Optimal Preservation of Oak Woodlands within a Municipality

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7/29/2010

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Abstract

In California, where the majority of oak woodlands are privately owned, local policymakers must make conservation decisions under uncertainty over future vegetative cover due to climate change. This paper develops a spatial-dynamic model of a municipality in order to analyze three alternative land use policies (urban growth boundaries, location-independent development fees, and location-dependent development fees) when policy makers account for or ignore the potential for future climatic information. Climate change is modeled as future land use externalities taking one of two possible states, which correspond to oak woodland services thriving or degenerating over time. Using this model, I derive the privately and socially optimal land allocations under open-loop and closed-loop control assumptions. By comparing the privately and socially optimal land allocations in each control problem, I identify the optimal trajectory of each policy instrument over time. While urban growth boundaries and location-independent development fees differ between the two control problems, location-dependent development fees are robust to the type of control problem when there are no cumulative environmental externalities from urban development. As a consequence, location-dependent development fees achieve the socially optimal outcome even if policymakers fail to account for the future availability of information about the effects of climate change when determining current land use policy.

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I. Introduction

California's 5 million acres of oak woodlands and the amenities that they provide (wildlife habitat, water supply services, soil enhancement services, carbon sequestration, aesthetic value, existence value, and recreation) are currently under threat from agricultural and residential development and the potential effects of climate change. Scientists predict that oak habitats will shrink and move north and upslope over the next century due to global warming (Kueppers et al., 2005; Hannah et al., 2008). However, the predicted future locations of oak habitat 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 over future amenity service values. Because 80% of California's oak woodlands are privately owned and the state does not have regulatory authority over the removal of oak trees on private lands (WCB, 2007; Ineich, 2007), it falls to local governments to adjust existing land use policies to account for the uncertainty surrounding the future amenity benefits from California's oak woodlands (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 of a municipality in order to analyze three alternative land use policies: urban growth boundaries, location-independent development fees, and location-dependent development fees. 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, represent 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 respond to new information, while in a closed-loop control problem they can. Equivalently, in an open-loop control problem the level of uncertainty remains constant, while in a closed-loop control problem it declines. 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 oak woodlands preservation, 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 oak woodlands and the associated value of 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 oak woodlands than they aim to achieve currently.

I obtain four major results. First, the socially optimal land use policies prevent more oak woodland 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 urban growth boundaries and location-independent development fees differ between the two control problems. While the socially optimal first-period urban growth boundary is larger in magnitude under open-loop control than under closed-loop control and the relative magnitudes of the socially optimal location-independent development fees under open-loop and closed-loop control are indeterminate, both socially optimal open-loop policies under-conserve oak woodland relative to the corresponding socially optimal closed-loop policies when there is no cumulative environmental externality from development. Third, the socially optimal location-dependent development fees are the same at each location for the two control problems when there is no cumulative environmental externality from development. This result implies that the location-dependent development fees are robust to the type of control problem when there is no cumulative environmental externality from development. Because many policymakers ignore the uncertainty over the future value of oak woodland amenities and uncertainty is likely to decline gradually and at an unknown rate, these results indicate that location-dependent development fees are likely to be a better suited policy for ensuring a socially optimal level of oak woodland conservation when there is no cumulative environmental externality from development. For example, location-dependent development fees 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 urban growth boundaries under-conserve oak woodland. Last, though under some conditions the socially optimal land use policies continue to prevent more oak woodland development in the first period under closed-loop control than under open-loop control when there is a cumulative environmental externality from development, the socially optimal location-dependent development fees are no longer independent of the type of control problem.

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 the uncertainty surrounding future clean technologies.

This work also has broader implications for ecosystem conservation. First, the results of this paper indicate that the conservation of vegetation potentially affected by climate change should increase. If public acquisition of private lands is one of the primary methods of accomplishing this goal, the amount acquired should increase to account for the uncertainty surrounding the effects of climate change. Second, current methods that rank land conservation choices for land and development right purchases in order to maximize the expected benefits of a conservation budget should be adjusted to account for the value of information. Current conservation targeting methods do not take into account the potential for vegetative, and thus ecosystem, movement. The government and private land trusts must be willing to return these lands to the private domain if an effort to conserve a specific ecosystem is unsuccessful, due to climate change or other factors eliminating the targeted vegetation, because then their economic value is larger for urban use than for conservation. Otherwise, no information value arises, due to the irreversibility of conservation, which eliminates the value of conserving ecosystems for future flexible land use choices.

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

II. Oak Woodlands in California

There are 9.8 million acres of oak habitat (oak woodland and forest) in California, covering about one-tenth of the state's land area (FRAP, 2003). Approximately 53% of this oak habitat is oak woodlands, while the remaining 47% is oak forests. Oak forests are denser, less dominated by oaks, and at higher elevations than oak woodlands, and receive more rainfall (Gaman and Firman, 2006); oaks are not the dominant species in oak forests as they are in oak woodlands. The majority of oak woodlands are in the Central Valley (Sacramento and San Joaquin Valleys), while oak forests are most common in the North Coast and Northern Interior regions (Gaman and Firman, 2006).

There are eight major species of oaks trees native to mainland California (black, blue, canyon-live, coastal live, Engelmann, Oregon white, interior live, valley), of which only blue and valley oaks are exclusive to California (Giusti and Pamela, 1993). There are also shrub and island species of oaks, as well as natural hybrids (UCCE, 2009; Giusti and Pamela, 1993). Blue oaks are approximately a third of California oaks, while canyon, coast, and interior live oak species account for another third (Gaman and Firman, 2006; FRAP, 2003).

80% of all California oak woodlands are privately owned, and 70% are used for grazing. 56% are owned by livestock producers and another 14% of oak woodlands are leased to ranchers by private landowners and the federal government (Campos-Palacin et al., 2002; Ineich, 2005). Because oak is classified as a hardwood, oak woodlands used primarily for grazing are economically categorized as hardwood rangelands. In addition to grazing, owners of oak woodlands can supplement their income by renting their land to hunters and cutting timber for firewood (Ineich, 2005).

In addition to being an input into various economic activities, California's oaks provide numerous non-market services to private landowners, nearby residents, and society. Landowners benefit from recreational and soil enhancement services. For example, blue oaks improve soil fertility underneath their canopy (Dalhgren et al., 2003). Landowners and nearby residents benefit from the aesthetics of oak woodlands. In terms of water supply services, oaks decrease nutrient runoff and help mitigate leaching (Ineich, 2005). Oaks also sequester large amounts of carbon (Camping et al, 2002). Landowners, nearby residents, and society all benefit from the unique habitat that California oaks provide “170 birds, 80 mammals, and 60 species of amphibians and reptiles” (UCCE, 2009). 20% of these species feed on acorns that oaks produce and a majority eats some of the 5,000 species of insects and arachnids that live on or around oaks (UCCE, 2009). California oak habitat supports several endangered species, including the California spotted owl (Ineich, 2005). Because over 300 animals rely on oak woodland services, California oaks are the most important natural resource in the state in terms of support of biological diversity (Ineich, 2005). Finally, landowners, nearby residents, and society benefit from any existence value that they place on oak habitat that is not already captured in the benefits discussed earlier.

Because oak woodlands suffer from increasing development pressures, their non-market services are increasingly at risk of disappearing. In recent years, the urban conversion of California oak woodlands has reached an annual rate of 30,000 acres (Ineich, 2005). Gaman and Firman (2006) found that 1 million acres of oaks statewide were already developed and an additional 750,000 acres of oak woodland will be developed by 2040.[1] Housing (urban and rural residential) and vineyard development will continue to drive this loss of oak woodland (Campos-Palacin et al., 2002). Of all California regions, the Central Valley is under the greatest pressure. Of the 20% of Sacramento Valley’s land area that is oak woodlands, one-sixth is already developed and Gaman and Firman (2006) predict another one-sixth will be developed by 2040. Although urban pressures are less in the San Joaquin Valley, its population is projected to increase substantially over the next 30 years. Of the 10% of San Joaquin Valley’s land area that is oak woodlands, one-tenth is already developed and another one-tenth is at a high risk of development by 2040 (Gaman and Firman, 2006).

There is little state-level protection of oaks within California. Because of the non-commercial nature of most California oaks, the California Department of Forestry has little regulatory authority over their removal on private lands (WCB, 2007; Ineich, 2007). The California Forest Practice Act (FPA) provides protection only to commercial forests, and thus only applies to a minority of California oaks (IHRMP, 2000). Though pure stands of blue and valley oaks are not covered by the FPA, commercial hardwood forests, such as Montane hardwood forests, are covered (IHRMP, 2000); Montane hardwood forests often include canyon live, valley live, California black, and Oregon white oaks (IHRMP, 2000).

The Williamson Act Program, also known as the California Land Conservation Act (LCA) Program, is a state supported voluntary agricultural preservation program that offers farmers and ranchers lower property taxes in exchange for a contract that restricts their land use to agricultural or open-space purposes. Though 70% of oak woodlands are enrolled under the Williamson Act, this only provides temporary protection; landowner initiated non-renewal takes only nine years to complete (Campos-Palacin et al., 2002; CDC, 2007). In addition, the state is

[1] Gaman and Firman (2006) define developed as thirty-two or more housing units per square mile. This is equivalent to defining developed as twenty acres or less per lot. For larger properties within this “developed” designation, there is not necessarily a huge amount of habitat destruction

currently not reimbursing counties for the tax revenue that they lose under the Williamson Act due to the current budget crisis. As a result, Imperial County in Southern California already has opted out of the Williamson Act, and it is possible that more counties will follow. The possible elimination of the Williamson Act further erodes state-protection of oak woodlands (Cornett, 2010).

The primary protection of California oak woodland is provided by county and municipality governments. The main methods of protection are tree cutting ordinances, zoning restrictions, urban growth boundaries, cluster development requirements, and voluntary guidelines (Ineich, 2007; Campos-Palacin et al., 2002). Though not specifically used to protect vegetation such as oaks, development fees are common in cities and counties throughout California (CHCD, 2009). Local governments purchase properties or their development rights for conservation purposes, as do private land trusts.

Development pressures are compounded by climate change, disease pressures, and the failure of some oaks to regenerate. Using a regional climate model (RCM), Kueppers et al. (2005) predicts that global warming will cause California Blue and Valley Oak habitats to shrink in size by 41% and 46%, and move north and upslope over the next century. According to the RCM, less than 50% of currently protected oak land areas will contain these species in 2100. Thus, conservation of traditional oak properties will not ensure the conservation of oak habitats in the future. Though these predictions are alarming, there is considerable uncertainty surrounding them. There are a multitude of climate models with different assumptions and scales of analysis, each producing different climate and habitat predictions. For instance, Kueppers et al. (2005) also utilize a global climate model (GCM) to predict a shrinking of California Blue and Valley Oak habitats by 19% and 27% by 2100. However, these uncertainties will decrease over time. Model fit and accuracy will improve as more climate and vegetation data becomes available and as more complex models are developed.

This uncertainty over the future amenity values of local California oaks caused by climate change is heightened by disease and regeneration problems. California oaks are susceptible to *Phytophora ramorum*, the organism that causes sudden oak death, a disease responsible for widespread diebacks of several oak species in the coastal ranges of California. Sudden oak death has no known method of control (COMF, 2004; UCIPM, 2002). In addition to mortality, sudden oak death decreases the aesthetic value of infected trees by affecting their foliage and branches. Some species of oaks (blue, Engelmann, and valley) are also suffering from regeneration problems where the oak recruitment rate, the number of oaks reaching adulthood, is less than the mortality rate (Giusti and Pamela, 1993). Recruitment is entirely absent in some areas, although even within a region there is great variety across sites (Campos-Palacin et al., 2002).

III. 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. The agricultural preservation literature provides the basic argument for the public support of land-use conservation on private lands. The non-market valuation literature regarding oak woodland provides empirical justification for extending this public support to this ecosystem. The irreversible investment literature develops the modeling framework for irreversible decision making under uncertainty, upon which this paper will expand. Though the subsequent quasi-option value literature and irreversibility effect literature explicitly explore the effects of uncertainty on irreversible land-use decisions, both focus 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.

<u>Agricultural preservation and non-market valuation.</u> Beginning with Gardner (1977), the agricultural preservation literature has recognized that open space, environmental amenities and other rural amenities provided by agricultural land are public goods, and thus constitute an argument for agricultural preservation. Two papers in the non-market valuation literature address the external benefit of oak woodland conservation programs to surrounding communities. Standiford and Scott (2001) analyze the effects of distance to the nearest stand of oaks and distance from an 8,300 acre oak woodland conservancy on housing and land prices in southern Riverside County using a hedonic housing price model. The authors find that "a decrease of 10 percent in the distance to the nearest oak stands and to the edge of the permanent open space land results" in increases of $4 million and $16 million in total home and land values in the community, respectively. Thompson, Noel, and Cross (2002) use contingent valuation to estimate San Louis Obispo County voters' willingness to pay for oak woodland. The authors find that county voters would be willing to allocate $12 million for the provision of conservation easements.

<u>Irreversible investment and quasi-option value.</u> Neither the agricultural preservation literature nor the non-market valuation studies capture the full benefit of conservation due to their implicit assumption that the benefits of conservation are known. In practice, the non-market benefits of agricultural land, including oak rangeland, are often uncertain. This uncertainty arises from various sources. In my context, the most important source is global climate change. This uncertainty is likely to decrease over time 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 option value in the discrete development literature.

In discrete development problems where decision makers choose whether or not to develop an entire area, the Dixit-Pindyck (D-P) option value is a consequence of this uncertainty, the flow of information over time that reduces it, and the irreversibility of urban development. The D-P value is made up of two values: quasi-option value, which is the expected value of information conditional on preserving undeveloped land in the current time period, and a second value, which is the value of waiting to develop due to a lower expected future cost of development. If a social welfare maximizing policymaker ignores the reduction over time of the uncertainty surrounding the net benefits to land development/preservation, Arrow and Fisher (1976) argue that quasi-option value is equivalent to the optimal development tax necessary to induce the policymaker to choose the socially optimal discrete development decision. I focus exclusively on quasi-option value, and assume that development is costless.

Because the literature based on Arrow and Fisher (1976) focuses on irreversible development decisions on public lands by a social planner, quasi-option values as traditionally defined do not apply to privately owned farmland. Due to the public good nature of agricultural amenities, landowners do not fully account for their land's amenity values or the corresponding quasi-option value that arises from preserving agricultural land when making their land use decisions. As a consequence, social welfare-maximizing land use policies must take into account the portions of quasi-option value and amenity values that landlords ignore when making their land use decisions.

Irreversibility Effect. The irreversibility effect literature extends the results of Arrow and Fisher (1976) to continuous irreversible development decisions made by a social planner. Epstein (1980) proves that 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), and two additional articles, Ulph and Ulph (1997) and Freixas and Laffont (1984), define sufficient conditions for the irreversibility effect to hold in two-period development problems. The Epstein (1980) sufficient conditions are that the benefit functions and the irreversibility constraints are concave with respect to the decision variables and that 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. The Ulph and Ulph (1997) sufficient condition is that the irreversibility constraint binds in the open-loop problem. Note that the Epstein (1980) and Ulph and Ulph (1997) sufficient conditions are neither mutually exclusive nor is one a subset of the other. The Freixas and Laffont (1984) sufficient conditions are that the value function is quasi-concave and that the first and second period benefit functions are separable in their decision variables. In other words, the cumulative effect of first period development on second period benefits is certain. Hanemann (1989) notes that the Epstein (1980) sufficient conditions are guaranteed to hold if in addition to the Freixas and Laffont (1984) conditions the value function is assumed to be concave.

Hanemann (1989) also demonstrates that quasi-option value defined by Arrow and Fisher (1976) does not exist in the continuous choice case, although there is still a value of information conditional on the first period land use decision. As in discrete development problems, a landowner does not fully account for her land's amenity value or the corresponding value of information that arises from preserving agricultural land when making her land use decision. 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, which will be referred to as the closed-loop social planner problem in this paper. The private value of information is the value of information that arises in the closed-loop competitive equilibrium, which will be referred to as the closed-loop landlord problem in this paper. Because information has no value in the open-loop social planner and landlord problems, the social (private) value of information is calculated as the difference between the closed-loop and open-loop value functions in the social planner (landlord) optimization problems (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 in the closed-loop landlord profit-maximization problem. Because the public good nature of oak rangelands' 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 Muth-Mills model. In order to analyze the effects of uncertainty regarding the future non-market benefits of oak woodland on private and socially optimal land use choices, the key assumptions and structure of the irreversible development literature are integrated into a spatial model similar to the Muth-Mills model. In this literature, cities are often measured as a radially symmetric city on a two-dimensional plane with a Central Business District (CBD) at the center of the city in which all residents of the city work. The assumption that the city is radially symmetric implies that the city can be modeled as a line with the CBD at one end. The equilibria are represented by the length of the line that is urbanized.

There are two types of actors considered in these models: landlords and tenants. Generally, landlords and tenants are each assumed to be homogenous in all respects except for location, although sometimes tenants are broken into high and low income groups. Another common assumption is that tenants are uniformly distributed across the city.[2] Though this assumption is somewhat limiting, it is a necessary assumption in spatial-temporal models because endogenous plot size almost always results in an intractable problem (Albers, 1996). Furthermore, this assumption is acceptable if urban density is of no particular interest as is true in this literature; the motivation for growth control in this literature is a negative externality related to city size or population that is equally experienced by all tenants.

Cities may be modeled as open or closed. An open city has an endogenous population size and an exogenous utility level (tenants' reservation utility) in each period. Open city models are appropriate when migration is possible. This implies that there is no population pressure because there is no excess demand for housing. Furthermore, the city must be small with respect to the surrounding economy in order for utility to be exogenous (Brueckner, 1990). A closed city implies that the population is exogenous in each period, while the utility level within the city is endogenous. The closed city approach is appropriate when migration is impossible in the short-run and expensive in the long-run (Kovacs and Larson, 2007). A closed city assumption is more appropriate when modeling a city that is large with respect to the surrounding economy.

In both models, equilibrium rental rates differ by location. Furthermore, landlords and tenants are price takers. In the open city case, rental rates increase until each tenant receives only his exogenous utility level (Brueckner, 1990). In a closed city model, rental rates are determined by equating a fixed demand with supply. If tenants are uniformly distributed then an exogenous

[2] If uniform density is not assumed, the Muth-Mills model includes the supply side of the housing market. Perfectly competitive producers buy or rent land from landowners, produce buildings with various combinations of land and capital (i.e. produce buildings of differing heights and thus floor space), and sell or rent land to tenants. By assuming a uniform density (i.e. a fixed capital to land ratio) like Brueckner (1990), I do not explicitly model the supply side of the housing market though it is implicitly included.

population implies an exogenous city size. In this case, the rental rate at each location must make each tenant indifferent to his location and the rental rate at the city boundary must equal the net return on the next best use. In both types of models, the next best use is assumed to be agriculture, which receives a uniform net return across space (Sakashita, 1995).

This paper builds on the framework of Brueckner (1990) by modifying an open city model in order to model oak rangeland development and preservation within a municipality. A municipality is defined as a city and its surrounding undeveloped sphere of influence.[3] The urban size-dependent externality is interpreted as a net land use externality, i.e. the value of agricultural externalities less the cost of urban externalities. I make several significant changes to the open city model. First, future net land use externalities are uncertain, and this uncertainty declines over time. Because urban development is irreversible, a consequence of this assumption is that the postponement of development has value to the decision maker because she acquires information over time. Second, the financial cost of land use change is assumed to be zero. Last, all urban and agricultural landlords rent their land to tenants. Together with the assumptions that the municipality's size is exogenously fixed and that tenants are uniformly distributed, this assumption implies that the population within the municipality is fixed over time.[4]

Albers (1996) and Albers and Robison (2007). My paper most closely resembles Albers (1996), a paper that extends the work of Arrow and Fisher (1974), in several ways. First, my paper and Albers (1996) are spatial-temporal land-use choice models. Second, they both have the necessary temporal components for the existence of option value: irreversibility and uncertainty. In Albers (1996), a tropical forest with an uncertain future value due to the possible survival of Thai elephants is lost for certain when developed. In my paper, development results in the loss of oak woodland, which has an uncertain future value due to climate change. Third, both papers address two types of government as represented by open-loop and closed-loop control. Both papers demonstrate that the closed-loop social planner undertakes less development than the open-loop social planner does. This difference is the result of the closed-loop social planner accounting for the value of information which is conditional on choosing flexible land-uses, i.e. land uses that do not restrict future land use decisions. Fourth, properties have the same qualities: property size is fixed and each property has two adjacent properties. Last, there exist land use externalities with uncertain future values in both papers. In Albers (1996), the land-use externalities are discrete benefits produced through the adjacency of tropical forest plots. In my paper, a continuous net land-use externality function equals the sum of urban and agricultural location-dependent and location-independent externalities experienced at any location.

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[3] In California, a local government's "sphere of influence" is defined legally as the area that the local government expects to serve in the future, including areas outside of its current boundary. Each local government is legally required to produce a general plan for future development and land use within its entire "sphere of influence." (LAFCO, 1997)

[4] An additional difference between the two models is the Brueckner (1990) assumes that tenants consume one unit of land, i.e. $A/P = 1$ where P is the population of tenants living within the municipality, whereas this paper assumes that tenants live on infinitely small units of land. However, Brueckner integrates over space when calculating the socially-optimal urban growth boundary instead of summing over all plots. The difference between this integral and the sum collapses to zero as A goes to infinity. In other words, Brueckner (1990) implicitly assumes that A is large and that the ratio of property size to city size, $1/A$, is small.

The primary difference between these models is that Albers (1996) models a centrally planned forest, whereas, I model privately owned oak woodlands. This difference is driven by the difference in our research questions. Albers (1996) is interested in how uncertainty, irreversibility, and externalities interact to affect various park managers' land use decisions, whereas I am interested in how these same spatial-temporal attributes affect social welfare-maximizing land use policies within a municipality characterized by private ownership. As a result, Albers (1996) integrates these spatial-temporal components into a discrete spatial model of a public park made up of four adjacent zones, whereas I integrate them into a modified open-city model. My framework allows for analysis of traditional urban economic factors of land-use choice, such as distance to CBD and tenant preferences, on the optimal land use policies. In addition, my paper solves for open-loop and closed-loop competitive and Pareto optimal land-use configurations, while Albers (1996) only solves for open and closed-loop Pareto optimal land-use configurations. Tables 1 and 2 below display the four problems examined in my paper and in Albers (1996), respectively, differentiating them by their assumptions. Through the comparison of the fully spatial and the independent zone models, Albers (1996) demonstrates that uncertain spatial externalities give rise to an additional option value unaccounted for by Arrow and Fisher (1976). Though Albers (1996) recognizes that this result indicates a possible difference between private and socially optimal land-use configurations, she does not solve for competitive equilibria in Albers (1996) or in Albers and Robinson (2007), which is an adaptation of Albers (1996) to Khao Yai National Park in Thailand. Though Albers and Robinson (2007) explores the land use configurations chosen by different park managers, each of whom weighs the various land-use benefits and costs differently, they never solve for a competitive equilibrium. Though Albers (1996) recognizes the need to account for quasi-option values when developing spatial-temporal land use policies under uncertainty, she does not model market instruments, as is done here.

Table 1. The four fully-spatial models solved for in my paper.

		Optimizer	
		Landlord	Social Planner
Control Problem	Open-Loop	*My paper*	*My paper* *Albers (1996)*
	Closed-Loop	*My paper*	*My paper* *Albers (1996)* *Albers and Robinson (2007)*

Table 2. The four social planner models solved for in Albers (1996)

		Spatial Assumption - Manager Type	
		Independent Zone	Full-Spatial
Control Problem	Open-Loop	*Albers (1996)* *Arrow and Fisher (1976)*	*My paper* *Albers (1996)*
	Closed-Loop	*Albers (1996)* Albers and Robinson (2007) Arrow and Fisher (1976)	*My paper* *Albers (1996)* *Albers and Robinson (2007)*

IV. 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 specific policy problem that I examine, the municipality can be conceptualized as a small California city and its undeveloped area of influence situated in oak woodland habitat used for grazing. The municipality's oak woodland either thrives or degenerates 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 oak 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.[5] By definition, the landlord cannot change the density of residents on her property. The Central Business District (CBD) is located at $X = 0$ where all tenants who rent urban land work.

<u>Tenants.</u> Tenants live on either urban land or oak rangeland. 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 oak rangeland, he

[5] 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.

raises cattle for sale and earns profits $\Pi_{j,t,k} = \Pi(X_j)$ in period t and state k and pays rent $r_{j,t,k}$. All agricultural 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 grazing 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. Ranch profits are unaffected by climate change. All cattle are sold outside the municipality in a perfectly competitive market and potential cattle producers in the municipality are sufficiently small relative to the market for the price to be unaffected. Agricultural tenants do not travel to work, so $\mathrm{T}_{j,t,k} = 0$ for all agricultural 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 $S_{j,t,k}$ $\left(\frac{\partial V}{\partial S_{j,t,k}} > 0\right)$.

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, $\bar{\bar{V}}_t$.[6] 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

$$\max_{c_{j,t,k},\, g_{j,t,k}} g_{j,t,k} V(c_{j,t,k}, g_{j,t,k} S_{j,t,k}) + (1 - g_{j,t,k}) \bar{\bar{V}}_t$$

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

[6] 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).

$$\max_{c_{j,t,k},\, g_{j,t,k}} g_{j,t,k} V(c_{j,t,k}, g_{j,t,k} S_{j,t,k}) + (1 - g_{j,t,k}) \bar{\bar{V}}_t$$

subject to:

$c_{j,t,k} + r_{j,t,k} = \Pi(X_j)$

$g_{j,t,k} = 0$ 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 state k, $Y_{i,t,k}$, equals $Y_{i,t,k} = w_{i,t,k} R_{i,t,k} + (1 - w_{i,t,k}) r_{i,t,k}$ 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.[7] Renting land for urban purposes requires development. Development is costless to the landlord, but 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 in oak rangeland, so that the first period development decision is unconstrained by an earlier development choice.

A key concept in this paper is the marginal landlord, who is 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 VII that guarantee $\tilde{X}_{t,k}$ is unique, urban space covers $X \in [0, \tilde{X}_{t,k}]$ and oak rangeland covers $X \in (\tilde{X}_{t,k}, \mathrm{A}]$.

The net land use externality. A net land use externality at a specific location is the sum of urban and agricultural 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 externalities, such as smog, and negative location-dependent externalities, such as noise pollution, while oak rangeland produces positive location-independent externalities, such as supporting local plant and animal populations, biodiversity, clean water, and carbon sequestration, and positive location-dependent externalities, such as aesthetics and proximity to plant and animal habitat. Both oak location-independent and location-dependent externalities have uncertain values in the second period due to climate change.

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 urban tenants, they are farther from the urban-agricultural boundary, strictly speaking, as the amount of urban space expands,

[7] In equilibrium, $R_{i,t,k}$ and $r_{i,t,k}$ are functions of location X_i and the amount of urban space $\tilde{X}_{t,k}$. Therefore, $Y_{i,t,k}$ is a function of these variables, and can be written as $Y_{i,t,k} = Y_{t,k}(X_i, \tilde{X}_{t,k})$.

which implies that they experience less of the positive location-dependent externalities from oak woodland. In the case of agricultural tenants, they are closer to the urban-rural boundary as the amount of urban space expands, which means that they are 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 agricultural tenants.

Formally, $S_{j,1} = S_1(X_j, \tilde{X}_1)$ is the net externality experienced by tenant j in period 1, and $\frac{\partial S_1(X_j,\tilde{X}_1)}{\partial X_j} \geq 0$ and $\frac{\partial S_1(X_j,\tilde{X}_1)}{\partial \tilde{X}_1} \leq 0$. I assume that it is a twice continuously differentiable function in all its arguments. 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 $\tilde{X}_2$.[8] As was the case for the first period net externality, $\frac{\partial S_{2,k}(X_j,\tilde{X}_1,\tilde{X}_2)}{\partial X_j} \geq 0$, $\frac{\partial S_{2,k}(X_j,\tilde{X}_1,\tilde{X}_2)}{\partial \tilde{X}_1} \leq 0$, and $\frac{\partial S_{2,k}(X_j,\tilde{X}_1,\tilde{X}_2)}{\partial \tilde{X}_2} \leq 0$ for all $k \in \{L, H\}$. Because of the cumulative environmental effects of the urbanization of oak woodlands, the net land use externality in period 2 and state k is a function of the amount of urban space in period 1. Therefore, expression **(1)** does not necessarily hold when there is development in the first period.

V. 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 oak woodland 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, location-independent development fees, and location-dependent development fees.

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. $S_{i,t,k}^{nm^*} = S_{t,k}(X_i, \tilde{X}_1^{nm^*}, \tilde{X}_{2,k}^{nm^*})$. Table 3 summarizes the four problems I analyze, including notation.

[8] 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 not the functional form itself. For simplicity, I utilize the alternative specification in **(1)**.

Table 3. Optimization Problems

		Optimizer	
		Landlord (*m*=*M*)	Social Planner (*m*=*P*)
Control Problem	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 oak woodlands in state k and the same a priori beliefs about 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. Landowners do not consider the effect of their land use decisions on surrounding tenants and landlords and take other landlords' land use decisions as given. In contrast, the benevolent 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 the net land use 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 $S_{i,1}^{nM^*} = S_1\left(X_i, \widetilde{X}_1^{nM^*}\right)$ in the first period and ${S_{i,2,k}^{nM}}^* = S_{2,k}\left(X_i, \widetilde{X}_1^{nM^*}, \widetilde{X}_{2,k}^{nM^*}\right)$ 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. Note that the net land use externality that the landowner perceives at location X_i is what actually exists at location X_i in equilibrium. The social planner problem, 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 the externalities vary with tenant location and the amount of urban space in periods one and two: $S_{i,1}^{nP} = S_1\left(X_i, \widetilde{X}_1^{nP}\right)$ and $S_{i,2,k}^{nP} = S_{2,k}\left(X_i, \widetilde{X}_1^{nP}, \widetilde{X}_{2,k}^{nP}\right)\ \forall n \in \{O, C\}$. In equilibrium, the net land use externality at location X_i in the n-type control problem equals $S_{i,1}^{nP^*} = S_1\left(X_i, \widetilde{X}_1^{nP^*}\right)$ in the first period and $S_{i,2,k}^{nP^*} = S_{2,k}\left(X_i, \widetilde{X}_1^{nP^*}, \widetilde{X}_{2,k}^{nP^*}\right)$ in the second period if state k occurs 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,

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

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

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 for all locations within the municipality. Thus, the open-loop problem for decision maker m has the following specification,

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

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

<u>Land use policies.</u> This paper analyzes three land use policies: urban growth boundaries, location-dependent development fees, and location-independent development fees. The first period closed-loop urban growth boundary is denoted $\bar{\bar{X}}_1^C$, and the state-dependent second period closed-loop urban growth boundaries are $\bar{\bar{X}}_{2,k}^C$. The growth boundaries enter as constraints on the amount of urban land in each period. Thus, the closed-loop landlord problem with urban growth boundaries has the following specification:

$$(4)\ \max_{\tilde{X}_1^{CM}} \left\{ \begin{array}{c} \int_0^{\tilde{X}_1^{CM}} R_{i,1}^{CM}\, dX_i + \int_{\tilde{X}_1^{CM}}^{A} r_{i,1}^{CM}\, dX_i \\ +B \sum_{k\in\{L,H\}} p_k \max_{\tilde{X}_{2,k}^{CM}} \left(\int_0^{\tilde{X}_{2,k}^{CM}} R_{i,2,k}^{CM}\, dX_i + \int_{\tilde{X}_{2,k}^{CM}}^{A} r_{i,2,k}^{CM} dX_i \right) \end{array} \right\}$$

$$s.t. \tilde{X}_{2,k}^{CM} \geq \tilde{X}_1^{CM},\ \tilde{X}_1^{CM} \leq \bar{\bar{X}}_1^C, \text{ and } \tilde{X}_{2,k}^{CM} \leq \bar{\bar{X}}_{2,k}^C\ \forall k \in \{L,H\}.$$

The first and second period open-loop urban growth boundaries are denoted as $\bar{\bar{X}}_1^O$ and $\bar{\bar{X}}_2^O$. The open-loop specification of the landlord problem with urban growth boundaries is

$$(5) \max_{\tilde{X}_1^{OM}, \tilde{X}_2^{OM}} \left\{ \begin{array}{c} \int_0^{\tilde{X}_1^{OM}} R_{i,1}^{OM}\, dX_i + \int_{\tilde{X}_1^{OM}}^{A} r_{i,1}^{OM}\, dX_i \\ +B \sum_{k\in\{L,H\}} p_k \left(\int_0^{\tilde{X}_2^{OM}} R_{i,2,k}^{OM}\, dX_i + \int_{\tilde{X}_2^{OM}}^{A} r_{i,2,k}^{OM}\, dX_i \right) \end{array} \right\}$$

$$s.t. \tilde{X}_2^{OM} \geq \tilde{X}_1^{OM},\ \tilde{X}_1^{OM} \leq \bar{\bar{X}}_1^O \text{ and } \tilde{X}_2^{OM} \leq \bar{\bar{X}}_2^O.$$

The first period closed-loop location-dependent development fee at location X_i is denoted $D_{i,1}^C = D_1^C(X_i)\ \forall i \in I$, and the state-dependent second period closed-loop location-dependent development fees at location X_i are $D_{i,2,k}^C = D_{2,k}^C(X_i)\ \forall i \in I$. The location-dependent development fee in period *t* and state *k* integrated over the land developed in that period and state enters as an additional term in the objective function. Therefore, the closed-loop landlord problem with location-dependent development fees has the following specification:

$$(6) \max_{\tilde{X}_1^{CM}} \left\{ \begin{array}{c} \int_0^{\tilde{X}_1^{CM}} R_{i,1}^{CM}\, dX_i + \int_0^{\tilde{X}_1^{CM}} D_1^C(X_i) dX_i + \int_{\tilde{X}_1^{CM}}^{A} r_{i,1}^{CM}\, dX_i \\ +B \sum_{k\in\{L,H\}} p_k \max_{\tilde{X}_{2,k}^{CM}} \left(\int_0^{\tilde{X}_{2,k}^{CM}} R_{i,2,k}^{CM}\, dX_i + \int_{\tilde{X}_1^{CM}}^{\tilde{X}_{2,k}^{CM}} D_{2,k}^C(X_i)\, dX_i + \int_{\tilde{X}_{2,k}^{CM}}^{A} r_{i,2,k}^{CM} dX_i \right) \end{array} \right\}$$

$$s.t. \tilde{X}_{2,k}^{CM} \geq \tilde{X}_1^{CM}.$$

The first and second period open-loop location-dependent development fees at location X_i are denoted $D^O_{i,1} = D^O_1(X_i)$ and $D^O_{i,2} = D^O_2(X_i)\ \forall i \in I$. The open-loop specification of the landlord problem with location-dependent development fees is

$$(7)\max_{\widetilde{X}_1^{OM},\widetilde{X}_2^{OM}}\left\{\begin{array}{c}\int_0^{\widetilde{X}_1^{OM}} R_{i,1}^{OM}\,dX_i + \int_0^{\widetilde{X}_1^{OM}} D_1^O(X_i)dX_i + \int_{\widetilde{X}_1^{OM}}^{A} r_{i,1}^{OM}\,dX_i \\ +B\sum_{k\in\{L,H\}} p_k\left(\int_0^{\widetilde{X}_2^{OM}} R_{i,2,k}^{OM}\,dX_i + B\int_{\widetilde{X}_1^{OM}}^{\widetilde{X}_2^{OM}} D_2^O(X_i)\,dX_i + \int_{\widetilde{X}_2^{OM}}^{A} r_{i,2,k}^{OM}\,dX_i\right)\end{array}\right\}$$

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

The first period closed-loop location-independent development fee is denoted F^C_1 and the state-dependent second period closed-loop location-independent development fees are $F^C_{2,k}$. The location-independent development fee in period *t* and state *k* integrated over the land developed in that period and state enters as an additional term in the objective function. The closed-loop landlord problem with the location-independent development fees has the following specification:

$$(8)\max_{\widetilde{X}_1^{CM}}\left\{\begin{array}{c}\int_0^{\widetilde{X}_1^{CM}} R_{i,1}^{CM}\,dX_i + \int_0^{\widetilde{X}_1^{CM}} F_1^C dX_i + \int_{\widetilde{X}_1^{CM}}^{A} r_{i,1}^{CM}\,dX_i \\ +B\sum_{k\in\{L,H\}} p_k \max_{\widetilde{X}_{2,k}^{CM}}\left(\int_0^{\widetilde{X}_{2,k}^{CM}} R_{i,2,k}^{CM}\,dX_i + \int_{\widetilde{X}_1^{CM}}^{\widetilde{X}_{2,k}^{CM}} F_{2,k}^C\,dX_i + \int_{\widetilde{X}_{2,k}^{CM}}^{A} r_{i,2,k}^{CM} dX_i\right)\end{array}\right\}$$

$$s.t. \widetilde{X}_{2,k}^{CM} \geq \widetilde{X}_1^{CM}.$$

The first and second period open-loop location-independent development fees are denoted F^O_1 and F^O_2. The open-loop specification of the landlord problem with location-independent development fees is

$$(9)\max_{\widetilde{X}_1^{OM},\widetilde{X}_2^{OM}}\left\{\begin{array}{c}\int_0^{\widetilde{X}_1^{OM}} R_{i,1}^{OM}\,dX_i + \int_0^{\widetilde{X}_1^{OM}} F_1^O dX_i + \int_{\widetilde{X}_1^{OM}}^{A} r_{i,1}^{OM}\,dX_i \\ +B\sum_{k\in\{L,H\}} p_k\left(\int_0^{\widetilde{X}_2^{OM}} R_{i,2,k}^{OM}\,dX_i + B\int_{\widetilde{X}_1^{OM}}^{\widetilde{X}_2^{OM}} F_2^O\,dX_i + \int_{\widetilde{X}_2^{OM}}^{A} r_{i,2,k}^{OM}\,dX_i\right)\end{array}\right\}$$

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

VI. Solution Method

I solve for $\tilde{X}_{t,k}^{nm}$ 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.[9]

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:

$$\textbf{(10a)}\ V\big(y_t - T(X_j) - R_{j,t,k}^{nm}, 1, S_{j,t,k}^{nm}\big) = \bar{\bar{V}}_t$$

when X_j is urbanized and

$$\textbf{(10b)}\ V\big(\Pi(X_j) - r_{j,t,k}^{nm}, 1, S_{j,t,k}^{nm}\big) = \bar{\bar{V}}_t$$

when X_j is in agriculture. I obtain the equilibrium rental rate for each landlord and social planner problem by substituting the appropriate definition of $S_{j,t,k}^{nm}$.

Substituting the landlord's net land use externality definitions into expressions **(10a)** and **(10b)** and invoking the implicit function theorem allows me to establish that the following urban and agricultural rental rates exist in the competitive equilibrium:

$$R_{j,1}^{nM} = \bar{R}_1\big(y_1, \bar{\bar{V}}_1, X_j\big)\ ,$$

$$R_{j,2,k}^{nM} = \bar{R}_{2,k}\big(y_2, \bar{\bar{V}}_2, X_j\big),$$

$$r_{j,1}^{nM} = \bar{r}_1\big(\bar{\bar{V}}_1, X_j\big)\ ,$$

and

$$r_{j,2,k}^{nM} = \bar{r}_{2,k}\big(\bar{\bar{V}}_2, X_j\big)\ \forall n \in \{O, C\}.$$

In the competitive equilibrium, urban and agricultural rental rates are functions of property location X_j only. Note that these definitions of the rental rates apply to both the open-loop and closed-loop landlord problems.

[9] In order to determine the socially optimal policies, I assume that the government can credibly bind its hands when determining land use policy. In addition, the issue of time-consistency is addressed in section VIII where I demonstrate that all three policies are time consistent if there is no cumulative environmental externality.

Substituting the social planner's net land use externality definitions into expressions **(10a)** and **(10b)** and invoking the implicit function theorem allows me to establish that the following urban and agricultural rental rates exist in the social planner problem:

$$R_{j,1}^{nP} = R_1\left(y_1, \bar{\bar{V}}_1, X_j, \tilde{X}_1^{nP}\right),$$

$$R_{j,2,k}^{nP} = R_{2,k}\left(y_2, \bar{\bar{V}}_2, X_j, \tilde{X}_1^{nP}, \tilde{X}_{2,k}^{nP}\right),$$

$$r_{j,1}^{nP} = r_1\left(\bar{\bar{V}}_1, X_j, \tilde{X}_1^{nP}\right),$$

and

$$r_{j,2,k}^{nP} = r_{2,k}\left(\bar{\bar{V}}_2, X_j, \tilde{X}_1^{nP}, \tilde{X}_{2,k}^{nP}\right) \forall n \in \{O, C\}.$$

Invoking the implicit function theorem, there exists some function $\hat{h}$ such that $c_{j,t,k}^{nm} = \hat{h}\left(g_{j,t,k}^{nm}, S_{j,t,k}^{nm}, \bar{\bar{V}}_t\right)$. Because the urban and agricultural rental rates are functions of $c_{j,t,k}^{nm}$, i.e. $R_{j,t,k}^{nm} = y_t - T_{j,t,k} - c_{j,t,k}^{nm}$ and $r_{j,t,k}^{nm} = \Pi_{j,t,k} - c_{j,t,k}^{nm}$, the urban and agricultural rental rate functions are of the forms $R_{j,t,k}^{nm} = y_t - T\left(X_j\right) - \hat{h}\left(g_{j,t,k}^{nm}, S_{j,t,k}^{nm}, \bar{\bar{V}}_t\right)$ and $r_{j,t,k}^{nm} = \Pi\left(X_j\right) - \hat{h}\left(g_{j,t,k}^{nm}, S_{j,t,k}^{nm}, \bar{\bar{V}}_t\right)$. Because the landlord incorrectly assumes that externalities vary only with the location of the tenant, the equilibrium consumption of the numeraire good for tenant *j* in period *t* and state *k* in the landlord profit-maximization problems varies only with tenant location: $c_{j,1}^{nM} = \hat{h}\left(1, \bar{S}_1\left(X_j\right), \bar{\bar{V}}_1\right) = \bar{h}_1\left(X_j, \bar{\bar{V}}_1\right)$ and $c_{j,2,k}^{nM} = \hat{h}\left(1, \bar{S}_{2,k}\left(X_j\right), \bar{\bar{V}}_2\right) = \bar{h}_{2,k}\left(X_j, \bar{\bar{V}}_2\right)$ $\forall n \in \{O, C\}$. Therefore, the following urban and agricultural rental rates exist in the landlord problem:

$$R_{j,1}^{nM} = \bar{R}_1\left(y_1, \bar{\bar{V}}_1, X_j\right) = y_1 - T\left(X_j\right) - \bar{h}_1\left(X_j, \bar{\bar{V}}_1\right),$$

$$R_{j,2,k}^{nM} = \bar{R}_{2,k}\left(y_2, \bar{\bar{V}}_2, X_j\right) = y_2 - T\left(X_j\right) - \bar{h}_{2,k}\left(X_j, \bar{\bar{V}}_2\right),$$

$$r_{j,1}^{nM} = \bar{r}_1\left(\bar{\bar{V}}_1, X_j\right) = \Pi\left(X_j\right) - \bar{h}_1\left(X_j, \bar{\bar{V}}_1\right),$$

and

$$r_{j,2,k}^{nM} = \bar{r}_{2,k}\left(\bar{\bar{V}}_2, X_j\right) = \Pi\left(X_j\right) - \bar{h}_{2,k}\left(X_j, \bar{V}_2\right) \forall n \in \{O, C\}.$$ [10]

Though the landowner perceives rental rates as varying with only location, urban and agricultural rental rates are also functions of the amount of urban space when in Nash equilibrium. The net land use externality at location X_j when the landlord problem is in competitive equilibrium equals $S_{j,1}^{nM^*} = S_1\left(X_j, \tilde{X}_1^{nM^*}\right)$ in the first period and $S_{j,2,k}^{nM^*} = S_{2,k}\left(X_j, \tilde{X}_1^{nM^*}, \tilde{X}_{2,k}^{nM^*}\right)$ in the second

[10] Because the random variable Z is in the second period net land use externality term, i.e. $S_{j,2,k}^{nM} = \bar{S}_2\left(X_j | Z = z_k\right) \forall n \in \{O, C\}$, we can write $c_{j,2,k}^{nM} = \bar{h}_2\left(X, \bar{\bar{V}}_2 | Z = z_k\right)$, $R_{j,2,k}^{nM} = \bar{R}_{2,k}\left(y_2, \bar{\bar{V}}_2, X_j | Z = z_k\right)$, and $r_{j,2,k}^{nM} = \bar{r}_{2,k}\left(\bar{\bar{V}}_2, X_j | Z = z_k\right) \forall n \in \{O, C\}$.

period $\forall n \in \{O, C\}$ if state k occurs. Tenant j's numeraire good consumption in competitive equilibrium is $c_{j,1}^{nM^*} = \hat{h}\left(1, S_1\left(X_j, \tilde{X}_1^{nM^*}\right), \bar{\bar{V}}_1\right) = h_1\left(X_j, \bar{\bar{V}}_1, \tilde{X}_1^{nM^*}\right)$ in the first period and $c_{j,2,k}^{nM^*} = \hat{h}\left(1, S_{2,k}\left(X_j, \tilde{X}_1^{nM^*}, \tilde{X}_{2,k}^{nM^*}\right), \bar{\bar{V}}_2\right) = h_{2,k}\left(X_j, \tilde{X}_1^{nM^*}, \tilde{X}_{2,k}^{nM^*}, \bar{\bar{V}}_2\right)$ in the second period $\forall n \in \{O, C\}$ when state k occurs. The competitive equilibrium rental rates at location X_j in the open-loop and closed-loop landlord problems are

$$R_{j,1}^{nM^*} = R_1\left(y_1, \bar{\bar{V}}_1, X_j, \tilde{X}_1^{nM^*}\right) = y_1 - T\left(X_j\right) - h_1\left(X_j, \tilde{X}_1^{nM^*}, \bar{\bar{V}}_1\right),$$

$$R_{j,2,k}^{nM^*} = R_{2,k}\left(y_2, \bar{\bar{V}}_2, X_j, \tilde{X}_1^{nM^*}, \tilde{X}_{2,k}^{nM^*}\right) = y_2 - T\left(X_j\right) - h_{2,k}\left(X_j, \tilde{X}_1^{nM^*}, \tilde{X}_{2,k}^{nM^*}, \bar{\bar{V}}_2\right),$$

$$r_{j,1}^{nM^*} = r_1\left(\bar{\bar{V}}_1, X_j, \tilde{X}_1^{nM^*}\right) = \Pi\left(X_j\right) - h_1\left(X_j, \tilde{X}_1^{nM^*}, \bar{\bar{V}}_1\right),$$

and

$$r_{j,2,k}^{nM^*} = r_{2,k}\left(\bar{\bar{V}}_2, X_j, \tilde{X}_1^{nM^*}, \tilde{X}_{2,k}^{nM^*}\right) = \Pi\left(X_j\right) - h_{2,k}\left(X_j, \tilde{X}_1^{nM^*}, \tilde{X}_{2,k}^{nM^*}, \bar{\bar{V}}_2\right) \forall n \in \{O, C\}.$$

In competitive equilibrium, the agricultural and urban rental rates that the landowner perceives at location X_i are what actually exist at location X_i.

In contrast, the social planner recognizes that the net land use externality varies with the amount of urban space. As a consequence, the equilibrium consumption of the numeraire good for tenant j in period t and state k in the social planner problem is a function of tenant location and the amount of urban land: $c_{j,1}^{nP} = \hat{h}\left(1, S_1\left(X_j, \tilde{X}_1^{nP}\right), \bar{\bar{V}}_1\right) = h_1\left(X, \tilde{X}_1^{nP}, \bar{\bar{V}}_1\right)$ and $c_{j,2,k}^{nP} = \hat{h}\left(1, S_{2,k}\left(X_j, \tilde{X}_1^{nP}, \tilde{X}_{2,k}^{nP}\right), \bar{\bar{V}}_2\right) = h_{2,k}\left(X, \tilde{X}_1^{nP}, \tilde{X}_{2,k}^{nP}, \bar{\bar{V}}_2\right)$ $\forall n \in \{O, C\}$. Therefore, the following urban and agricultural rental rates exist in the social planner problem:

$$R_{j,1}^{nP} = R_1\left(y_1, \bar{\bar{V}}_1, X_j, \tilde{X}_1^{nP}\right) = y_1 - T\left(X_j\right) - h_1\left(X_j, \tilde{X}_1^{nP}, \bar{\bar{V}}_1\right),$$

$$R_{j,2,k}^{nP} = R_{2,k}\left(y_2, \bar{\bar{V}}_2, X_j, \tilde{X}_1^{nP}, \tilde{X}_{2,k}^{nP}\right) = y_2 - T\left(X_j\right) - h_{2,k}\left(X_j, \tilde{X}_1^{nP}, \tilde{X}_{2,k}^{nP}, \bar{\bar{V}}_2\right),$$

$$r_{j,1}^{nP} = r_1\left(\bar{\bar{V}}_1, X_j, \tilde{X}_1^{nP}\right) = \Pi\left(X_j\right) - h_1\left(X_j, \tilde{X}_1^{nP}, \bar{\bar{V}}_1\right),$$

and

$$r_{j,2,k}^{nP} = r_{2,k}\left(\bar{\bar{V}}_2, X_j, \tilde{X}_1^{nP}, \tilde{X}_{2,k}^{nP}\right) = \Pi\left(X_j\right) - h_{2,k}\left(X_j, \tilde{X}_1^{nP}, \tilde{X}_{2,k}^{nP}, \bar{\bar{V}}_2\right) \forall n \in \{O, C\}.$$ [11]

Determining the Euler Conditions. The mathematical specifications of the problems described in Section V can be found by substituting the agricultural and urban rental rates into the open-loop

[11] Because the random variable Z is in the second period net land use externality term, i.e. $S_{j,2,k}^{nP} = S_2\left(X_j, \tilde{X}_1^{nP}, \tilde{X}_{2,k}^{nP} | Z = z_k\right)$, we can write $c_{j,2,k}^{nP} = h_2\left(X, \tilde{X}_1^{nP}, \tilde{X}_{2,k}^{nP}, \bar{\bar{V}}_2 | Z = z_k\right)$, $R_{j,2,k}^{nP} = R_2\left(y_2, \bar{\bar{V}}_2, X_j, \tilde{X}_1^{nP}, \tilde{X}_{2,k}^{nP} | Z = z_k\right)$, and $r_{j,2,k}^{nP} = r_2\left(\bar{\bar{V}}_2, X_j, \tilde{X}_1^{nP}, \tilde{X}_{2,k}^{nP} | Z = z_k\right)$.

and closed-loop problems defined in Section V, i.e. expressions **(2) - (9)**. The closed-loop landowner profit-maximization problem becomes

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

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

The open-loop landowner profit-maximization problem becomes

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

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

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

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

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

By substituting the landlord's urban and agricultural rental rates into expressions **(4)**, **(6)**, and **(8)**, I find the specifications of the closed-loop landowner profit-maximization problem with urban growth boundaries, location-dependent development fees, and location-independent development fees, respectively. Similarly, I substitute these rental rates into expressions **(5)**, **(7)**, and **(9)**, to find the specifications of the open-loop landlord problem with urban growth boundaries, location-dependent development fees, and location-independent development fees, respectively. These specifications are given in the appendix. 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.

In order to obtain each problem's Euler conditions, I rewrite it as a Lagrangian function as depicted in the appendix. The key difference between the open-loop problems and the closed-loop problems is the role of the Lagrange multiplier. In the open-loop problems, the Lagrange multiplier is the expected present value of the additional municipality-wide landlord rent gained if the irreversibility constraint is relaxed one unit. According to the Kuhn-Tucker conditions, the shadow value on the irreversibility constraint is positive when the irreversibility constraint binds, and zero when it does not. In the closed-loop problem, the irreversibility constraint is conditional on the realized second period state $k \in \{L, H\}$. The closed-loop Lagrange multiplier in state *k* is the additional total rent gained if the irreversibility constraint is relaxed one unit and state *k* is realized. According to the Kuhn-Tucker conditions, the shadow value on the irreversibility constraint when state *k* is realized is positive when the irreversibility constraint binds in state *k*, and zero when it does not. As a consequence of this difference, the Euler conditions for the open-loop problems are found by solving the Lagrangian in the traditional manner, whereas the Euler conditions for the closed-loop problems are found by solving recursively.

An additional step is required to solve for the Euler conditions of the landlord problems. Because the landlord treats the net land use externality at each X_j as constant with respect to the amount of urban land, while tenants do not, the final stage in solving for the competitive equilibrium Euler conditions is to replace the landlord rental rates, $R_{j,t,k}^{nM}$ and $r_{j,t,k}^{nM}$, with those of the social planner, $R_{j,t,k}^{nP}$ and $r_{j,t,k}^{nP}$, in the first order conditions of the landlord problems.

<u>Solving for the difference between private and social values of information.</u> For each decision maker, the value of information is obtained by subtracting the open-loop value function from the closed-loop value function. The difference between the private and social values of information is greater than or equal to zero due to the public good nature of oak woodland amenities.

VII. 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, which are derived from the first-order conditions of the Lagrangian functions using the procedure detailed in Section VI. The appendix displays the Euler conditions for the open-loop and closed-loop social planner and landlord problems without land-use policies and the Euler conditions for the open-loop and closed-loop landlord problems with the modeled land use polices: urban growth boundaries, location-independent development fees, and location-dependent development fees. Second, using these Euler conditions, this section derives three propositions about the relative size of urban land in each of the four models without land use policies. Third, 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.

Open-loop competitive equilibria.
There are two potential solution regimes for the open-loop landlord problem, which are differentiated by whether or not the irreversibility constraint binds. The irreversibility constraint binds if and only if $\tilde{X}_2^{OM^*} = \tilde{X}_1^{OM^*}$.

The Euler conditions for the open-loop landlord problem 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 oak woodland. If the irreversibility constraint is non-binding, the marginal landlord in the first period is the landlord for whom the rent that she can charge her tenant in the first period is equal across land uses, or $R_1\left(y_1, \bar{\bar{V}}_1, \tilde{X}_1^{OM^*}, \tilde{X}_1^{OM^*}\right) = r_1\left(\bar{\bar{V}}_1, \tilde{X}_1^{OM^*}, \tilde{X}_1^{OM^*}\right)$. The marginal landlord in the second period is the landlord for whom the expected amount of rent that she can charge her tenant in the second period is equal across land uses, or $\sum_{k\in[L,H]} p_k * R_{2,k}\left(y_2, \bar{\bar{V}}_2, \tilde{X}_2^{OM^*}, \tilde{X}_1^{OM^*}, \tilde{X}_2^{OM^*}\right) = \sum_{k\in[L,H]} p_k * r_{2,k}\left(\bar{\bar{V}}_2, \tilde{X}_2^{OM^*}, \tilde{X}_1^{OM^*}, \tilde{X}_2^{OM^*}\right)$. If the irreversibility constraint binds, the marginal landowner is the landlord for whom the expected present value of rent that she can charge her tenant in both periods is equal across land uses; this marginal landlord is characterized by the equality of her income gain in the first period from developing her land and her expected income loss in the second period from not being able to return her land to agricultural use, or $R_1\left(y_1, \bar{\bar{V}}_1, \tilde{X}_1^{OM^*}, \tilde{X}_1^{OM^*}\right) + B\sum_{k\in[L,H]} p_k * R_{2,k}\left(y_2, \bar{\bar{V}}_2, \tilde{X}_2^{OM^*}, \tilde{X}_1^{OM^*}, \tilde{X}_2^{OM^*}\right) = r_1\left(\bar{\bar{V}}_1, \tilde{X}_1^{OM^*}, \tilde{X}_1^{OM^*}\right) + B\sum_{k\in[L,H]} p_k * r_{2,k}\left(\bar{\bar{V}}_2, \tilde{X}_2^{OM^*}, \tilde{X}_1^{OM^*}, \tilde{X}_2^{OM^*}\right)$ where $\tilde{X}_2^{OM^*} = \tilde{X}_1^{OM^*}$.

Open-loop social optima.
The Euler conditions for the open-loop social planner problem differ from the Euler conditions for the open-loop 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 open-loop social planner problem:

$$C_1^{OP} = C_1\left(\tilde{X}_1^{OP^*}\right) = \int_0^{\tilde{X}_1} \frac{\partial R_1\left(y_1, \bar{\bar{V}}_1, X_i, \tilde{X}_1\right)}{\partial \tilde{X}_1} dX_i + \int_{\tilde{X}_1}^{A} \frac{\partial r_1\left(\bar{\bar{V}}_1, X_i, \tilde{X}_1\right)}{\partial \tilde{X}_1} dX_i = \int_0^A \frac{\frac{\partial V}{\partial S_1}\left(h_1\left(X_i, \tilde{X}_1, \bar{\bar{V}}_1\right), 1, S_1\left(X_i, \tilde{X}_1\right)\right)}{\frac{\partial V}{\partial C_1}\left(h_1\left(X_i, \tilde{X}_1, \bar{\bar{V}}_1\right), 1, S_1\left(X_i, \tilde{X}_1\right)\right)} \frac{\partial S_1}{\partial \tilde{X}_1} dX_i,$$

$$G_k^{OP} = G_k\left(\tilde{X}_1^{OP^*}, \tilde{X}_2^{OP^*}\right) = \int_0^{\tilde{X}_2} \frac{\partial R_{2,k}(y_2, \bar{\bar{V}}_2, X_i, \tilde{X}_1, \tilde{X}_2)}{\partial \tilde{X}_1} dX_i + \int_{\tilde{X}_2}^{A} \frac{\partial r_{2,k2}(\bar{\bar{V}}_2, X_i, \tilde{X}_1, \tilde{X}_2)}{\partial \tilde{X}_1} dX_i = \int_0^A \frac{\frac{\partial V}{\partial S_{2,k}}\left(h_{2,k}(X_i, \tilde{X}_1, \tilde{X}_{2,k}, \bar{\bar{V}}_2), 1, S_{2,k}(X_i, \tilde{X}_1, \tilde{X}_2)\right)}{\frac{\partial V}{\partial C_{2,k}}\left(h_{2,k}(X_i, \tilde{X}_1, \tilde{X}_{2,k}, \bar{\bar{V}}_2), 1, S_{2,k}(X_i, \tilde{X}_1, \tilde{X}_2)\right)} \frac{\partial S_{2,k}}{\partial \tilde{X}_1} dX_i,$$

and

$$C_{2,k}^{OP} = C_{2,k}\left(\tilde{X}_1^{OP^*}, \tilde{X}_2^{OP^*}\right) = \int_0^{\tilde{X}_2} \frac{\partial R_{2,k}(y_2, \bar{\bar{V}}_2, X_i, \tilde{X}_1, \tilde{X}_2)}{\partial \tilde{X}_2} dX_i + \int_{\tilde{X}_2}^{A} \frac{\partial r_{2,k}(\bar{\bar{V}}_2, X_i, \tilde{X}_1, \tilde{X}_2)}{\partial \tilde{X}_2} dX_i = \int_0^A \frac{\frac{\partial V}{\partial S_{2,k}}\left(h_{2,k}(X_i, \tilde{X}_1, \tilde{X}_{2,k}, \bar{\bar{V}}_2), 1, S_{2,k}(X_i, \tilde{X}_1, \tilde{X}_2)\right)}{\frac{\partial V}{\partial C_{2,k}}\left(h_{2,k}(X_i, \tilde{X}_1, \tilde{X}_{2,k}, \bar{\bar{V}}_2), 1, S_{2,k}(X_i X, \tilde{X}_1, \tilde{X}_2)\right)} \frac{\partial S_{2,k}}{\partial \tilde{X}_2} dX_i.$$

.

The first term $C_1\left(\tilde{X}_1^{OP^*}\right)$ 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. $G_k\left(\tilde{X}_1^{OP^*}, \tilde{X}_2^{OP^*}\right)$ 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 $C_{2,k}\left(\tilde{X}_1^{OP^*}, \tilde{X}_2^{OP^*}\right)$ depends on whether the irreversibility constraint binds because $C_{2,k}\left(\tilde{X}_1^{OP^*}, \tilde{X}_2^{OP^*}\right)$ is captured in the Lagrange multiplier λ^{OP^*} where

$$\lambda^{OP^*} = B \sum_{k \in [L,H]} p_k \times \left\{ r_{2,k}\left(\bar{\bar{V}}_2, \tilde{X}_2^{OP^*}, \tilde{X}_1^{OP^*}, \tilde{X}_2^{OP^*}\right) - R_{2,k}\left(y_2, \bar{\bar{V}}_2, \tilde{X}_2^{OP^*}, \tilde{X}_1^{OP^*}, \tilde{X}_2^{OP^*}\right) - C_{2,k}\left(\tilde{X}_1^{OP^*}, \tilde{X}_2^{OP^*}\right) \right\}.$$

If the irreversibility constraint is non-binding then $C_{2,k}^{OP}$ 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 irreversibility constraint is binding, $C_{2,k}^{OP}$ 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 derive these marginal external cost components and prove that each of them is non-positive.

Because the interpretation of $C_{2,k}^{OP}$ depends on whether the irreversibility constraint binds, the expected marginal external cost of first period urban development and the expected marginal external cost of second period urban development do also. If the irreversibility constraint is non-binding, the expected marginal external cost of first period urban development is $C_1^{OP} +$

$B\sum_{k\in[L,H]} p_k G_k^{OP}$ and the expected marginal external cost of second period urban development is $\sum_{k\in[L,H]} p_k\, C_{2,k}^{OP}$. If the irreversibility constraint is binding, the expected marginal external cost of first period urban development is $C_1^{OP} + B\sum_{k\in[L,H]} p_k G_k^{OP} + B\sum_{k\in[L,H]} p_k\, C_{2,k}^{OP}$. There is no marginal external cost of second period urban development because there is no second period urban development.

This discussion leads to the following proposition, which is proved formally in the appendix.

Proposition 1: *In each period, the socially optimal amount of urban land is always less than or equal to the privately optimal amount under open-loop control.*

Closed-loop competitive equilibria.
There are four potential solution regimes in the closed-loop landlord problem, which are differentiated by whether or not the irreversibility constraints in state *H* and state *L* bind. The irreversibility constraint in state *k* binds if and only if $\tilde{X}_1^{CM^*} = \tilde{X}_{2,k}^{CM^*}$.

The Euler conditions for the closed-loop landlord problem imply that the amount of urban land in the first period should increase until the expected value of the marginal unit of urban land equals the expected value of the marginal unit of oak woodland. If the irreversibility constraint is non-binding in both states *H* and *L*, the marginal landlord in the first period is the landlord for whom the rent that she can charge her tenant in the first period is equal across land uses, or $R_1\big(y_1, \bar{\bar{V}}_1, \tilde{X}_1^{CM^*}, \tilde{X}_1^{CM^*}\big) = r_1\big(\bar{\bar{V}}_1, \tilde{X}_1^{CM^*}, \tilde{X}_1^{CM^*}\big)$. Given that the true state of nature is known in the second period, the marginal landowner in the second period is the landlord for whom the rent that she can charge her tenant is equal across land uses in the realized state, or $R_{2,k}\big(y_2, \bar{\bar{V}}_2, \tilde{X}_{2,k}^{CM^*}, \tilde{X}_1^{CM^*}, \tilde{X}_{2,k}^{CM^*}\big) = r_{2,k}\big(\bar{\bar{V}}_2, \tilde{X}_{2,k}^{CM^*}, \tilde{X}_1^{CM^*}, \tilde{X}_{2,k}^{CM^*}\big)\ \forall k \in \{L, H\}$. If the irreversibility constraint binds in both states, the marginal landowner is the landlord for whom the expected present value of rent that she can charge her tenant in both periods is equal across land-uses, or $R_1\big(y_1, \bar{\bar{V}}_1, \tilde{X}_1^{CM^*}, \tilde{X}_1^{CM^*}\big) + B\sum_{k\in[L,H]} p_k\, R_{2,k}\big(y_2, \bar{\bar{V}}_2, \tilde{X}_{2,k}^{CM^*}, \tilde{X}_1^{CM^*}, \tilde{X}_{2,k}^{CM^*}\big) = r_1\big(\bar{\bar{V}}_1, \tilde{X}_1^{CM^*}, \tilde{X}_1^{CM^*}\big) +$
$B\sum_{k\in[L,H]} p_k\, r_{2,k}\big(\bar{\bar{V}}_2, \tilde{X}_{2,k}^{CM^*}, \tilde{X}_1^{CM^*}, \tilde{X}_{2,k}^{CM^*}\big)$ where $\tilde{X}_1^{CM^*} = \tilde{X}_{2,L}^{CM^*} = \tilde{X}_{2,H}^{CM^*}$.

Proposition 2: *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.*

The proof of the proposition has several steps, detailed in the appendix. The intuition behind this result 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 gain no additional valuable information, i.e. information that has relevance to their decision making process, under closed-loop control than under open-loop control.

Closed-loop social optima.
The Euler conditions for the closed-loop social planner problem differ from the Euler conditions for the closed-loop 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 closed-loop social planner problem:

$$C_1^{CP} = C_1\left(\tilde{X}_1^{CP^*}\right) = \int_0^{\tilde{X}_1} \frac{\partial R_1\left(y_1,\bar{\bar{V}}_1,X_i,\tilde{X}_1\right)}{\partial \tilde{X}_1} dX_i + \int_{\tilde{X}_1}^{A} \frac{\partial r_1\left(\bar{\bar{V}}_1,X_i,\tilde{X}_1\right)}{\partial \tilde{X}_1} dX_i = \int_0^A \frac{\frac{\partial V}{\partial S_1}\left(h_1\left(X_i,\tilde{X}_1,\bar{\bar{V}}_1\right),1,S_1\left(X_i,\tilde{X}_1\right)\right)}{\frac{\partial V}{\partial C_1}\left(h_1\left(X_i,\tilde{X}_1,\bar{\bar{V}}_1\right),1,S_1\left(X_i,\tilde{X}_1\right)\right)} \frac{\partial S_1}{\partial \tilde{X}_1} dX_i,$$

$$G_k^{CP} = G_k\left(\tilde{X}_1^{CP^*},\tilde{X}_{2,k}^{CP^*}\right) = \int_0^{\tilde{X}_{2,k}} \frac{\partial R_{2,k}\left(y_2,\bar{\bar{V}}_2,X_i,\tilde{X}_1,\tilde{X}_{2,k}\right)}{\partial \tilde{X}_1} dX_i + \int_{\tilde{X}_{2,k}}^{A} \frac{\partial r_{2,k}\left(\bar{\bar{V}}_2,X_i,\tilde{X}_1,\tilde{X}_{2,k}\right)}{\partial \tilde{X}_1} dX_i = \int_0^A \frac{\frac{\partial V}{\partial S_{2,k}}\left(h_{2,k}\left(X_i,\tilde{X}_1,\tilde{X}_{2,k},\bar{\bar{V}}_2\right),1,S_{2,k}\left(X_i,\tilde{X}_1,\tilde{X}_{2,k}\right)\right)}{\frac{\partial V}{\partial C_{2,k}}\left(h_{2,k}\left(X_i,\tilde{X}_1,\tilde{X}_{2,k},\bar{\bar{V}}_2\right),1,S_{2,k}\left(X_i,\tilde{X}_1,\tilde{X}_{2,k}\right)\right)} \frac{\partial S_{2,k}}{\partial \tilde{X}_1} dX_i,$$

and

$$C_{2,k}^{CP} = C_{2,k}\left(\tilde{X}_1^{CP^*},\tilde{X}_{2,k}^{CP^*}\right) = \int_0^{\tilde{X}_{2,k}} \frac{\partial R_{2,k}\left(y_2,\bar{\bar{V}}_2,X_i,\tilde{X}_1,\tilde{X}_{2,k}\right)}{\partial \tilde{X}_{2,k}} dX_i + \int_{\tilde{X}_{2,k}}^{A} \frac{\partial r_{2,k}\left(\bar{\bar{V}}_2,X_i,\tilde{X}_1,\tilde{X}_{2,k}\right)}{\partial \tilde{X}_{2,k}} dX_i = \int_0^A \frac{\frac{\partial V}{\partial S_{2,k}}\left(h_{2,k}\left(X_i,\tilde{X}_1,\tilde{X}_{2,k},\bar{\bar{V}}_2\right),1,S_{2,k}\left(X_i,\tilde{X}_1,\tilde{X}_{2,k}\right)\right)}{\frac{\partial V}{\partial C_{2,k}}\left(h_{2,k}\left(X_i,\tilde{X}_1,\tilde{X}_{2,k},\bar{\bar{V}}_2\right),1,S_{2,k}\left(X_i,\tilde{X}_1,\tilde{X}_{2,k}\right)\right)} \frac{\partial S_{2,k}}{\partial \tilde{X}_{2,k}} dX_i.$$

In the appendix, I derive these marginal external cost components and prove that each of them is non-positive. The only difference between the components of the closed-loop and open-loop marginal external costs of urban development is that they are functions of different solutions for the amounts of urban land. Thus, the open and closed-loop marginal external cost components differ in magnitude across the social planner problems except when one of two special cases holds: $\tilde{X}_1^{OP^*} = \tilde{X}_1^{CP^*}$ 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 in all periods and states.

As in the open-loop social planner problem, the interpretation of $C_{2,k}^{CP}$ depends on the value of the corresponding Lagrange multiplier $\lambda_k^{CP^*}$. However, unlike under open-loop control, the Lagrange multiplier is state dependent under closed-loop control. As a consequence, the expected marginal external cost of first period urban development and the marginal external cost of second period urban development depend on which irreversibility constraints bind. If the irreversibility constraints for both period 2 states are non-binding, then the expected marginal external cost of first period urban development is $C_1^{CP} + B\sum_{k\in[L,H]} p_k G_k^{CP}$ and $C_{2,k}^{CP}$ is the marginal external cost of second period urban development in state *k*. 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 $C_{2,L}^{CP}$. If only the irreversibility constraint in state *L* binds then there is no development in period 2 if state *L* is realized, the expected marginal external cost of first period urban development is $C_1^{CP} + B\sum_{k\in[L,H]} p_k G_k^{CP} + Bp_L C_{2,L}^{CP}$, and the marginal external cost of second period urban development in state *H* is $C_{2,H}^{CP}$. If the irreversibility constraint is binding in both states then there is no development in period 2 and the expected marginal external cost of first period urban development is $C_1^{CP} + B\sum_{k\in[L,H]} p_k G_k^{CP} + B\sum_{k\in[L,H]} p_k C_{2,k}^{CP}$.

This discussion leads to the following proposition, which is proved formally in the appendix.

Proposition 3: *In each period, the socially optimal amount of urban land is always less than or equal to the privately optimal amount under closed-loop control.*

Second order conditions. If specific assumptions hold, the solutions to the Euler conditions for the four models depicted in Table 3 are unique global maxima. Because there are no equality constraints in these problems, there exists a global maximum in each open-loop problem if the Kuhn-Tucker (KT) conditions and the constraint qualification (CQ) condition for binding constraints hold for some $\tilde{X}_1^{Om^*}$ and $\tilde{X}_{2,k}^{Om^*}$, each inequality constraint is a quasiconvex function, and the value function is concave. Similarly, there exists a global maximum in each closed-loop problem if the KT conditions and the CQ condition hold for some $\tilde{X}_1^{Cm^*}$, $\tilde{X}_{2,L}^{Cm^*}$, and $\tilde{X}_{2,H}^{Cm^*}$, each inequality constraint is a quasiconvex function, and the value function is concave (Mass-Colell, Whinston, and Green, 1995). As stated in the previous section, I restrict attention to interior solutions for expositional convenience. As a consequence, the KT and the CQ conditions hold for each of the four problems.

The irreversibility constraints are convex, implying that they are quasiconvex. By rewriting them, as $g\left(\tilde{X}_1^{Om^*}, \tilde{X}_2^{Om^*}\right) = \tilde{X}_1^{Om^*} - \tilde{X}_2^{Om^*} \leq 0$ in the open-loop problems and $g_k\left(\tilde{X}_1^{Cm^*}, \tilde{X}_{2,k}^{Cm^*}\right) = \tilde{X}_1^{Cm^*} - \tilde{X}_{2,k}^{Cm^*} \leq 0$ in the closed-loop problems, it is easy to see that the second derivatives of all of the irreversibility constraints equal zero. Consequently, all elements in each constraint's Hessian matrix equal zero. This implies that each matrix is positive semi-definite, and therefore, each constraint is convex. Because a convex function is quasiconvex, all irreversibility constraints are quasiconvex.

The objective functions in the open-loop and closed-loop landlord and social planner problems are all strictly concave if certain restrictions hold. For convenience, I restrict attention to strictly concave objective functions, which obviously ensures concavity. The objective function is strictly concave when its Hessian matrix is negative definite. The Hessian matrix for the open-loop landlord problem is

$$\begin{bmatrix} -\left(\dfrac{\partial T}{\partial X} + \dfrac{\partial \Pi}{\partial X}\right) & 0 \\ 0 & -B\left(\dfrac{\partial T}{\partial X} + \dfrac{\partial \Pi}{\partial X}\right) \end{bmatrix},$$

and the Hessian matrix for the closed-loop landlord problem is

$$\begin{bmatrix} -\left(\frac{\partial T}{\partial X}+\frac{\partial \Pi}{\partial X}\right) & 0 & 0 \\ 0 & -BP_H\left(\frac{\partial T}{\partial X}+\frac{\partial \Pi}{\partial X}\right) & 0 \\ 0 & 0 & -BP_L\left(\frac{\partial T}{\partial X}+\frac{\partial \Pi}{\partial X}\right) \end{bmatrix}.$$

Because the closed-loop problem is solved recursively, $-\left(\frac{\partial T}{\partial X}+\frac{\partial \Pi}{\partial X}\right) < 0$ must hold in addition to the Hessian matrix being negative definite in order for the objective functions to be strictly concave. In the open-loop and closed-loop landlord problems, the objective functions are strictly concave because the sum of the derivative of commuter cost with respect to location and the derivative of agricultural profit with respect to location, i.e. $\frac{\partial T(X)}{\partial X}+\frac{\partial \Pi(X)}{\partial X}\ \ \forall X_j$, is greater than zero and the probability of state *H* occurring is greater than zero and less than one, i.e. $0 < p_H < 1$.

In the open-loop and closed-loop social planner problems, the necessary and sufficient conditions for the Hessian matrix to be negative definite are more complicated. The Hessian matrix for the open-loop social planner problem is

$$\begin{bmatrix} -\left(\frac{\partial T}{\partial X}+\frac{\partial \Pi}{\partial X}\right)+\frac{\partial C_1}{\partial \tilde{X}_1}+B\sum\limits_{k\in\{L,H\}} p_k\frac{\partial G_k}{\partial \tilde{X}_1} & B\sum\limits_{k\in\{L,H\}} p_k\frac{\partial C_{2,k}}{\partial \tilde{X}_1} \\ B\sum\limits_{k\in\{L,H\}} p_k\frac{\partial G_k}{\partial \tilde{X}_2} & -B\left(\frac{\partial T}{\partial X}+\frac{\partial \Pi}{\partial X}-\sum\limits_{k\in\{L,H\}} p_k\frac{\partial C_{2,k}}{\partial \tilde{X}_1}\right) \end{bmatrix}$$

where $B\sum_{k\in\{L,H\}} p_k\frac{\partial C_{2,k}}{\partial \tilde{X}_1} = B\sum_{k\in\{L,H\}} p_k\frac{\partial G_k}{\partial \tilde{X}_2}$ by Young's Theorem. There is a pair of necessary and sufficient conditions for a strictly concave objective function in the open-loop social planner problem:

$$\frac{\partial C_1}{\partial \tilde{X}_1}+B\sum_{k\in\{L,H\}} p_k\frac{\partial G_k}{\partial \tilde{X}_1}-\frac{\partial T}{\partial X}-\frac{\partial \Pi}{\partial X} < 0$$

and

$$\left(\frac{\partial C_1}{\partial \tilde{X}_1}+B\sum_{k\in\{L,H\}} p_k\frac{\partial G_k}{\partial \tilde{X}_1}-\frac{\partial T}{\partial X}-\frac{\partial \Pi}{\partial X}\right)\left(\sum_{k\in\{L,H\}} p_k\frac{\partial C_{2,k}}{\partial \tilde{X}_2}-\frac{\partial T}{\partial X}-\frac{\partial \Pi}{\partial X}\right) > B\left(\sum_{k\in\{L,H\}} p_k\frac{\partial C_{2,k}}{\partial \tilde{X}_1}\right)^2.$$

The first condition states 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. The latter condition states that the product of the rate of change described in the former 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 resulting from an increase in the amount of urban land in the second period 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 resulting from an increase in the amount of urban land in the first period. In other words, this condition states 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.

The Hessian matrix for the closed-loop social planner problem is

$$\begin{bmatrix} -\left(\frac{\partial T}{\partial X}+\frac{\partial \Pi}{\partial X}\right)+\frac{\partial C_1}{\partial \tilde{X}_1}+B\sum_{k\in\{L,H\}} p_k \frac{\partial G_k}{\partial \tilde{X}_1} & Bp_H \frac{\partial C_{2,H}}{\partial \tilde{X}_1} & Bp_L \frac{\partial C_{2,L}}{\partial \tilde{X}_1} \\ Bp_H \frac{\partial G_H}{\partial \tilde{X}_{2,H}} & -BP_H\left(\frac{\partial T}{\partial X}+\frac{\partial \Pi}{\partial X}-\frac{\partial C_{2,H}}{\partial \tilde{X}_{2,H}}\right) & 0 \\ Bp_L \frac{\partial G_L}{\partial \tilde{X}_{2,L}} & 0 & -BP_L\left(\frac{\partial T}{\partial X}+\frac{\partial \Pi}{\partial X}-\frac{\partial C_{2,L}}{\partial \tilde{X}_{2,L}}\right) \end{bmatrix}$$

where $\frac{\partial G_H}{\partial \tilde{X}_{2,H}}=\frac{\partial C_{2,H}}{\partial \tilde{X}_1}$ and $\frac{\partial G_L}{\partial \tilde{X}_{2,L}}=\frac{\partial C_{2,L}}{\partial \tilde{X}_1}$ by Young's Theorem. Because the closed-loop problem is solved recursively, $-BP_k\left(\frac{\partial T}{\partial X}+\frac{\partial \Pi}{\partial X}-\frac{\partial C_{2,k}}{\partial \tilde{X}_{2,k}}\right)<0\ \forall k\in\{L,H\}$ must hold in addition to the Hessian matrix being negative definitive in order for the objective functions to be strictly concave. There are three necessary and sufficient conditions for strictly concave objective functions in the closed-loop social planner problem:

$$\frac{\partial C_1}{\partial \tilde{X}_1}+B\sum\nolimits_{k\in\{L,H\}} p_k \frac{\partial G_k}{\partial \tilde{X}_1}-\frac{\partial T}{\partial X}-\frac{\partial \Pi}{\partial X}<0,$$

$$\left(\frac{\partial C_1}{\partial \tilde{X}_1}+B\sum\nolimits_{k\in\{L,H\}} p_k \frac{\partial G_k}{\partial \tilde{X}_1}-\frac{\partial T}{\partial X}-\frac{\partial \Pi}{\partial X}\right)\left(\frac{\partial C_{2,H}}{\partial \tilde{X}_{2,H}}-\frac{\partial T}{\partial X}-\frac{\partial \Pi}{\partial X}\right)>Bp_H\left(\frac{\partial C_{2,H}}{\partial \tilde{X}_1}\right)^2,$$

and

$$\frac{\partial C_1}{\partial \tilde{X}_1}+B\sum\nolimits_{k\in\{L,H\}} p_k \frac{\partial G_k}{\partial \tilde{X}_1}-\frac{\partial T}{\partial X}-\frac{\partial \Pi}{\partial X}<\frac{Bp_H\frac{\partial C_{2,H}}{\partial \tilde{X}_1}\frac{\partial G_H}{\partial \tilde{X}_{2,H}}}{\frac{\partial C_{2,H}}{\partial \tilde{X}_{2,H}}-\left(\frac{\partial T}{\partial X}+\frac{\partial \Pi}{\partial X}\right)}+\frac{Bp_L\frac{\partial C_{2,L}}{\partial \tilde{X}_1}\frac{\partial G_L}{\partial \tilde{X}_{2,L}}}{\frac{\partial C_{2,L}}{\partial \tilde{X}_{2,L}}-\left(\frac{\partial T}{\partial X}+\frac{\partial \Pi}{\partial X}\right)}.$$

The first condition is the same as in the open-loop social planner problem. The second necessary and sufficient condition in the closed-loop social planner problem states that 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. The third condition is difficult to interpret.

Because many of the results in Section VIII depend on whether or not there are cumulative environmental externalities from urban development, I define two sets of sufficient conditions from these necessary and sufficient conditions that guarantee that the objective function is strictly concave in all four problems. While both sets of sufficient conditions guarantee that the Hessian matrix is negative definite for the open-loop and closed-loop landlord and social planner 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, both attributes result in first period urban development incurring a cost in terms of lost total second period rent. As a consequence, a cumulative environmental externality from urban development affects the cost of irreversibility 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 $G_k\left(\tilde{X}_1^{nm}, \tilde{X}_{2,k}^{nm}\right) = 0$ $\forall k \in \{L, H\}$, $\forall n \in \{O, C\}$, and $\forall m \in \{M, P\}$ and that there exists a function, $\hat{C}_{2,k}$, such that $C_{2,k}\left(\tilde{X}_1^{nm}, \tilde{X}_{2,k}^{nm}\right) = \hat{C}_{2,k}\left(\tilde{X}_{2,k}^{nm}\right)$ $\forall k \in \{L, H\}$, $\forall n \in \{O, C\}$, and $\forall m \in \{M, P\}$.

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′)** $\frac{\partial S_{2,k}}{\partial \tilde{X}_1 \partial \tilde{X}_{2,k}} \leq 0$

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

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.

VIII. Key Results

While the strong sufficient conditions are intuitively appealing, the results of this paper depend on whether the weak or strong sufficient conditions for a unique global maximum hold. 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. One such assumption is that 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). Another possible assumption is that the open-loop social planner problem is binding (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. Some of the results that hold under the strong sufficient conditions may still hold under weaker conditions depending on parameter values, functional forms, and/or additional conditions.

Strong sufficient conditions. As proven earlier, the open-loop and closed-loop competitive equilibrium amounts of urban land are equal given the structure of the model. In addition, the socially optimal amount of urban land in the first period is less than the corresponding competitive amount under both the open-loop and closed-loop assumptions. The last comparison is of the open-loop and closed-loop socially optimal amounts of urban land, and this section will show that sign of the difference between these amounts partially depends on whether the strong or weak sufficient conditions hold.

First and second period land use decisions in the social planner problems.
Here I compare the socially optimal amounts of urban land in the open-loop and closed-loop social planner problems. There are eight possible pairs of solution regimes for the open-loop and closed-loop social planner problems, identified by whether or not the irreversibility constraints bind.[12] Because the first and second period rental rates are separable in their decision variables when the strong sufficient conditions hold, Freixas and Laffont (1984) implies Proposition 4 and establishes a series of corollaries when applied to this problem.

[12] In the appendix, I prove that $C_{2,H}\left(\tilde{X}_1^{CP^*}, \tilde{X}_{2,H}^{CP^*}\right) \leq C_{2,L}\left(\tilde{X}_1^{CP^*}, \tilde{X}_{2,L}^{CP^*}\right)$ is necessary for the solution to the closed-loop social planner problem to be binding in only state H, $C_{2,H}\left(\tilde{X}_1^{CP^*}, \tilde{X}_{2,H}^{CP^*}\right) \geq C_{2,L}\left(\tilde{X}_1^{CP^*}, \tilde{X}_{2,L}^{CP^*}\right)$ is necessary for the solution to the closed-loop social planner problem to be binding in only state L, and the sign of the difference between $C_{2,H}\left(\tilde{X}_1^{CP^*}, \tilde{X}_{2,H}^{CP^*}\right)$ and $C_{2,L}\left(\tilde{X}_1^{CP^*}, \tilde{X}_{2,L}^{CP^*}\right)$ is unknown. Together these results imply that the closed-loop social planner problem has four obtainable solution regimes: binding in both, neither or only one (state H or state L) future state.

Proposition 4: *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 4a: *If the solution to the closed-loop social planner problem has one and only one binding irreversibility constraint, then the socially optimal amount of urban land in the first period under closed-loop control is less than the amount under open-loop control, assuming the strong sufficient conditions hold.*
Corollary 4b: *If the magnitude of the marginal external cost of second period urban development on total second period rent is greater in state H than in state L, the socially optimal amount of urban land in the second period under closed-loop control is less than or equal to the amount under open-loop control when state H occurs and greater than or equal to the amount under open-loop control when state L occurs. If the magnitude of the marginal external cost of second period urban development on total second period rent is less in state H than in state L, the socially optimal amount of urban land in the second period under closed-loop control is greater than or equal to the amount under open-loop control when state H occurs and less than or equal to the amount under open-loop control when state L.*
Corollary 4c: *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 4d: *The socially optimal first-period urban growth boundary is equal or greater in magnitude under open-loop control than closed-loop control.*

The proposition and its corollaries are proved in the appendix. Proposition 4 holds by results established in Freixas and Laffont (1984). Corollary 4a follows because knowledge of the future availability of information only has value in the first period when knowing the true state would allow the decision maker to increase expected social welfare by restricting her first period land use decision, and thus expanding her second period choice set. If all irreversibility constraints are non-binding or if all irreversibility constraints bind, the knowledge that future climate information will be available does not provide an incentive to the decision maker to change her first period decision. Corollary 4b follows intuitively from the fact that the social planner chooses to conserve more oaks when the marginal external cost of urban development is high. In closed-loop control, the social planner knows the true state in the second period and adjusts her decision accordingly. In open-loop control, the social planner hedges her bets between the two possible states by choosing an amount of urban land in the second period in between those chosen by the closed-loop social planner. Corollary 4c is implied by propositions 2 and 4, which together guarantee that $\tilde{X}_1^{CM^*} - \tilde{X}_1^{CP^*} \geq \tilde{X}_1^{OM^*} - \tilde{X}_1^{OP^*}$ under the strong sufficient conditions. Last, corollary 4d follows directly from proposition 4 because the socially optimal urban growth boundary 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. $\bar{\bar{X}}{}_{t,k}^{n\,*} = \tilde{X}_{t,k}^{nP^*}\ \forall t \in \{1,2\}, k \in \{L, H\}$, and $n \in \{O, C\}$.

Proposition 4 and its corollaries indicate that the socially optimal amount of urban land can differ between open-loop and closed-loop control. As a result 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. Local policymakers should pay particular attention if climate change has a wide range of potential effects on oak habitat in their area. In such cases, policymakers who account for the future availability of information when setting land use policies, such as zoning or urban growth boundaries, prevent a greater amount of development than those who ignore it.

Private and social values of information.

In all four problems shown in Table 3, the value function is the present value of expected land rents:

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

The private and social values of information differ due to the different equilibrium amounts of urban land in the two solutions. The private value of information is the difference between the value function evaluated at the closed-loop and open-loop competitive equilibrium amounts of urban land; i.e. $W\left(\tilde{X}_1^{CM^*}, \tilde{X}_{2,H}^{CM^*}, \tilde{X}_{2,L}^{CM^*}\right) - W\left(\tilde{X}_1^{OM^*}, \tilde{X}_2^{OM^*}, \tilde{X}_2^{OM^*}\right)$. The social value of information is the difference between the value function evaluated at the closed-loop and open-loop socially optimal amounts of urban land; i.e. $W\left(\tilde{X}_1^{CP^*}, \tilde{X}_{2,H}^{CP^*}, \tilde{X}_{2,L}^{CP^*}\right) - W\left(\tilde{X}_1^{OP^*}, \tilde{X}_2^{OP^*}, \tilde{X}_2^{OP^*}\right)$. The difference between the social and private values of information, Δ, equals

$$\Delta = \left[W\left(\tilde{X}_1^{CP^*}, \tilde{X}_{2,H}^{CP^*}, \tilde{X}_{2,L}^{CP^*}\right) - W\left(\tilde{X}_1^{OP^*}, \tilde{X}_2^{OP^*}, \tilde{X}_2^{OP^*}\right)\right] - \left[W\left(\tilde{X}_1^{CM^*}, \tilde{X}_{2,H}^{CM^*}, \tilde{X}_{2,L}^{CM^*}\right) - W\left(\tilde{X}_1^{OM^*}, \tilde{X}_2^{OM^*}, \tilde{X}_2^{OM^*}\right)\right].$$

The private value of information is zero because the competitive equilibrium amounts of urban land are the same in the two control problems. As a consequence, the difference between the social and private values of information reduces to the social value of information, i.e. $\Delta = W\left(\tilde{X}_1^{CP^*}, \tilde{X}_{2,H}^{CP^*}, \tilde{X}_{2,L}^{CP^*}\right) - W\left(\tilde{X}_1^{OP^*}, \tilde{X}_2^{OP^*}, \tilde{X}_2^{OP^*}\right)$. By theory, $W\left(\tilde{X}_1^{CP^*}, \tilde{X}_{2,H}^{CP^*}, \tilde{X}_{2,L}^{CP^*}\right) - W\left(\tilde{X}_1^{OP^*}, \tilde{X}_2^{OP^*}, \tilde{X}_2^{OP^*}\right) \geq 0$ because a decision maker cannot be made worse off by new information.

From the results in the previous subsection regarding the difference between the amounts of urban land in the open-loop and closed-loop social planner problems, it is possible to draw several conclusions about the social value of information. First, the social value of information equals zero when all irreversibility constraints bind in the solutions to the open-loop and closed-loop social planner problems because the solutions for the amount of urban land in each period and state are equal across the two control problems. Second, the social value of information is greater than zero when no irreversibility constraints bind in the solutions to the open-loop and closed-loop social planner problems and the strong sufficient conditions for a unique global maximum hold. Though the socially optimal amount of urban land in the first period under closed-loop control equals the corresponding amount under open-loop control, the socially amount of urban land in the second period differs between closed-loop and open-loop control. Third, the social value of information is greater than zero when the open-loop social planner problem has a non-binding solution, the solution to the closed-loop social planner problem binds in only state *H* or state *L*, and the strong sufficient conditions for a unique global maximum hold. This is because the socially optimal amount of urban land in the first and second periods differs between closed-loop and open-loop control. Last, the social value of information is greater than zero when the solution to the open-loop social planner problem binds, the solution to the closed-loop social planner problem binds in only state *H* or state *L*, and the strong sufficient conditions hold. This is because the socially optimal amount of urban land in the first and second periods differs between closed-loop and open-loop control. These cases are summarized in the following proposition:

Proposition 5: *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.*

Location-dependent development fees.

In both the open-loop and closed-loop problems, the first and second period location-dependent development fees 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 the property located at *X* in the first period regardless of the type of control problem. Because 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. Formally,

$$D_{i,1}^{O\,*} = D_1^{O\,*}(X) = C_1(X) + B \sum_{k \in \{L,H\}} p_k \hat{C}_{2,k}(X)$$

and

$$D_{i,2}^{O\,*} = D_2^{O\,*}(X) = \sum_{k \in \{L,H\}} p_k \hat{C}_{2,k}(X).$$

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,

$$D_{i,1}^{C\ *} = D_1^{C^*}(X) = C_1(X) + B \sum_{k \in \{L,H\}} p_k \hat{C}_{2,k}(X),$$

$$D_{i,2,H}^{C\ \ *} = D_{2,H}^{C\ \ *}(X) = \hat{C}_{2,H}(X),$$

and

$$D_{i,2,L}^{C\ \ *} = D_{2,L}^{C\ \ *}(X) = \hat{C}_{2,L}(X).$$

If the strong sufficient conditions for a unique global maximum hold, the optimal open-loop and closed-loop location-dependent development fees 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 6: *Assuming that the strong sufficient conditions for a unique global maximum hold, the open-loop and closed-loop optimal location-dependent development fees are identical in the first period. The expected value of the optimal second period location-dependent development fees under closed-loop control equals the second-period optimal second-period location-dependent development under open-loop control.*

This proposition is proved in the appendix.

Location-independent development fees.
In both the open-loop and closed-loop problems, the optimal first period location-independent development fee 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. Formally,

$$F_1^{O^*} = C_1\left(\tilde{X}_1^{OP^*}\right) + B \sum_{k \in \{L,H\}} p_k \hat{C}_{2,k}\left(\tilde{X}_2^{OP^*}\right)$$

and

$$F_2^{O^*} = \sum_{k \in \{L,H\}} p_k \hat{C}_{2,k}\left(\tilde{X}_2^{OP^*}\right).$$

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,

$$F_1^{C^*} = C_1\left(\tilde{X}_1^{CP^*}\right) + B \sum_{k\in\{L,H\}} p_k \hat{C}_{2,k}\left(\tilde{X}_{2,k}^{CP^*}\right),$$

$$F_{2,H}^{C}{}^* = \hat{C}_{2,H}\left(\tilde{X}_{2,H}^{CP}{}^*\right),$$

and

$$F_{2,L}^{C}{}^* = \hat{C}_{2,L}\left(\tilde{X}_{2,L}^{CP^*}\right).$$

For location-independent development fees, a result corresponding to proposition 6 does not exist. Unlike location-dependent development fees, location-independent development fees are functions of the socially optimal amounts of urban land. Consequently, the optimal open-loop and closed-loop first period location-independent development fees 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 each component of the marginal external cost of urban development is constant with respect to the amount of urban land in period 1 and the amount of urban land in period 2 for both states *k*. For the same reason, the expected value of the optimal closed-loop second period location-independent development fees differs from the optimal open-loop second-period location-independent development fee when the strong sufficient conditions hold. When the open-loop and closed-loop location-independent development fees differ, no definitive statement can be made about the sign or magnitude of the difference because the expected value of the marginal external cost of second period urban development on second period total rent is unknown.

The analysis in this section has established that under the strong sufficient conditions for a unique global maximum, the location-dependent development fees are robust to the type of control problem, while urban growth boundaries and location-independent development fees are not robust. More specifically, the first-period open-loop urban growth boundary is equal to or larger than the corresponding closed-loop urban growth boundary. While the sign of the difference between open-loop and closed-loop location-independent development fees is unknown without additional assumptions, location-independent development fees differ across the control problems, except under limited conditions. This suggest an advantage of location-dependent development fees over location-independent development fees and urban growth boundaries: location-dependent development fees 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, as long as landowners recognize the future availability of such information.

Time consistency of the socially optimal policies.

The issue of time-consistent policies first arose in Kydland and Prescott (1977). The authors argue that optimal control theory results in time inconsistent policies when the expectations of economic agents are rational, unless the 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 $\frac{\partial \tilde{X}_1^{CM^*}}{\partial F_{2,k}^{C}} = 0$. Time inconsistency occurs if these additional conditions do not hold because rational economic agents choose their first period action knowing that the government has an incentive to re-optimize in the second period. In this context, time inconsistency corresponds to first period land use decisions depending on the expected second period policy. Kydland and Prescott (1977) prove that the time-consistent policies that occur when the economic agents' first period decisions are affected by the second period policy, i.e. $\frac{\partial \tilde{X}_1^{CM^*}}{\partial \bar{\bar{X}}_{2,k}^C} \neq 0$, $\frac{\partial \tilde{X}_1^{CM^*}}{\partial D_{i,2,k}^C} \neq 0$, and $\frac{\partial \tilde{X}_1^{CM^*}}{\partial F_{2,k}^C} \neq 0$, are not socially optimal.

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. By definition, the socially optimal open-loop policies are time consistent. In the closed-loop problems, it can be proven that the socially optimal policies found earlier under the strong sufficient conditions are time-consistent by solving for the Stackelberg equilibrium under each policy; the first period closed-loop policy in each case equals the first-period time consistent policy found in the corresponding Stackelberg problem. An alternative proof of the time consistency of these closed-loop policies is to observe that all of the second period closed-loop policies are independent of the amount of urban land in the first period because of the assumption that there is no cumulative environmental effect from first period urban development.

Proposition 7: *When the strong sufficient conditions for a unique global maximum hold, the socially optimal land use policies (urban growth boundaries, location-dependent development fees, and location independent policies) are time consistent.*

Open-loop feedback control

As stated earlier, a closed-loop control problem corresponds more closely to the real world. To the extent that policymakers do not account for future learning, their 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. In the optimal control literature, this type of social planner problem is referred to as an open-loop feedback control problem: the first period land use policy is determined as in the open-loop social planner problem and the second period land use policy is determined as in the closed-loop social planner problem given the amount of urban land in the first period. In this situation, the landlord problem is best described as a closed-loop problem.

This problem is solved by modifying the Stackelberg two period game discussed in the previous subsection. The problem is identical to the Stackelberg equilibrium, except that the first period policy is the socially optimal first period open-loop policy. The model is solved recursively as before, and as a result the second period policy and land use decision are socially optimal given the first period land use decision of the landlord. The landlord makes her first period land use decision subject to the first period open-loop policy and the policy updating process.

Proposition 8. *If location-dependent development fees 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 will equal the amount in the closed-loop social planner problem.*

This result follows from three previously established results: the first period open-loop and closed-loop location-dependent development fees are identical (Proposition 6), the expected value of second period location-dependent development fees in the closed-loop problem equals the second-period location-dependent development fee in the open-loop problem (Proposition 6), and the location-dependent development fees are independent of the socially optimal amount of urban land. This final condition implies that the second period location-dependent development fees are independent of the landlord's first period land use decision.

If urban growth boundaries or location-independent development fees are chosen by a welfare-maximizing social planner and the strong sufficient conditions hold, the amount of development in an open-loop feedback problem will not equal the amount in the closed-loop social planner problem, except under limited circumstances. Intuitively, this is because the socially optimal first period policy and the expected value of the socially optimal second period policy differ between the open-loop and closed-loop control problems when the social planner uses urban growth boundaries or location-independent development fees. Consequently, the following proposition holds:

Proposition 9: *If a social planner optimally chooses urban growth boundaries 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 if state k occurs is greater than or equal to the corresponding amount in the closed-loop social planner problem.*

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 location-independent development fees, the sign of the difference is dependent upon functional forms and parameters.

Weak sufficient conditions. While the strong sufficient conditions guarantee both that there are unique global maximums for all four problems in Table 3 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. Consequently, the simplifying assumptions $G_k\left(\tilde{X}_1^{nm^*}, \tilde{X}_{2,k}^{nm^*}\right) = 0$ and $C_{2,k}\left(\tilde{X}_1^{nm^*}, \tilde{X}_{2,k}^{nm^*}\right) = \hat{C}_{2,k}\left(\tilde{X}_{2,k}^{nm^*}\right)$ no longer hold. As a consequence, two results do not hold under the weak sufficient conditions: the irreversibility effect does not hold without additional assumptions (proposition 4) and location-dependent development fees are not robust to the type of control problem (proposition 6). In addition, socially optimal development fees are likely to be time inconsistent under the weak sufficient conditions. The time consistency of the socially optimal urban growth boundaries under the weak sufficient conditions is less clear. If future work proves that urban growth boundaries are time consistent under the weak sufficient conditions, urban growth boundaries may be the best policy option when a cumulative externality is present. If urban growth boundaries prove to be time inconsistent, it is unclear which of three land use policies analyzed in this paper is the best policy option.

First and second period land use decisions in the social planner problems.
As stated above, the results contained within proposition 4 no longer unanimously hold under the weak sufficient conditions for a unique global maximum. This is because, unlike under the strong sufficient conditions, second period rental rates are functions of the amount of urban land in the first period, and thus the second period objective function in the closed-loop social planner problem is also a function of the amount of urban land in the first period (Freixas and Laffont, 1984). As a consequence, the closed-loop socially optimal amount of urban land in the first period can be greater than or less than the corresponding amount in the open-loop social planner problem, i.e. 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. The Epstein (1980) sufficient conditions are that the benefit functions and the irreversibility constraints are concave with respect to the decision variables and 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. These assumptions ensure that the expected marginal cost of first period development increases with the availability of information (Ulph and Ulph, 1997; Gollier, Jullien, and Treich, 2000). The Ulph and Ulph (1997) sufficient condition is that the irreversibility constraint binds in the open-loop social planner problem. If either the Epstein (1980) or Ulph and Ulph (1997) sufficient conditions for the irreversibility effect hold in addition to the weak sufficient conditions for a unique global maximum, then unique global maximums exist for all four problems in Table 3 and the irreversibility effect holds.

Proposition 10: *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 10a: *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 proposition 10 hold in addition to the weak sufficient conditions.*
Corollary 10b: *The socially optimal first-period urban growth boundary under open-loop control is greater than or equal to the corresponding urban growth boundary under closed-loop control when either of the assumptions discussed above in proposition 10 hold in addition to the weak sufficient conditions.*

Proposition 10 holds by Theorem 1 in Epstein (1980) and Theorem 3 in Ulph and Ulph (1997). Corollaries 10a and 10b follow.

Under the weak sufficient conditions, the socially optimal amount of urban land can differ between open-loop and closed-loop control, and as a result policymakers should account for the difference between private and social values of information when determining land use policies.

However, the irreversibility effect does not always hold under the weak sufficient conditions. As a consequence, 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) and Ulph and Ulph (1997) conditions hold in addition to the weak sufficient conditions, Proposition 10 implies that the irreversibility effect holds and that policymakers who account for the future availability of information when setting land use policies, such as zoning or urban growth boundaries, prevent a greater amount of development than those who ignore it.

Development fees.
The open-loop and closed-loop location-dependent and location-independent development fees under the weak sufficient conditions differ from those under the strong sufficient conditions. Under the weak sufficient conditions, location-dependent development fees 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, $B\sum_{k\in\{L,H\}} p_k G_k\big(X, \tilde{X}_{2,k}^{nP^*}\big)\ \forall n \in \{O, C\}$, is included in the first-period location dependent development fees. 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 $C_{2,k}\big(\tilde{X}_1^{nP^*}, X\big)\ \forall n \in \{O, C\}$.

The optimal first period location–dependent development fee equals the present value of the expected external cost of developing the property located at *X* in the first period for each location within the municipality, i.e. $\forall X \in [0, A]$, regardless of the type of control problem. Because there is a 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, 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 cumulative environmental effect of development, 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. Formally,

$$D_1^{O^*}\big(X, \tilde{X}_1^{OP^*}, \tilde{X}_2^{OP^*}\big) = C_1(X) + B\sum_{k\in\{L,H\}} p_k G_k\big(X, \tilde{X}_2^{OP^*}\big) + B\sum_{k\in\{L,H\}} p_k C_{2,k}\big(\tilde{X}_1^{OP^*}, X\big)$$

and

$$D_2^{O^*}\big(X, \tilde{X}_1^{OP^*}\big) = \sum_{k\in\{L,H\}} p_k C_{2,k}\big(\tilde{X}_1^{OP^*}, X\big).$$

In the closed-loop problem, the optimal second period development fee at location *X* in state *k* is the external cost developing the property located at *X* in the second period on total second period rent if state *k* occurs. Formally,

$$D_1^C\left(X,\tilde{X}_1^{CP^*},\tilde{X}_{2,k}^{CP^*}\right)=C_1(X)+B\sum_{k\in\{L,H\}}p_kG_k\left(X,\tilde{X}_{2,k}^{CP^*}\right)+B\sum_{k\in\{L,H\}}p_kC_{2,k}\left(\tilde{X}_1^{CP^*},X\right),$$

$$D_{2,H}^C\left(X,\tilde{X}_1^{CP^*}\right)=C_{2,H}\left(\tilde{X}_1^{CP^*},X\right),$$

and

$$D_{2,L}^C\left(X,\tilde{X}_1^{CP^*}\right)=C_{2,L}\left(\tilde{X}_1^{CP^*},X\right).$$

Because two components of the external cost of developing a property located at X, i.e. $B\sum_{k\in\{L,H\}}p_kG_k\left(X,\tilde{X}_{2,k}^{nP^*}\right)$ and $C_{2,k}\left(\tilde{X}_1^{nP^*},X\right)\ \forall k\in\{L,H\}$, are functions of the amount of urban land, the expected external cost of developing a property at location X in period t is a function of location and the amount of urban land. As a consequence, the expected external cost of developing a property at location X in period t may differ between the open-loop and closed-loop problems. Because, the socially optimal location-dependent development fee 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. Consequently, the following proposition holds:

Proposition 11: *Assuming that the weak sufficient conditions hold, the first period closed-loop location-dependent development fee differs from the first period open-loop location-dependent development fee and the expected value of second period closed-loop location-dependent development fees differs from the second-period open-loop location-dependent development fee, unless $\tilde{X}_1^{OP^*}=\tilde{X}_1^{CP^*}$ and $\tilde{X}_2^{OP^*}=\tilde{X}_{2,H}^{CP^*}=\tilde{X}_{2,L}^{CP^*}$ or each component of the marginal external cost of urban development is constant with respect to the amounts of urban land in periods 1 and 2.*

This proposition holds regardless of whether or not the irreversibility effect holds. This is similar to the results for the location-independent development fees under both the weak and strong sufficient conditions.

Under the weak sufficient conditions, the possible existence of a cumulative environmental effect from urban development effects location-independent development fees in two ways. First, first-period location-independent development fees 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, $B\sum_{k\in\{L,H\}}p_kG_k\left(\tilde{X}_1^{nP^*},\tilde{X}_{2,k}^{nP^*}\right)\ \forall n\in\{O,C\}$. 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 $C_{2,k}\left(\tilde{X}_1^{nP^*},\tilde{X}_{2,k}^{nP^*}\right)\ \forall n\in\{O,C\}$, in the first and second period location-independent development fees.

The open-loop and closed-loop first period location-independent development fees both equal 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. Formally,

$$F_1^{O^*} = C_1\left(\tilde{X}_1^{OP^*}\right) + B \sum_{k\in\{L,H\}} p_k G_k\left(\tilde{X}_1^{OP^*}, \tilde{X}_2^{OP^*}\right) + B \sum_{k\in\{L,H\}} p_k C_{2,k}\left(\tilde{X}_1^{OP^*}, \tilde{X}_2^{OP^*}\right)$$

and

$$F_2^{O^*} = \sum_{k\in\{L,H\}} p_k C_{2,k}\left(\tilde{X}_1^{OP^*}, \tilde{X}_2^{OP^*}\right).$$

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,

$$F_1^{C^*} = C_1\left(\tilde{X}_1^{CP^*}\right) + B \sum_{k\in\{L,H\}} p_k\, G_k\left(\tilde{X}_1^{CP^*}, \tilde{X}_{2,k}^{CP^*}\right) + B \sum_{k\in\{L,H\}} p_k C_{2,k}\left(\tilde{X}_1^{CP^*}, \tilde{X}_{2,k}^{CP^*}\right),$$

$$F_{2,H}^{C\ *} = C_{2,H}\left(\tilde{X}_1^{CP^*}, \tilde{X}_{2,H}^{CP\ *}\right),$$

and

$$F_{2,L}^{C\ *} = C_{2,L}\left(\tilde{X}_1^{CP^*}, \tilde{X}_{2,L}^{CP^*}\right).$$

Because location-independent development fees are functions of the socially optimal amounts of urban land, the optimal first period closed-loop location-independent development fee differs from the optimal first-period open-loop location-independent development fee and the expected value of optimal second period closed-loop location-independent development fees differs from the optimal second-period open-loop location-independent development fee, except under limited circumstances. These exceptions 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 each component of the marginal external cost of urban development is constant with respect to the amounts of urban land in periods 1 and 2. No definitive statement can be made about the sign of the difference between the optimal open-loop and closed-loop first period location-independent development fees.

Unlike under the strong sufficient conditions, location-dependent development fees are not robust to the type of control problem under the weak sufficient conditions. Furthermore, the sign of the difference between open-loop and closed-loop location-dependent development fees is difficult to determine under the weak sufficient conditions for a unique global maximum. This is also true for the sign of the difference between open-loop and closed-loop location-independent development fees. The sign of this difference 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 external cost of developing the property located at X in the second period on total second period rent if state k occurs, i.e. $C_{2,k}\left(\tilde{X}_1^{CP^*}, X\right)$, is a function of the amount of urban land in the first period for all locations within the municipality,

i.e. $\forall X \in [0, A]$. As a consequence, the socially optimal second period closed-loop location-dependent and location-independent development fees 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 urban growth boundaries are functions of the amount of urban land in the first period, rather than the urban growth boundaries themselves, it is less clear whether urban growth boundaries are time inconsistent. Analysis is further complicated by the landlord's ability to at least partially determine when irreversibility constraints and urban growth boundaries bind through her first period land use decision. Future research will determine when development fees and urban growth boundaries are time consistent, and when they are not. This work is necessary to clarify which policy is the best policy option when a cumulative environmental externality is present.

IX. Conclusion

Local governments in California are faced with the challenge of preserving oak woodlands from urban and agricultural development when the future of this habitat is uncertain due to climate change. Because the majority of oak woodlands are privately owned, the economic argument for oak woodland conservation is the positive amenities that oak woodlands produce, which benefit surrounding neighbors and society as a whole. Assuming that local policymakers set current oak woodland policy to maximize social-welfare within their municipality, this paper attempts to address how local policymakers should adjust land use 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 three land use policies (urban growth boundaries, location independent-development fees, location-dependent development fees) within a spatial-temporal model of a municipality. I developed a two-period model of a municipality by modifying an open-city model. Two land uses were modeled: urban and oak woodland. I assumed urban development was irreversible, while oak woodland 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. While closed-loop control problems are likely to be more accurate depictions of the evolution of available information in the real-world, policymakers who ignore the possibility of the future availability of climate information are more accurately modeled by open-loop control problems. I identified the optimal trajectory of each policy instrument through time and proved several key propositions about conservation under uncertainty: the irreversibility effect held under the strong sufficient conditions (proposition 4) and held with additional assumptions under the weak sufficient conditions (proposition 10), location-dependent development fees were robust to the type of control problem under the strong sufficient conditions (proposition 6) and were not robust under the weak sufficient conditions (proposition 11), and the socially optimal policies were time consistent under the weak sufficient conditions (proposition 7). 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 proved four key propositions under the assumption that there was no cumulative environment cost from first period urban development. First, the socially optimal amount of oak woodland in the closed-loop control problem was greater than or equal to the corresponding amount in the open-loop control problem. Because the privately optimal amounts of oak woodland were equal across these control problems, this result implied that a greater amount of oak woodland development was prevented by socially optimal land use policies under closed-loop control than open-loop control. Second, social welfare-maximizing urban growth boundaries and location-independent development fees could differ between the two control problems. These results implied that if local policymakers ignore the potential effects of climate change when setting urban growth boundaries or location-independent development fees, they do not restrict urban development enough. Third, the social welfare-maximizing location-dependent development fees did not differ between the open-loop and closed-loop control problems. As a result, location-dependent development fees achieved the socially optimal land use allocation in the open-loop feedback control problem, while urban growth boundaries and location-independent development fees did not achieve optimality. Last the socially optimal closed-loop policies were time-consistent, which indicated that they are achievable.

I proved two key propositions under the assumption that there was a cumulative environment cost from first period urban development. First, the socially optimal amount of oak woodland in the closed-loop control problem was not necessarily greater than or equal to the corresponding amount in the open-loop control problem. Because the privately optimal amounts of oak woodland were equal across these control problems, this result implied that socially optimal land use policies potentially prevented less oak woodland development under closed-loop control than open-loop control. Second, all three social welfare-maximizing land use policies, including location-dependent development fees, 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. In addition, preliminary theoretical results indicated that socially optimal closed-loop location-dependent and location-independent development fees were time inconsistent, while the intuition for urban growth boundaries was less clear. This suggests that use of urban growth boundaries and zoning instead of development fees to manage land use, as is currently observed in land use planning, could be socially desirable if urban growth boundaries prove to be time consistent.

The robustness of location-dependent development fees 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 urban growth boundaries or location-independent development fees 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 location-dependent development fees are under real-world parameters when the strong sufficient conditions do not hold.

The results under the strong sufficient conditions apply to a general set of spatial-temporal 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, and only one, land use is irreversible. Fourth any effect of previous land use allocations on current net land use externalities through the cumulative environmental effect of urban development must be small. 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, over protects 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 allocations differed 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, as discussed earlier, is to prove the time consistency or inconsistency of land use policies when a cumulative environmental externality from urban development is present. Another potential direction for future research is to analyze the effects of relaxing the model's most important simplifying assumptions, such as the effect of climate change on agricultural profits. Standiford (1989) indicates that forage production is affected by precipitation and oak canopy cover. Because climate change has uncertain effects on precipitation and oak habitat, its potential effect on forage is also uncertain. Because relaxing this assumption introduces uncertainty into a market return that is already accounted for by landowners when making their land use decisions, it will result in a difference between the solutions for the open-loop landlord problem and the closed-loop landlord problem even in the absence of a cumulative environmental externality. This difference in the competitive equilibrium land use allocations between open-loop and closed-loop control will result in a non-zero private value of information.

Another direction that can be explored is the robustness of location-dependent policies to different types of information assumptions. Because location-dependent development fees 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 location-dependent development fees in these situations.

Another direction for future research is the estimation of the value of location-dependent and location-independent amenities produced by oak woodlands. A solid starting point is a comprehensive hedonic analysis of urban, rural residential, ranch, and agricultural land prices in which oak vegetation is a key explanatory variable. Some of the variables critical for inclusion are distance to nearest oak stand and open-space, land uses (including open-space) of surrounding properties, and the volume of oak on the property and on surrounding properties. This type of econometric model allows for several pieces of key analysis. First, the marginal value of oak habitat in terms of its addition to the value of location-dependent externalities is measurable if the volume of oaks on surrounding properties and distance to nearest stand are included in the hedonic analysis. Second, the model can be used to differentiate the value of preserving oak woodlands from the value of preserving open-space in general. Last, the econometric model can be used to test whether the strong sufficient conditions for a unique global maximum hold if the econometric analysis is done with panel data.

A final direction for future work is to extend the current model to develop a calibrated model of land use choice within a municipality. Functional form assumptions and parameter values are required for such a model; sensitivity analysis is necessary when parameter values and functional forms cannot be estimated or obtained from existing data. This model also requires that it be calibrated to existing land uses. By assuming that the observed land use pattern represents a closed-loop competitive equilibrium, a quadratic cost function for urban development can be calibrated using existing land use data. This type of model allows for additional analysis. First, this type of calibrated model can be used to estimate social welfare-maximizing policy instruments for oak woodland preservation in cities and small counties. Second, this model can be used to explore the effects of relaxing the assumptions that climate change has no effect on agricultural profits and that all properties are identical in size. Third, this model can be used to explore the effects of including only the non-market benefits of oak woodland accruing to individuals living within the municipality versus the effects of including the non-market benefits gained by society as in Albers and Robinson (2007). Last, this model can be utilized to test whether the key results that hold under the strong sufficient conditions still hold under realistic parameter values if the strong sufficient conditions for a unique global maximum no longer hold. In particular, this model can determine the policy that is closest to achieving the socially optimal land use allocation when there are two counter-veiling issues: time-consistency, which potentially favors urban growth boundaries, and sensitivity to the type of control problem, which favors location-dependent development fees.

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