision variables and the value function is quasi-concave. As a consequence, the irreversibility effect holds (Freixas and Laffont, 1984). Under the weak sufficient conditions, the irreversibility effect does not necessarily hold without additional assumptions, such as the sufficient conditions laid out in Epstein (1980) and Ulph and Ulph (1997). I explore the effect of these assumptions in this section.

This section is divided into two parts. The first subsection derives a series of propositions about optimal land use policies under the strong sufficient conditions for a unique global maximum. The second subsection demonstrates that some of these results do not necessarily hold under the weak sufficient conditions for a unique global maximum.

Strong sufficient conditions. Here I compare the socially optimal amounts of urban land in the open-loop and closed-loop social planner problems. Because the first and second period rental rates are separable in their decision variables under the strong sufficient conditions, Freixas and Laffont (1984) has the following implications in this context.

Remark 3: *Assuming that the strong sufficient conditions for a unique global maximum hold, the socially optimal amount of urban land in the first period under closed-loop control is less than or equal to the amount under open-loop control. In other words, the irreversibility effect holds (Felix and Laffont, 1984).*
Corollary 3a: *In the first period, the difference between the socially and privately optimal amounts of urban land under closed-loop control is greater than or equal to this difference under open-loop control.*
Corollary 3b: *The socially optimal first-period UGB is equal or greater in magnitude under open-loop control than closed-loop control.*

Corollary 3a is implied by Remark 1 and Remark 3, which together guarantee that $\tilde{X}_1^{CM^*} - \tilde{X}_1^{CP^*} \geq \tilde{X}_1^{OM^*} - \tilde{X}_1^{OP^*}$. Corollary 3b follows directly from Remark 3 because the socially optimal UGB in period *t* and state *k* equals the socially optimal amount of urban land in period *t* and state *k* regardless of the type of control problem, i.e. $\bar{\bar{X}}_{t,k}^{n*} = \tilde{X}_{t,k}^{nP^*}$.[5]

Remark 3 and its corollaries indicate that the socially optimal amount of urban land can differ between open-loop and closed-loop control. Hence, policymakers should account for the difference between private and social values of information when determining land use policy if the strong sufficient conditions for a unique global maximum hold. Policymakers who account for the future availability of information when setting land use policies may reduce development more than those who ignore it. For example, urban growth boundaries are more restrictive under closed-loop control than under open-loop control. Local policymakers should pay particular attention if climate change has a wide range of potential effects on vegetation in their area.

Private and social values of information.

In all four problems shown in Table 1, the value function is the present value of expected land rents:

$$\mathbf{W}^{\mathbf{nm}*} = W\left(\tilde{X}_1^{nm^*}, \tilde{X}_{2,H}^{nm^*}, \tilde{X}_{2,L}^{nm^*}\right)$$
$$= \int_0^{\tilde{X}_1^{nm^*}} R_1^{nm*} dX + \int_{\tilde{X}_1^{nm^*}}^{A} r_1^{nm*} dX + B \sum_{k\in\{L,H\}} p_k \left\{ \int_0^{\tilde{X}_{2,k}^{nm^*}} R_{2,k}^{nm*} dX + \int_{\tilde{X}_{2,k}^{nm*}}^{A} r_{2,k}^{nm*} dX \right\}.$$

The private and social values of information are the difference between the value function evaluated at the closed-loop and open-loop competitive equilibrium and socially optimal amounts of urban land, respectively; i.e. $\mathrm{I}^{\mathrm{m}*} = \mathrm{W}^{\mathrm{Cm}*} - \mathrm{W}^{\mathrm{Om}*}$. Because Remark 1 implies that the private value of information equals zero, i.e. $\mathrm{I}^{\mathrm{M}*} = 0$, the difference between the social and private values of information reduces to the social value of information. A decision maker cannot be made worse off by new information, so $\mathrm{I}^{\mathrm{P}*} \geq 0$. More specifically,

[5] A closely related finding is that the socially optimal amount of urban land in the first period under closed-loop control is less than the amount under open-loop control if the strong sufficient conditions hold and one and only one irreversibility constraint binds in the closed-loop social planner problem. The proof can be provided by the author on request.

Remark 4: *The social value of information must be greater than zero when the additional information available under closed-loop control causes the social planner to change her optimal land-use decision in at least one of the periods or future states from the solution under open-loop control.*

However, a positive social value of information is not a sufficient condition for the irreversibility effect to hold.

Development fees.

In both the open-loop and closed-loop problems, the first and second period LDFs are non-decreasing in landlord distance from the CBD. For each location within the municipality, i.e. $\forall X \in [0, A]$, the optimal first period location–dependent development fee equals the present value of the expected external cost of developing X in the first period regardless of the type of control problem. When there is no cumulative environmental externality, the external cost of developing the property located at X in the first period is the sum of the external cost of developing the property located at X in the first period on total first period rent and the present value of the expected external cost of developing the property located at X in the first period on total second period rent resulting from the irreversibility of development. The optimal second period development fee at location X in the open-loop problem is the expected external cost of developing the property located at X in the second period on total second period rent. In the closed-loop problem, the optimal second period development fee at location X in state k is the external cost of developing the property located at X in the second period on total second period rent if state k occurs. Formally, ${D_{i,1}^{n}}^{*} = D_1^{n*}(X) = C_1(X) + B \sum_{k\in\{L,H\}} p_k \hat{C}_{2,k}(X)\ \forall n \in \{O, C\}$, ${D_{i,2}^{O}}^{*} = {D_2^{O}}^{*}(X) = \sum_{k\in\{L,H\}} p_k \hat{C}_{2,k}(X)$, and ${D_{i,2,k}^{C}}^{*} = {D_{2,k}^{C}}^{*}(X) = \hat{C}_{2,k}(X)$.

If the strong sufficient conditions for a unique global maximum hold, the optimal open-loop and closed-loop LDFs in period t at location $X_i \in [0, A]$ are not functions of the socially optimal amounts of urban land, and thus their expected values are equal. Intuitively, the components of the closed-loop and open-loop marginal external costs of urban development only differ because they are functions of different solutions for the amounts of urban land. Because the marginal external cost of development in period *t* is a function of only the amount of urban land in period *t* under the strong sufficient conditions, the expected external cost of developing a property at location *X* in period *t* is only a function of location. As a consequence, the expected external cost of developing a property at location *X* in period *t* is identical for the open-loop and closed-loop problems. Summarizing,

Proposition 1: *Assuming that the strong sufficient conditions for a unique global maximum hold, the open-loop and closed-loop optimal LDFs are identical in the first period. The expected value of the optimal second period LDFs under closed-loop control equals the optimal second-period location-dependent development under open-loop control.*

This proposition is proved in the appendix.

In both the open-loop and closed-loop problems, the optimal first period LIF equals the present value of the expected marginal external cost of urban development over time. In the open-loop problem, the optimal second period development fee equals the expected marginal external cost of second period urban development. In the closed-loop problem, the optimal second period development fee in state k equals the marginal external cost of second period urban development if state k occurs. Formally, $F_1^{n^*} = C_1\left(\tilde{X}_1^{nP^*}\right) + B \sum_{k \in \{L,H\}} p_k \hat{C}_{2,k}\left(\tilde{X}_{2,k}^{nP^*}\right)$ $\forall n \in \{O, C\}$, $F_2^{O^*} = \sum_{k \in \{L,H\}} p_k \hat{C}_{2,k}\left(\tilde{X}_2^{OP^*}\right)$, and ${F_{2,k}^{C}}^* = \hat{C}_{2,k}\left(\tilde{X}_{2,k}^{CP^*}\right)$ $\forall k \in \{L, H\}$.

For LIFs, a result corresponding to proposition 1 does not exist. Unlike LDFs, LIFs are functions of the socially optimal amounts of urban land. Consequently, the optimal open-loop and closed-loop first period LIFs differ in value unless $\tilde{X}_1^{OP^*} = \tilde{X}_1^{CP^*}$ and $\tilde{X}_2^{OP^*} = {\tilde{X}_{2,H}^{CP}}^* = {\tilde{X}_{2.L}^{CP}}^*$, which occurs when both irreversibility constraints bind in the closed-loop social planner problem, or when each component of the marginal external cost of urban development is constant with respect to the amount of urban. Because the second period LIFs are also functions of the socially optimal amounts of urban land, the expected value of the optimal closed-loop second period LIFs differs from the optimal open-loop second-period LIF when the strong sufficient conditions hold, unless one of the previous exceptions hold.

The preceding analysis in this section has established that under the strong sufficient conditions for a unique global maximum, the LDFs are robust to the type of control problem, while UGBs and LIFs are not robust. More specifically, the first period closed-loop UGB is more restrictive than the first-period open-loop UGB because the former is less than or equal to the latter (corollary 3b). While the sign of the difference between open-loop and closed-loop LIFs is unknown without additional assumptions, LIFs differ across the control problems, except under limited conditions. This suggests an advantage of LDFs: LDFs may be able to achieve the socially optimal outcome even if policymakers do not account for the future availability of information about the effects of climate change when determining current land use policy. However, this conclusion cannot be drawn unless LDFs are time consistent.

Time consistency of the socially optimal policies.

Earlier, I assumed that the government could credibly bind its hands when determining land use policy in order to solve for the socially optimal policies. If this assumption is relaxed, the possibility of time inconsistency must be addressed because rational landlords choose their first period action knowing that the government has an incentive to re-optimize in the second period, unless economic agents' first period decisions are unaffected by the second period policy, i.e. $\frac{\partial \tilde{X}_1^{CM^*}}{\partial \bar{\bar{X}}_{2,k}^C} = 0$, $\frac{\partial \tilde{X}_1^{CM^*}}{\partial D_{i,2,k}^C} = 0$, and $\frac{\partial \tilde{X}_1^{CM^*}}{\partial F_{2,k}^C} = 0$ (Kydland and Prescott 1977).

Under the strong sufficient conditions, socially optimal open-loop and closed-loop policies are time consistent, as demonstrated in the appendix. The first period optimal closed-loop policy in each case equals the first-period time consistent policy found in the corresponding Stackelberg problem.

Proposition 2: *When the strong sufficient conditions for a unique global maximum hold, the socially optimal land use policies (UGBs, LDFs, and LIFs) are time consistent.*

Intuitively, landlords have no incentive to deviate from the socially optimal decision if such a deviation has no effect on the socially optimal second period policy.

Open-loop feedback control

Together, the robustness of location-dependent development fees to the type of control problem (proposition 1) and their time consistency (proposition 2) indicate that LDFs are likely to achieve the socially optimal amount of urban land under a variety of informational assumptions. To the extent that policymakers do not account for future learning, an open-loop feedback control problem is an alternative set of informational assumptions observable in the real world. In this type of problem, the social planner's decision making processes are best represented by an open-loop control problem. Accordingly, rational landowners recognize that policymakers will update policies when future information becomes available.

This problem is solved by modifying the Stackelberg two period game such that the landlord makes her first period land use decision subject to the first period open-loop policy and the policy updating process. Two resulting propositions hold.

Proposition 3. *If LDFs are chosen optimally by a social planner and the strong sufficient conditions for a unique maximum hold, then the amount of development in an open-loop feedback control problem equals the amount in the closed-loop social planner problem.*

Proposition 4: *If a social planner optimally chooses UGBs and the strong sufficient conditions for a unique maximum hold, the amount of urban land in the first period of the open-loop feedback control problem is greater than or equal to the corresponding amount in the closed-loop social problem and less than or equal to the corresponding amount in the open-loop social planner problem. In addition, the amount of urban land in the second period of the open-loop feedback control problem is greater than or equal to the corresponding amount in the closed-loop social planner problem.*

In other words, UGBs fail to restrict enough development and LDF achieve the socially optimal amount of urban land when policymakers fail to account for future learning that landowners anticipate. Though it is clear that the amount of development in an open-loop feedback control problem differs from the amount in the closed-loop social planner problem when the social planner uses LIFs, the sign of the difference is dependent upon functional forms and parameters. Intuitively, the LDFs achieve the social optimal amount of urban land and the other policies do not because the socially optimal first period policy and the expected value of the socially optimal second period policy only coincide between the open-loop and closed-loop control problems when the social planner uses LDFs.

Weak sufficient conditions. While the strong sufficient conditions guarantee both that there are unique global maximums for all four problems in Table 1 and that the irreversibility effect holds, the weak sufficient conditions guarantee only uniqueness. This difference is due to the fact that the weak sufficient conditions allow for a cumulative environmental effect. As a consequence, the irreversibility effect does not hold without additional assumptions (remark 3) and LDFs are not robust to the type of control problem (proposition 1). In addition, socially optimal development fees are time inconsistent and UGBs are time consistent under the weak sufficient conditions. As a consequence, UGBs may be the best policy option when a cumulative externality is present.

First period land use decisions in the social planner problems.

Unlike under the strong sufficient conditions, the second period objective function in the closed-loop social planner problem is a function of the amount of urban land in the first period (Freixas and Laffont, 1984). As a consequence, the irreversibility effect does not necessarily hold (Epstein, 1980).

Epstein (1980) and Ulph and Ulph (1997) each define a set of sufficient conditions for the irreversibility effect to hold when the first and second period benefit functions are not separable in their respective decision variables.

Remark 5: *Assuming that the weak sufficient conditions for a unique global maximum hold, the socially optimal amount of urban land in the first period under closed-loop control is less than or equal to the corresponding amount under open-loop control if the derivative of the second period value function with respect to the amount of urban land in the first period is concave with respect to the posterior probabilities (Epstein, 1980) or if the open-loop social planner problem is binding (Ulph and Ulph, 1997).*

Corollary 5a: *In the first period, the difference between the socially and privately optimal amounts of urban land under closed-loop control is greater than or equal to this difference under open-loop control when either of the assumptions discussed above in remark 5 hold in addition to the weak sufficient conditions.*

Corollary 5b: *The socially optimal first-period UGB under open-loop control is greater than or equal to the corresponding UGB under closed-loop control when either of the assumptions discussed above in remark 5 hold in addition to the weak sufficient conditions.*

The intuition behind the Epstein (1980) condition is that it ensures that the expected marginal cost of first period development increases with the availability of information (Ulph and Ulph, 1997; Gollier, Jullien, and Treich, 2000).

Under the weak sufficient conditions, policymakers should account for the difference between private and social values of information when determining land use policies. Though the socially optimal amount of urban land may differ between open-loop and closed-loop control, the irreversibility effect does not always hold and socially optimal land use policies do not always prevent a greater amount of development under closed-loop control than under open-loop control. If the Epstein (1980) or Ulph and Ulph (1997) conditions hold in addition to the weak sufficient conditions, policymakers who account for the future availability of information when setting land use policies, such as zoning or UGBs, reduce the amount of development more than those who ignore it.

Development fees.

The open-loop and closed-loop LDFs and LIFs under the weak sufficient conditions differ from those under the strong sufficient conditions. Under the weak sufficient conditions, LDFs are functions of the socially optimal amounts of urban land because the possible existence of a cumulative environmental effect from urban development has two effects. First, the present value of the expected external cost of developing a property located at X in the first period on total second period rent resulting from the cumulative environmental effect of urban development, $B\sum_{k\in\{L,H\}} p_k G_k\left(X, \tilde{X}_{2,k}^{nP^*}\right)$, is included in the first-period LDFs. Second, the external cost of developing a property located at X in the second period on total second period rent in state k becomes a function of the amount of urban land in the first period, i.e. $\hat{C}_{2,k}(X)$ becomes $C_{2,k}\left(\tilde{X}_1^{nP^*}, X\right)$, in the first and second period LDFs. Formally, $D_1^n\left(X, \tilde{X}_1^{nP^*}, \tilde{X}_{2,k}^{nP^*}\right) = C_1(X) + B\sum_{k\in\{L,H\}} p_k G_k\left(X, \tilde{X}_{2,k}^{nP^*}\right) + B\sum_{k\in\{L,H\}} p_k C_{2,k}\left(\tilde{X}_1^{nP^*}, X\right)$ $\forall n \in \{O, C\}$, $D_2^{O^*}\left(X, \tilde{X}_1^{OP^*}\right) = \sum_{k\in\{L,H\}} p_k C_{2,k}\left(\tilde{X}_1^{OP^*}, X\right)$, and $D_{2,k}^C\left(X, \tilde{X}_1^{CP^*}\right) = C_{2,k}\left(\tilde{X}_1^{CP^*}, X\right)$ $\forall k \in \{L, H\}$. In both the open-loop and closed-loop problems, the socially optimal LDFs have the same interpretation as under the strong sufficient conditions.

Under the weak sufficient conditions, the possible existence of a cumulative environmental effect from urban development affects LIFs in two ways. First, first-period LIFs include the present value of the expected marginal external cost of urban development in the first period on total second period rent resulting from the cumulative environmental effect of urban development, $B\sum_{k\in\{L,H\}} p_k G_k\left(\tilde{X}_1^{nP^*}, \tilde{X}_{2,k}^{nP^*}\right)$. Second, the marginal external cost of urban development in the second period on total second period rent in state k becomes a function of the amount of urban land in the first period, i.e. $\hat{C}_{2,k}\left(\tilde{X}_{2,k}^{nP^*}\right)$ to $C_{2,k}\left(\tilde{X}_1^{nP^*}, \tilde{X}_{2,k}^{nP^*}\right)$, in the first and second period LIFs. Formally, $F_1^{O^*} = C_1\left(\tilde{X}_1^{nP^*}\right) + B\sum_{k\in\{L,H\}} p_k G_k\left(\tilde{X}_1^{nP^*}, \tilde{X}_{2,k}^{nP^*}\right) +$

$B\sum_{k\in\{L,H\}} p_k C_{2,k}\left(\tilde{X}_1^{nP^*}, \tilde{X}_{2,k}^{nP^*}\right)$ $\forall n \in \{O, C\}$, $F_2^{O^*} = \sum_{k\in\{L,H\}} p_k C_{2,k}\left(\tilde{X}_1^{OP^*}, \tilde{X}_2^{OP^*}\right)$, and $F_{2,k}^{C}{}^* = C_{2,k}\left(\tilde{X}_1^{CP^*}, \tilde{X}_{2,k}^{CP^*}\right)$ $\forall k \in \{L, H\}$. In both the open-loop and closed-loop problems, the socially optimal LIFs have the same interpretation as under the strong sufficient conditions.

Because LDFs and LIFs are now both functions of the socially optimal amounts of urban land, the optimal LDF and LIF differ between the open-loop and closed-loop problems. Under the weak sufficient conditions, the expected external cost of developing a property at location *X* in period *t* may differ between the open-loop and closed-loop problems. In turn, because the socially optimal LDF at location *X* in period *t* equals the expected external cost of developing the property at location *X* in period *t*, it too may differ between the open-loop and closed-loop problems. Therefore, the following proposition holds:

Proposition 5: *Assuming that the weak sufficient conditions hold, the first period closed-loop LDF may differ from the first period open-loop LDF and the expected value of second period closed-loop LDFs may differ from the second-period open-loop LDF.*

For similar reasons, LIFs can differ between the open-loop and closed-loop problems under both the weak and strong sufficient conditions. The exceptions for both policies are when $\tilde{X}_1^{OP^*} = \tilde{X}_1^{CP^*}$ and $\tilde{X}_2^{OP^*} = \tilde{X}_{2,H}^{CP^*} = \tilde{X}_{2,L}^{CP^*}$ or when each component of the marginal external cost of urban development is constant with respect to the amounts of urban land.

Unlike under the strong sufficient conditions, LDFs are not robust to the type of control problem under the weak sufficient conditions. Furthermore, the signs of the differences between open-loop and closed-loop LDFs and LIFs are difficult to determine under the weak sufficient conditions for a unique global maximum. The sign of these differences depends upon functional forms and parameters for both types of development fees.

Time-consistency of the socially optimal policies.

Because a cumulative externality may exist, the socially optimal second period closed-loop LDFs and LIFs are functions of the socially optimal amount of urban land in the first period. In general, Kydland and Prescott (1977) implies that these socially optimal development fees are time inconsistent because $\frac{\partial \tilde{X}_1^{CM^*}}{\partial D_{i,2,k}^C} \neq 0$ and $\frac{\partial \tilde{X}_1^{CM^*}}{\partial F_{2,k}^C} \neq 0$. Because the shadow values associated with the second period UGBs are functions of the amount of urban land in the first period, rather than the UGBs themselves, it is less clear whether socially optimal UGBs are time inconsistent.

Under the weak sufficient conditions, only urban growth boundaries are time consistent, as demonstrated in the appendix. While the first period closed-loop socially optimal UGB equals the first-period time consistent UGB found in the corresponding Stackelberg problem, the first period socially optimal development fees differ from the corresponding first period time consistent policies.

Proposition 6: *When the weak sufficient conditions for a unique global maximum hold, the socially optimal UGBs are time consistent and the socially optimal LDFs and LIFs are time inconsistent.*

In the case of development fees, landlords have an incentive to deviate from the socially optimal amount of urban land because they are able to affect the values of the second period socially optimal development fees, which are functions of the amount of urban land in the first period under the weak sufficient conditions. Depending on the parameters of the model, landlords at the optimal urban-agricultural fringe in the first period can increase their profits by decreasing development below the socially optimal amount of urban land to decrease the magnitude of the fee that they will face in the second period or by increasing development beyond the socially optimal amount of urban land to increase the magnitude of the fee that other landlords will face in the second period. In the case of UGBs, landlords do not deviate from the socially optimal amount of urban land because they can only respond to this type of policy by decreasing development below the socially optimal amount of urban land and the resulting benefits of such a decrease are only distributed to landowners beyond the corresponding UGB. As a consequence, urban growth boundaries are the preferred policy when a large cumulative environmental externality from urban development exists.

VIII. Conclusion

Local governments are faced with the challenge of preserving vegetation from urban and agricultural development when the future locations of these habitats are uncertain due to climate change. Because many key habitats are primarily privately owned, the economic argument for conserving these vegetation types is the positive amenities that private open space produces that benefit surrounding neighbors and society as a whole. Assuming that local policymakers set land use policies to maximize social-welfare within their municipality, this paper attempts to address how they should adjust these policies to account for the potential effects of climate change.

In order to answer this question, I analyzed how climate change affects the social welfare-maximizing magnitudes of land use policies within a spatial-temporal model of a municipality. Two land uses were modeled: urban and private open space. Urban development was specified as irreversible. Open space produced positive location-dependent and location-independent externalities of uncertain future magnitudes. In order to guarantee a unique global maximum, these externalities were assumed to be decreasing in urban development at a non-decreasing rate.

Using this model, I solved for the privately and socially optimal land allocations under open-loop and closed-loop control. I identified the optimal time trajectory of each policy instrument through time and proved several key propositions about conservation under uncertainty: LDFs were robust to the type of control problem under the strong sufficient conditions (proposition 1) and were not robust under the weak sufficient conditions (proposition 5), the socially optimal policies were time consistent under the strong sufficient conditions (proposition 2), and only socially optimal urban growth boundaries were time consistent under the weak sufficient conditions (proposition 4). My results were separated into two potentially important cases: no cumulative environmental externality from urban development and the possible existence of a cumulative environmental externality.

I made several key findings under the assumption that there was no cumulative environment cost from first period urban development. First, the socially optimal amount of open space in the closed-loop control problem was greater than or equal to the corresponding amount in the open-loop control problem. This result implied that less development was allowed by socially optimal land use policies under closed-loop control than open-loop control. Second, the social welfare-maximizing LDFs did not differ between the two control problems, while the social welfare maximizing UGBs and LIFs could differ. These results implied that if local policymakers ignore the potential effects of climate change when setting UGBs or LIFs, they do not restrict urban development enough. Alternatively, LDFs achieved the socially optimal land use allocation in the open-loop feedback control problem. Last, the socially optimal closed-loop policies were time-consistent, which indicated that they are achievable.

I also made three key findings under the assumption that there was a cumulative environment cost from first period urban development. First, the socially optimal amount of open space in the closed-loop control problem was not necessarily greater than or equal to the corresponding amount in the open-loop control problem. Potentially, the socially optimal land use policies prevented less open space development under closed-loop control than open-loop control. Second, all three social welfare-maximizing land use policies, including LDFs, could differ between the open-loop and closed-loop control problems. These results implied that if local policymakers ignore the potential effects of climate change when setting land use policies, they fail to achieve the socially optimal land use allocation. Last, socially optimal closed-loop LDFs and LIFs were time inconsistent, while UGBs were time consistent. This suggests that use of UGBs and zoning instead of development fees to manage land use, as is currently observed in land use planning, is socially desirable if there are large cumulative environmental externalities from urban development.

The robustness of LDFs to the type of control problem under the strong sufficient conditions indicates that they are likely to be a more suitable land use policy in situations of uncertainty than either UGBs or LIFs when there is no cumulative environmental externality from development. Demonstrating their value is particularly important in order to overcome the difficulty of their implementation. Policies that treat landowners within a municipality differently can be politically controversial. This can be particularly true when this differential treatment is based on benefits accruing to adjacent urban properties developed prior to the implementation of the policy. Because cumulative environmental effects are likely to be significant in many real world situations, future research is necessary to ascertain how robust LDFs are under real-world parameters when the strong sufficient conditions do not hold.

The results of this paper apply to a general set of spatial-temporal problems. The results under the strong sufficient conditions apply to problems that have the following characteristics. First, private landowners must choose between two land uses. Second, one land use must produce a positive or negative externality with an uncertain future value. Third, one land use is irreversible. Fourth, previous land use allocations have no effect on current net land use externalities through the cumulative environmental effect of urban development. The results under the weak sufficient conditions apply to spatial-temporal problems characterized by only the first three characteristics. Because disease, regeneration problems and climate change have uncertain implications for many habitats, the results of this paper apply to a host of local conservation programs that aim to preserve threatened habitats on private lands from human activities.

Another implication is that public and private conservation programs that purchase private lands or development rights, such as local land trusts, should amend their current methods for ranking conservation choices to take into account the potential risk of vegetative movement or loss. The expected benefit-cost targeting approach, which ranks land conservation choices in order to minimize the expected loss of non-market services due to future land development subject to a conservation budget, overprotects properties with high risks of future habitat loss. Because the social value of information is greater than zero when the social welfare-maximizing land use allocation differs between the control problems, the expected benefit targeting approach can be adjusted by including the social value of information when calculating the expected loss of non-market services. In order to adjust the expected benefit targeting approach in this manner, conservation programs must be willing to return these lands to the private domain if their effort to conserve the targeted habitat is unsuccessful. Otherwise, no option value arises because conservation is, effectively, irreversible.

There exist several fruitful directions for future work to explore. One such direction is to analyze the effects of relaxing the model's most important simplifying assumptions, such as the effect of climate change on agricultural profits. Because climate change has uncertain effects on precipitation, temperature, and vegetation, its potential effect on agriculture is also uncertain. Relaxing this assumption will result in a non-zero private value of information and a difference between the solutions for the open-loop and closed-loop landlord problems because it introduces uncertainty into a market return that is already accounted for by landowners when making their land use decisions.

Another direction that can be explored is the robustness of location-dependent policies to different types of information assumptions. Because LDFs proved robust to the type of control problem when there were zero environmental externalities, location-dependent policies may also have value in situations where uncertainty declines gradually and/or at an unknown rate. Future research is necessary to evaluate the potential of LDFs and other policies in these situations.

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