Optimal Economic Landscapes with Habitat Fragmentation Effects

David J. Lewis
PhD Candidate
(lewisda@onid.orst.edu)

&

JunJie Wu
Professor
(junjie.wu@orst.edu)

Department of Agricultural and Resource Economics
Oregon State University
213 Ballard Ext. Hall
Corvallis, OR 97331
Ph: 541-737-8703

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Abstract: Habitat fragmentation is widely considered a primary threat to biodiversity. This paper develops a theoretical model of land use to analyze the optimal conservation of landscapes when land quality is spatially heterogeneous and wildlife habitat is fragmented and socially valuable. When agriculture is the primary cause of fragmentation, we show that reforestation efforts should be targeted to the most fragmented landscapes with an aggregate share of forest equal to a threshold, defined by the ratio of the opportunity cost of conversion to the social value of core forest. When urban development is the primary cause of fragmentation, we show how spatial heterogeneity in amenities and household neighbor preferences affect the optimal landscape and the design of land-use policies.

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1. Introduction

It has been widely recognized that it is not just the amount of habitat that matters for the persistence of wildlife species, but the spatial location of habitat and its degree of fragmentation (Armsworth et al. 2004). The fragmentation of forestland is perceived as a threat to terrestrial biodiversity (Askins 2002, Faaborg 2002) and occurs when an originally contiguous tract of forest becomes separated into isolated patches by human land-use conversion. While there are many ways to quantify the extent of habitat fragmentation on a particular landscape, it is widely recognized in the biological literature that a patch of habitat bordered by a patch of land in some alternative use will potentially suffer a negative spatial externality referred to as an edge effect (Temple and Cary 1988, Paton 1994, Van Horn 1995). When a forest ends and a field begins, or where a patch of grassland ends and a house lot begins, there is an edge[1]. The edge effect on forest habitat typically declines as one gets further from the nearest edge[2]. Parcels of forestland which are greater than some specified distance from an edge are often labeled as core forest and provide the best habitat for many sensitive species (Askins 2002, Robbins et al. 1989, Robinson et al. 1995). Recent GIS analyses have concluded that 62% of continental U.S. forestland is less than 150m from the nearest non-forest edge, and therefore fragmentation related to edge-effects is pervasive and ecologically significant on U.S. forest habitat (Riiters et al. 2002).

In this paper we develop a theoretical model to analyze optimal landscape conservation in the presence of spatial externalities associated with habitat fragmentation. In particular, our focus

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[1] Edge-effects are known to influence the quality of breeding habitat for species such as birds. For example, potential externalities that impact forest birds from non-forest habitat include parasitism (e.g. from Cowbirds) and increased predation (from house cats, raccoons, snakes, etc.).

[2] Research indicates that edge-effects on birds may extend from a distance of 50 m (Paton 1994) to 300 m (Van Horn et al. 1995).

is on analyzing conservation policies to increase core forest and reduce edge effects. While there is an extensive literature on the ecological consequences of fragmentation, an economic understanding of policies to mitigate fragmentation is not well developed.[3] This paper examines the effects of spatial externalities on optimal landscape conservation in the classical tradition: a) the choice of land use on any particular parcel depends on the quality of that parcel, and b) land quality is heterogeneous across the landscape. Land quality affects market returns to land and can include parcel-specific attributes such as distance to an urban center or soil quality. Land parcels are also assumed to produce non-market benefits which are a function of the amount and spatial pattern of forestland on the landscape. The optimal landscape is the spatial pattern of land use which maximizes the sum of market and non-market values from the landscape as a whole.

When urban development is the primary cause of forest fragmentation, distance to urban centers and distance to amenities are assumed to be the primary determinants of land quality and returns to development (Capozza and Helsley 1989, Wu and Plantinga 2003, Turner 2004). In the urban economics literature such distances are typically assumed to be observable. When agriculture is the primary cause of fragmentation, regulators rarely have complete information on parcel-level land quality because land quality is not necessarily based on observable distance to cities or amenities. Soil quality is one of the most important attributes of land quality for agricultural and forestland (Plantinga 1996). Soil quality is driven by exogenous geologic factors and there are numerous potential configurations of parcel-level soil quality that will not necessarily resemble the smooth monotonic functions describing urban land quality. There may

[3] One exception is Smith and Shogren (2002), who propose an incentive mechanism for endangered species protection that yields a bonus payment (e.g. an agglomeration bonus) for the creation of contiguous habitat across property lines. However, Smith and Shogren focus on analyzing the design of the agglomeration bonus contract rather than the optimal degree of conservation on a landscape with habitat fragmentation.

also be individual-specific attributes which will be unobserved by the regulator and which may affect the quality of the parcel for forest and agriculture[4]. With these considerations, we analyze optimal landscape conservation by developing separate models for the cases when urban development and agriculture are the primary cause of fragmentation.

We explore the optimal reforestation strategy on agricultural landscapes when regulators have incomplete information on land quality and where the regulator can control the total amount of reforestation but not its exact location. Under these assumptions, we show that it's optimal to either a) convert all agricultural parcels to forest, or b) reforest none of the market equilibrium landscape. This corner solution arises because the spatial relationships which influence fragmentation yield marginal forest benefits which are increasing and convex in the amount of afforestation on the landscape. We also show that the net social benefits of the optimal reforestation strategy vary significantly across market equilibrium landscapes with different amounts of forest and different degrees of fragmentation. In general, efforts to reduce fragmentation should be targeted to the most fragmented landscapes with an aggregate share of forest equal to a threshold, defined by the ratio of the opportunity cost of conversion to the social value of core forest.

We draw on the urban economics literature to analyze the optimal urban landscape under two alternative assumptions of the spatial configuration of land quality: a) a central city with spatial heterogeneity in amenities, and b) a central city with neighbor preferences. We define the conditions under which fragmentation in land use is economically optimal and develop incentive-based policies to achieve the optimal landscape. We show that while a simple spatially-uniform Pigouvian incentive is optimal on very simple landscapes, this policy is not generally optimal when amenities are not uniform across the landscape or when people prefer to

[4] For example, individual landowners may have different levels of managerial expertise regarding forestry.

live near open space. We define incentive policies for achieving the optimal landscape in these cases.

There is a relatively small theoretical literature on land use patterns and spatial externalities. Parker (2000) and Saak (2004) develop agent-based models to analyze private and socially-optimal land use patterns in agricultural settings under spatial externalities. Albers (1995) and Swallow et al. (1997) develop models of spatial externalities on forestland. In the ecology literature, optimization techniques have been applied to the problem of optimally arranging the spatial allocation of wildlife habitat (Hof and Bevers 2002, Hof and Raphael 1997). There is also a set of papers in the urban economics literature which relax the featureless plain assumption of central city models and focus on urban spatial structure and open space amenities (Wu and Plantinga 2003, Walsh 2004, Turner 2004).

This paper makes two primary contributions to the literature. First, this paper analyzes the optimal spatial structure of land use under multiple assumptions of the spatial structure of land quality. The previous literature either assumes land quality is homogeneous (Albers 1995, Parker 2000, Saak 2004) assumes only one specific spatial structure of land quality (Turner 2004), or doesn't account for land quality (Hof and Bevers 2002, Hof and Raphael 1997). Second, we propose an optimal conservation strategy when agriculture is the primary cause of fragmentation and we derive simple incentive schemes for achieving the optimal landscape when urban development is the primary cause of fragmentation. Optimal policies to address fragmentation issues have not been modeled explicitly in the previous literature, but have been recognized as an important topic of research in environmental economics (Deacon et al. 1998).

2. Model Set-Up

Consider a landscape along a one-dimensional line of length N. A one-dimensional landscape is considered in this paper to simplify the analysis, although the results are applicable to two-dimensions. For simplicity, the landscape is broken into N discrete parcels, each of equal length l. Each parcel has a measure of land quality q associated with it, which affects the potential market returns to various uses of the parcel. Land quality q encompasses all factors that affect market returns from the land. For example, q could represent the distance from a city center and environmental amenities, which are potential determinants of returns to developed land. Also, q could represent soil quality, which is a determinant of returns to agricultural and forest land. Land quality is assumed to be homogeneous *within* a parcel and heterogeneous *across* parcels.

2.1 Market and Non-Market Returns to Land

We assume that there are two distinct uses to which each parcel can be devoted: forest (f) and an alternative use (a), such as agriculture or urban. The market-based net returns to uses f and a are defined as functions of land quality: $R^f=R^f(q)$ and $R^a=R^a(q)$, where $\partial R^f/\partial q > 0, \partial R^a/\partial q > 0, \partial^2 R^f/\partial q^2 \leq 0, \partial^2 R^a/\partial q^2 \leq 0$. Also, assume that market returns to forestry are higher than market returns to the alternative use for land quality less than or equal to q^* and lower than the returns to the alternative use for land quality above q^*, where q^* is defined by $R^f(q^*)=R^a(q^*)$. Without loss of generality, we assume that the landscape is bordered by a parcel in F at one end and by a parcel in A at the other end.

Land use also generates non-market benefits or costs. We assume that parcels in the alternative use produce an ‘edge-effect’ that extends for the length of one parcel. Therefore, forest parcels which are surrounded on both sides are considered core, while all other forest parcels are considered edge. Let δ_i be the proportion of parcel i in forested use, where $0 \leq \delta_i \leq 1$.

The core habitat benefits to parcel i (B_i) can be formally defined as:

$$B_i(\delta_i, \delta_{i-1}, \delta_{i+1}) = \begin{cases} B & if \quad \delta_i = \delta_{i-1} = \delta_{i+1} = 1 \\ 0 & otherwise \end{cases}$$

The total core benefits on landscape L are defined as $TB(L) = \sum_i B_i(\delta_i, \delta_{i-1}, \delta_{i+1})$. The value of any particular parcel in forest depends on the land use of its immediate neighbors. Further, define $L = \{\delta_1, \delta_2, ..., \delta_n\}$ as a landscape. Fragmentation in land use is formally defined as follows:

Definition: *Fragmentation in use f occurs on landscape L if and only if there exists a* $\delta_i, \delta_j, \delta_k \in L$ *such that* $\delta_i, \delta_k > 0$, $\delta_j < 1$, *and i<j<k.*

In words, fragmentation in use f occurs if there are two parcels i and k with positive amounts of forest, which are not fully connected by forested parcels. If use f is not fragmented then we consider it to be contiguous. As defined above, the measure of fragmentation used in this paper is core forest. According to the following lemma, the total core benefit TB on the landscape is maximized when there is no fragmentation in use f.

Lemma: *Given a landscape with total forest area* N_f*, total core benefits, TB, are maximized when L has no fragmentation in f. The maximum total core benefits for area* N_f*, is given by* $TB^* = N_f - 1$.

Proof: See appendix.

By definition, TB is inversely related to fragmentation, where high levels of TB indicate low levels of fragmentation while low levels of TB indicate high levels of fragmentation.

2.2 Equilibrium and Optimal Landscapes

The objective of private landowners is to select a use for their land to maximize profits, while the objective of a regulator is to maximize the sum of profits and core forest benefits over the landscape by selecting the optimal use for each parcel δ_i. In this framework wildlife benefits are considered public goods and do not enter the decision calculus of private landowners. Suppose landowners make land-use decisions based on the expected market returns to land. A parcel will be allocated to forest if $R^f(q_i) \geq R^a(q_i)$ and to agriculture if $R^a(q_i) > R^f(q_i)$. Given the assumptions about the profit functions, all land with quality below q^* is allocated to forest, and all land with q above q^* is allocated to the alternative use. The range of land quality is defined as [0, 1] such that q^* is in the interior of this interval. When all land parcels with quality above q^* are not clustered together, private land use decisions will result in fragmentation and loss of core benefits. Since land quality determines the profitability of land, and the spatial configuration of forestland determines the non-market returns from the landscape, then the spatial configuration of land quality will determine the optimal landscape. Section 3 explores optimal conservation when agriculture is the primary cause of forest fragmentation while section 4 explores the optimal landscape with urban development being the primary cause of forest fragmentation.

3. Optimal Conservation on Forest Landscapes with Agriculture

In this section we consider the optimal conservation strategy when agriculture is the primary cause of forest fragmentation. We assume that the regulator knows the distribution of land quality, f(q), but does not have parcel-specific information on land quality. Most major U.S. conservation programs on agricultural lands are voluntary and offer a subsidy to farmers who adopt conservation practices or retire land from production. When regulators don't know the spatial configuration of land quality, they won't know the exact location of restored forestland under incentive-based land-use policies. This section assumes that the regulator can control the total amount of reforestation on agricultural land by adjusting the subsidy level but cannot control the exact location where reforestation will occur. Under these assumptions, we examine the following two questions. First, given the aggregate amount and spatial configuration of forestland, how much reforestation should the regulator choose on a given landscape? Second, across multiple equilibrium landscapes with different amounts of forest and different levels of fragmentation, which types of landscapes should the regulator target first to maximize the social benefits of reducing fragmentation?

3.1 Optimal Reforestation

If the regulator can observe the equilibrium share of forest and agricultural land on a landscape then they can infer the share of high and low quality land on that landscape. This is because high quality land ($q>q^*$) is allocated to agriculture and low quality land ($q\leq q^*$) is allocated to forest. Denote the probability of low quality land as p_o. Expected market returns to agriculture and forestry on low quality lands are denoted $R_L^a = \int_0^{q^*} R^a(q)f(q)dq$ and $R_L^f = \int_0^{q^*} R^f(q)f(q)dq$, where $R_L^f > R_L^a$. Likewise, expected market returns to agriculture and forestry on high quality lands are denoted $R_H^a = \int_{q^*}^1 R^a(q)f(q)dq$ and $R_H^f = \int_{q^*}^1 R^f(q)f(q)dq$, where $R_H^a > R_H^f$. While the regulator can observe whether the parcel is in the high quality range ($q>q^*$) or low quality range ($q\leq q^*$), the parcel-specific value of q is unobservable.

A landscape with a probability of low quality land equal to p_o can have many potential spatial configurations of land quality and forest. The expected share of core forest on a landscape in which forest is randomly distributed equals the probability of three adjacent low-quality parcels, p_o^3. However, if the equilibrium share of a landscape in core forest is observable, then we can compute it directly as C_o. The degree of fragmentation expected on a randomly distributed landscape can be related to fragmentation on the actual landscape as $\beta_o=C_o/p_o^3$. The parameter β_o denotes the ratio of the actual share of the landscape in core forest to the expected share of the landscape in core forest from a randomly distributed landscape. For notational simplicity we assume that the share of a randomly distributed landscape in core forest (β_o=1) represents the minimum probability of a core parcel and the maximum degree of fragmentation.[5] While this assumption eases notation below, it does not alter the intuition of the results. The parameter β_o has an upper bound[6] equal to p_o^{-2}.

The expected social benefit from an equilibrium landscape of N parcels defined in section 2 is observable and equal to:

$$EB^E = N[p_o R_L^f + (1-p_o)R_H^a + B\beta_o p_o^{\ 3}] \qquad (1)$$

Since parcel-specific q is unobservable, the problem is to choose the aggregate amount of land to convert to forest that maximizes the sum of expected market and non-market returns on the landscape. We assume that the regulator uses an incentive-based mechanism such as an afforestation subsidy to increase the amount of land converted to forest. Let p_c be the share of the landscape which the regulator converts from agriculture to forest, resulting in a share of forestland of $p= p_o+p_c$. By definition, all land converted to forest will be high quality since all low quality land will already be forested. Converting land to forest will increase the share of the landscape in core forest because converting land to forest increases the probability that every forest parcel has neighboring forest parcels, regardless of where the new forest is located. For example, if β_o=1 and p_c>0 then the probability of a core parcel will be $p^3>p_o^{\ 3}$. Generally, the

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[5] If $p_o \leq 0.5$ the lower bound of β_o corresponds to the case where no parcels are core and $\beta_o^L=0$. If $p_o>0.5$, then at least one parcel must be core and the lower bound of β_o on a landscape with N parcels is $\beta_o^L=(2(p_o-0.5)-1/N)$.

[6] The upper bound of β_o will correspond to a landscape with minimum fragmentation (e.g. all forestland is clustered into one patch). In this case the probability that a randomly selected parcel on a large landscape will be core forest will equal p_o. In other words, if all forest is clustered then the probability that a forest parcel has neighboring forest parcels equals one. So the maximum value of β_o will equal p_o^{-2} and the minimum value of β_o will occur on a random landscape where β=1.

share of the reforested landscape in core habitat will depend on the spatial configuration of land quality, denoted γ for simplicity, and will be a function of β_o, p_c, p_o, and γ as follows: $\beta(\beta_o, p_o, p_c, \gamma) \cdot (p_o + p_c)^3$. While β_o, p_c, and p_o are ex-ante observable, γ is not, and thus the share of the reforested landscape in core habitat is ex-ante unknown.

The regulator's problem is to choose the optimal amount of agricultural land to convert to forest to maximize the expected social benefits from the landscape:

$$\begin{aligned} \max_{p^c} \quad & EB^O = N\{p_o R_L^f + p_c R_H^f + (1 - p_c - p_o) R_H^a + BE[\beta(\beta_o, p_o, p_c, \gamma)] \cdot [(p_c + p_o)]^3\} \\ s.t. \quad & 0 \le p_c \le 1 - p_o \end{aligned} \tag{2}$$

For notational simplicity, define $\Delta = [R_H^a - R_H^f]/3B$ as the ratio of opportunity costs of conversion on high quality parcels to the maximum core benefits from conversion on a random landscape. Proposition 1 presents the solution to the regulator's problem and answers the first question posed in this section, namely how much reforestation is optimal.

Proposition 1: *Suppose a regulator knows the distribution of low quality land p_o and the initial clustering parameter β_o. Then the solution to the regulator's conservation problem (2) is:*

$$p_c^* = \begin{cases} 0 & if \quad p_o < \overline{p} \\ 1 - p_o & if \quad p_o \ge \overline{p} \end{cases}$$

where $\overline{p} = \min\{1, \overline{p}^*\}$*, and* $\overline{p}^*$ *is a positive, implicit solution to* $(1 - \beta_o \overline{p}^3) - 3\Delta(1 - \overline{p}) = 0$.

Proof: *See appendix.*

With incomplete information the regulator should either reforest nothing on the equilibrium landscape (i.e. $p_c = 0$) or cluster every parcel into a forested use (i.e. $p_c = 1 - p_o$). A corner solution is optimal because (2) is a convex function of the share of converted forestland p_c (see appendix for proof). The convexity of (2) in p_c is due to core forest benefits and arises because a) core forest benefits are a function of the spatial adjacency of forest parcels, and b) the exact spatial location of restored forestland is ex-ante unknown.[7] As the share of the landscape in forest increases, the probability of each forest parcel having a neighboring forest parcel increases at an increasing rate.

The point $p_o = \bar{p}$ is the switching point between the corner solutions. It represents the share of low quality land at which the expected benefits of clustering every parcel in forest exceed the expected benefits of reforesting nothing on the equilibrium landscape. The probability of low quality land is crucial in determining the switching point because it represents the probability of spatially adjacent forestland. The switching point $\bar{p}$ is an implicit function of Δ and β_o. Implicit differentiation reveals $\partial \bar{p} / \partial \Delta > 0$ and $\partial \bar{p} / \partial \beta_o > 0$ (see appendix for proof). So, the less fragmented the initial landscape, the lower the *net* benefits from reforestation and the higher the switching point between corner solutions, ceteris paribus. Likewise, higher values of Δ imply an increased opportunity cost of forest conversion, increasing the value of $\bar{p}$ and decreasing the likelihood of clustering as an optimal solution.

The corner solution to (2) was derived with the assumption of a one-dimensional landscape, although it can be easily shown that a corner solution holds for a two-dimensional landscape. To show this, note that in the two dimensional case, the only component of (2) that changes is the share of the landscape in core forest. For example, if we let parcel i have non-zero core forest benefits if and only if its eight immediate neighbors are forested, then specifying (2) in two dimensions doesn't affect the key feature of the model, namely the convexity of core forest benefits in p_c. Therefore, (2) would still be convex in p_c and a corner solution would still

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[7] If the regulator knows the spatial configuration of land quality and can select where to locate new forestland, then an interior solution with some level of fragmentation is possible. This case is discussed in section 4.

be optimal.[8] In fact, since it takes more adjacent parcels to create a core forest parcel in two dimensions, the regulator's expected benefit function becomes more convex than the one-dimensional case.

In the above analysis we also assume that the costs of converting agricultural land to forest are linear. If the costs of conversion are increasing at a decreasing rate, or increasing at a rate slower than core forest benefits, then the corner solution would still hold. However, if the costs of conversion are increasing in p_c at a faster rate than core forest benefits, then an interior solution is possible. More specifically, marginal core forest benefits would have to be equal to marginal costs at some value of $p_c>0$ such that $p_o+p_c<1$, and marginal costs of conversion would have to be increasing faster than marginal core forest benefits at some value of $p_c' > p_c$. Note that an interior solution is less likely in the two-dimensional case because core forest benefits are more convex than in the one-dimensional case.

3.2 Targeting Conservation Efforts

We now explore the second major question posed above, that is, on which types of landscapes should the regulator target conservation efforts? The expected net social benefits of the regulator's optimal solution, NB*, can be derived by subtracting (1) from (2) and substituting the regulator's optimal solution to p^c, which gives us equations (3) and (4) below. NB* is defined as a function of p_o, Δ, and β_o.

$$NB^*(p_o,\Delta,\beta_o)=\begin{cases} 0 \quad if \quad p_o<\overline{p} & (3)\\ B(1-\beta_o p_o{}^3)-(R_H^a-R_H^f)(1-p_o) \quad if \quad p_o\geq\overline{p} & (4)\end{cases}$$

Examining how NB* behaves as a function of p_o and β_o is the same as exploring how NB* behaves with alternative assumptions of spatial heterogeneity[9]. First, we explore how NB* will

[8] The switching point would be different between one and two dimensions.

change with p_o for a given level of β_o. It is easy to show that for a given β_o, NB* is concave in p_o for $p_o \geq \bar{p}$ and reaches a maximum point at $p_o^* = \sqrt{\Delta / \beta_o}$. In words, the landscape whose equilibrium is furthest from the optimum is the landscape whose share of low quality land is equal to $\sqrt{\Delta / \beta_o}$. Another way to write this rule is $3B\beta_o p_o^2 = (R_H^a - R_H^f)$; which states that the marginal benefit of forest conversion equals the marginal cost at p_o^*. Figure 1 presents graphs of $p=p_o+p_c$ and NB* against p_o for the simple case where β_o=1, and for alternative values of Δ.

The net benefit curves in figure 1 have several features worthy of discussion. First, note that when $p_o < \bar{p}$ the equilibrium landscape is optimal and NB*=0 because the corner solution p_c=1-p_o yields lower net benefits than p_c=0. Second, to explain the increasing portion of the curves, note that marginal benefits of forest conversion increase at an increasing rate with p_o. Therefore, the opportunity cost of creating a new core parcel relative to expected benefits is high at values of p_o close to $\bar{p}$. However, as land quality becomes less heterogeneous (e.g. higher values of p_o), it is more likely for clusters of low quality land to form, and at moderate levels of heterogeneity marginal benefits of forest conversion are higher relative to opportunity costs than at values of p_o close to $\bar{p}$. Third, to explain the decreasing portion of the curve, note that on landscapes which are mostly homogeneous (e.g. p_o =0.95), almost the entire equilibrium landscape is forested and is thus likely to be close to the optimum. So, there will be few sub-optimal parcels on the equilibrium landscape when land quality is mostly homogeneous, and therefore NB* will be low. In summary, the shape of NB* reflects a tradeoff between the marginal and aggregate net benefits of reforestation. At higher values of p_o, *marginal* benefits of

[9] In particular, define heterogeneity in land quality as the number of edges between high and low quality land. The probability that any particular high quality parcel has an edge with a low quality parcel is equal to $p_o(1-p_o)$. So the number of edges on the landscape equals $Np_o(1-p_o)$, which is a strictly concave function of p_o with a maximum at p=0.5. Therefore, maximum spatial heterogeneity occurs on landscapes with values of p_o close to 0.5, and landscapes become more homogeneous as p_o approaches either 1 or 0.

converting a randomly selected parcel to forest are high relative to marginal cost because of the increased likelihood of spatially adjacent forest. However, the set of parcels available for conversion becomes lower at higher values of p_o, implying low levels of *aggregate* net benefits.

Targeting conservation resources to landscapes where $p_o = \sqrt{\Delta / \beta_o}$ will yield the highest net social gains. In addition, figure 1 shows that reducing the value of core forest relative to opportunity cost (e.g. increasing Δ) shifts NB^* down, and shifts the maximum point and $\bar{p}$ to the right. One implication is that equilibrium landscapes with lower opportunity costs of conversion are likely to be further from the optimum. Therefore, focusing a fragmentation policy on landscapes with lower opportunity costs of conversion is likely to yield larger welfare gains than focusing on landscapes with higher opportunity costs. A second implication is that the value of p_o which maximizes NB^* will be lower on landscapes with lower opportunity costs of conversion relative to core forest values. So, the lower the social value of a core forest parcel, the more conservation efforts should shift to landscapes with more low quality land, and more equilibrium forestland.

In order to compare the net social benefits of two landscapes with different levels of β_o we derive iso-net benefit curves to analyze combinations of p_o and β_o which yield identical net social benefits. We construct these curves for landscapes with p_o greater than the switching point $\bar{p}$ and thus focus on combinations of p_o and β_o which yield a given level of NB^*. For a constant NB^*, differentiating (4) with respect to β_o yields $\partial p_o / \partial \beta_o \,|_{dNB^O=0} = p_o^2 / 3(\Delta - \beta_o p_o^2)$. Since p_o^2 is always positive, $\partial p_o / \partial \beta_o \,|_{dNB^O=0} > 0$ if $\sqrt{\Delta / \beta_o} > p_o$ and $\partial p / \partial \beta_o \,|_{dNB^O=0} < 0$ if $\sqrt{\Delta / \beta_o} < p_o$. The NB^* for landscapes with different combinations of equilibrium forest (p_o) and equilibrium fragmentation levels (β_o) can be compared using the iso-net benefit curves in figure 2. For example, consider the two landscapes (1 and 2) marked in figure 2 with the following properties: $p_1 > p_2$ and $\beta_1 < \beta_2$. Since points on iso-net benefit curves closer to the left side of figure 3 have higher net social benefits we can see that landscape 1 has higher net social benefits than landscape 2. Examination of figure 2 highlights that reforesting landscapes with more fragmentation yields unambiguously higher net benefits than reforesting landscapes with less fragmentation, ceteris paribus. However, reforesting equilibrium landscapes with more forest may or may not yield higher net benefits than reforesting landscapes with less forest. If $p_o < (>) \sqrt{\Delta / \beta_o}$, then reforesting equilibrium landscapes with more forest will yield larger (smaller) net benefits than reforesting landscapes with less forest, ceteris paribus.

The regulator should always target landscapes with (β_o, p_o) close to $(1, \sqrt{\Delta})$. The value (β_o^*, p_o^*) equal to $(1, \sqrt{\Delta})$ is the solution to the problem of maximizing *net* social benefits from reforestation rather than *total* expected benefits. While the regulator's optimal reforestation strategy is to convert all land to forest on landscapes in which the expected benefits of doing so are positive, the net social benefits of this strategy vary considerably depending on the amount and spatial configuration of equilibrium forestland. Therefore, efforts to reduce fragmentation should be targeted to the most fragmented landscapes with an aggregate amount of forest equal to a threshold, defined by the ratio of the opportunity cost of conversion to the social value of core forest. This threshold represents the point at which every parcel converted has a high enough probability of adjacent forestland to generate positive expected net benefits.

3.3 Landscape Simulations

If the regulator knows the spatial configuration of land quality, then they can simply solve the optimization problem directly for each landscape. We hypothesize that the average net benefits of the optimal landscape observed across multiple assumptions of the spatial configuration of land quality for each given p_o will have properties that match the net benefit curve found in section 3.2. We use simulation methods and neutral landscape models[10] to explore the net benefits of an optimal landscape across multiple assumptions of the spatial configuration of land quality and to test the insights derived above. We use a neutral landscape model on a two-dimensional 14x14 grid where each parcel has a probability p_o of having low land quality land and probability (1-p_o) of having high quality land.[11] By altering p_o we can use random number generators to simulate a rich variety of potential spatial configurations of land quality.

Our simulation model works in the following way. First, we parameterize core benefits B and market returns to land for both uses such that $R_L^f > R_L^a$ and $R_H^a > R_H^f$. Core benefits B will be non-zero for a parcel if and only if all *eight* neighboring parcels are forested. These parameters are held constant throughout the simulations. Second, we specify a value of p_o and generate a random number on each parcel to create a spatial configuration of land quality across the two-dimensional landscape. If the random number generated for parcel (i,j) is less than p_o then this parcel is assigned to be low quality land. Next, we calculate the value of the equilibrium landscape with the following equation:

$$Value = \sum_{i=1}^{N}\sum_{j=1}^{N}\delta_{ij}R^f(q) + (1-\delta_{ij})R^a(q) + B_{ij}$$

Third, we solve the regulator's problem using integer programming with a branch-and-bound solution algorithm. Once the regulator's problem is solved, we calculate the value of the optimal landscape using the above equation and then calculate NB*. Fourth, we vary p_o between 0.05 and 0.95 in intervals of 0.05, and simulate 100 potential landscapes for each value of p_o. For each

[10] Neutral landscape models are used extensively in landscape ecology and consist of random maps which lack all factors that might organize or structure the pattern of the landscape (e.g. Gardner et al. 1987). Random maps are typically organized into grids with two primary types of land use, where each parcel in the landscape has a specified probability of being in one of the two uses.

[11] The size 14x14 was chosen due to computational limitations.

landscape simulation we solve the regulator's problem and calculate the net benefits of the optimal landscape, and then take the mean of all simulations for each value of p_o. This results in a total of 1900 potential configurations of land quality. The following parameters are used for market returns to the two land uses: R_L^f =2; R_H^f =3; R_L^a =1; R_H^a =4. As discussed above, the optimal landscape is also a function of the opportunity cost of converting a high quality parcel to forest relative to the social value of core forest (Δ). Therefore we run the simulations with different relative values of core forest parcels. This simulation model is a direct test of the model in section 3.1 with randomly distributed land quality. Figure 3 presents a graph of NB^* against p_o as p_o is altered from 0.05 to 0.95.

Examination of figure 3 indicates that the properties of the simulated net benefit function are largely consistent with the analytical net benefit function presented in 3.2. First, there is a non-linear relationship between the net benefits of the optimal landscape and the probability of low quality land. When core benefits are modest, NB^* first increases as land quality becomes less heterogeneous and then decreases as land quality becomes completely homogeneous. Second, decreasing the social value of a core parcel relative to the opportunity cost of converting a high quality parcel to forest (e.g. increasing Δ) shifts the net benefits curve down and the maximum point to the right. Third, the value of p_o which maximizes the simulated net benefit function is close in value to the point predicted analytically. In two dimensions, the probability of a random parcel being core is equal to Bp_o^9. So, $\Delta = [(R_H^a - R_H^f)/9B]$ and the value of p_o which maximizes NB^* occurs when $p_o = \Delta^{1/8}$. When Δ=0.15, the maximum value of NB^* should occur at p_o =0.79, whereas the simulations place this point at approximately p_o =0.8. When Δ=0.25 the maximum value of NB^* should occur at p_o =0.84, whereas the simulations place this point at approximately p_o =0.85. So the value of p_o which maximizes NB^* in the simulations is largely consistent with that predicted by the analytical results and the simulated landscapes confirm the major analytical insights.

4. Optimal Forest Landscapes with Urban Land

In this section we consider optimal landscapes when urban development is the primary cause of fragmentation. We present two models of urban development with spatial externalities. In the first model, the net return to developed land depends on its distance to the central business district (CBD)-- as assumed extensively in the urban economics literature (e.g. Mills 1981; Capozza and Helsley 1989)-- and distance to an exogenous amenity (e.g. a scenic hill) outside of the city boundary (Wu and Plantinga 2003). In the second model urban returns are a declining function of distance to the CBD and a function of the developed status of each parcel's immediate neighbors (e.g. Turner 2004). In each model we assume two uses to land, urban (u) and forest (f), but, in contrast to section 3, we assume that distances are observable and therefore parcel-specific land quality is known by the regulator. We consider the equilibrium landscape and compare it with the optimal landscape when core forest benefits are valuable. We then develop simple incentive policies to achieve the optimal landscape for each model. Denote Z = {1,…,N} as the set of parcels on the landscape where $z \in Z$ is a particular location with distance z from the CBD. Implicitly, z=0 locates the CBD while each subsequent location is one-unit distance further from the CBD. Before we present the models, consider the following definitions of terms used in this section.

Definition: *Development on parcel z is considered* **leapfrog** *if parcels z-1 and z+1 are undeveloped. Development on parcel z is considered* **in-fill** *if parcels z-1 and z+1 are developed.*

Leapfrog development is defined as development which occurs outside the city boundary where neither immediate neighbor is urban. In-fill development is defined as urban development on a parcel adjacent to two urban parcels.

Since the regulator knows the spatial configuration of land quality they can explicitly select a land use on each parcel $\{\delta_1, \delta_2, \ldots, \delta_N\}$ to solve the following:

$$\max_{\{\delta_i\}} \sum_{i=1}^{n} [\delta_i R^f(q_i) + (1-\delta_i) R^a(q_i) + B_i(\delta_i, \delta_{i-1}, \delta_{i+1})] \tag{5}$$

$$\text{s.t.} \qquad \delta_i \in [0,1] \quad i = 1, \ldots, N \tag{6}$$

The regulator's decision is dependent on market returns to urban and forestry on each parcel i relative to the wildlife benefits generated by i being forested. If parcel i is converted from u to f, the marginal wildlife benefits are a function of i's four immediate neighbors:

$$MB_i = \begin{cases} 1 & if \quad (\delta_{i-1} = 0; \delta_{i+1} = \delta_{i+2} = 1) \quad or \quad (\delta_{i+1} = 0; \delta_{i-1} = \delta_{i-2} = 1) \\ 2 & if \quad (\delta_{i-2} = 0; \delta_{i-1} = \delta_{i+1} = \delta_{i+2} = 1) \quad or \quad (\delta_{i+2} = 0; \delta_{i+1} = \delta_{i-1} = \delta_{i-2} = 1) \\ 3 & if \quad (\delta_{i-2} = \delta_{i-1} = \delta_{i+1} = \delta_{i+2} = 1) \end{cases}$$

The marginal benefit for parcel i is highest when its immediate four neighbors are all forested. If parcel i's immediate four neighbors are forested then conversion of parcel i into forest creates three new core parcels.

4.1 Central City with Heterogeneous Amenities

Assume the quality of land as an urban lot is measured by its distance to an urban center and its distance to an exogenous amenity. Land quality q is a decreasing function of distance to the CBD (located at z=0) and the amenity (located at $z=Z_A$). Figure 4a illustrates this landscape graphically in one-dimension, where market returns to urban are above market returns to forest in two distinct ranges: $0 \leq z \leq z^*$, and $z_{AL} \leq z \leq z_{AH}$. Wu and Plantinga (2003) show the conditions which generate the urban bid-rent function shown in figure 4a. Proposition 2 presents conditions for the equilibrium and optimal landscapes.

Proposition 2: *Consider a landscape where land quality satisfies the central city with an amenity assumption.* L^* *is the equilibrium landscape and* L^{**} *is the optimal landscape with the following characteristics:*

1. L^* *consists of a fragmented set of urban parcels* U^* *and a fragmented set of forest parcels* F^*.
2. *If* $R^u(z_A, 0) \leq (>) R^f + 3B$, *then* L^{**} *consists of a contiguous (fragmented) set of urban parcels* U^{**} *and a contiguous (fragmented) set of forest parcels* F^{**}.
3. $U^{**} \subset U^*$, $F^* \subset F^{**}$ *and* $TB(L^*) \leq TB(L^{**})$.

Proposition 2 shows that the equilibrium landscape consists of fragmented sets of both urban and forest parcels. Urban parcels are found clustered near the CBD and clustered near the amenity. It is the inclusion of preferences for living near an amenity outside the city which results in a fragmented landscape. Fragmentation may be socially optimal when amenities influence urban land values. If urban returns at the amenity exceed forest returns plus benefits from *three* core parcels, then social welfare is higher with at least one urban lot outside the city. The social value of three core parcels is the point of comparison rather than the value of one parcel because conversion of the first parcel at Z_A from forest to urban would result in a loss of *three* core parcels rather than one. If urban returns at the amenity are less than forest returns plus benefits from three core parcels, then social welfare is highest with no fragmentation. The optimal city boundary (z^{**}) is closer to the CBD than the equilibrium city boundary (z^*)— $z^{**} < z^*$ — and the optimal urban region centered near the amenity is always smaller than the equilibrium urban area centered near the amenity. Therefore, the equilibrium forest area is never greater than the optimal forest area and total core benefits on the equilibrium landscape are never larger than total core benefits on the optimal landscape. Proposition 2 presents an incentive policy to achieve the optimal landscape L^{**}.

Proposition 3: *Consider a landscape where land quality satisfies the central city with an amenity assumption. The following policy will achieve the socially optimal landscape configuration L^{**}:*

1. *A development impact fee (subsidy) of B on non-leapfrog development (non-core forest parcels).*
2. *A development impact fee (subsidy) of 3B on leapfrog development (core forest parcels).*

A spatially-uniform incentive of one would achieve the optimal city boundary z^{**}, but would fail to keep land around the amenity forested if $R^u(z_A,0) > R^f + B$. If $R^u(z_A,0) \leq R^f + 3B$ then this land is optimally forested and a uniform policy doesn't provide the correct incentive. This problem arises because leapfrog development has a larger effect on fragmentation than development at the city boundary. Our proposed optimal incentive policy is coined the 'punish-the-leapfrogger' policy. The incentive offered to landowners is contingent on the land use of their neighbors. An impact fee of one is imposed on development adjacent to an urban use, while an impact fee of three is assessed to leapfrog development. Thus, leapfrog developers must internalize the large initial impact on fragmentation. If $R^u(z_A,0) > R^f + 3B$ the landowner at Z_A will pay the tax and develop at Z_A. Each subsequent developer near the amenity is a profit-maximizer and will locate adjacent to the first 'leapfrogger' to avoid paying the extra fee. If $R^u(z_A,0) \leq R^f + 3B$, the tax will remove the incentive for anyone to 'leapfrog' and the land around the amenity will optimally remain forested.

If there were no amenity outside of the city boundary then there would be no fragmentation in either the equilibrium or optimal landscapes. Since the bid rent function for urban returns is monotonically decreasing from the CBD, all $z \leq z^*$ would be urban while all $z > z^*$ would be forested in the equilibrium landscape, where z^* is defined by $R^u(z^*)=R^f$. Consideration of core benefits would only imply that the optimal city boundary (z^{**}) is closer to the CBD than in the equilibrium landscape, identical to the optimal boundary in proposition 2. The policy presented in proposition 3 would achieve the optimal landscape if there were no amenity present, although a simple Pigouvian incentive (tax or subsidy) of B would also achieve the socially optimal landscape. This is not surprising given that there is no fragmentation in the equilibrium landscape and only those urban parcels closest to the equilibrium city edge (z^*) are not optimal.

4.2 Central city with neighbor preferences

An alternative model of urban rents which yields a fragmented landscape is developed by Turner (2004). In Turner's model, fragmentation results from household's preference for open space (undeveloped land around the house). Land quality in this model is a declining function of distance to the CBD and a function of whether each parcel's immediate neighbors are undeveloped. In particular, urban rents for parcel z are raised by ρ if and only if z-1 and z+1 are forested (figure 4b).

Turner (2004) analyzes the equilibrium and optimal landscapes under this model with no core forest benefits, and we briefly review his results. When neighbor preferences are valuable and core forest benefits are not, both the equilibrium and optimal landscapes consist of an urban, suburban, and forested region. Turner shows that in the equilibrium landscape, all $z<z^*$ are urban parcels, all $z>z^{**}$ are forest parcels, and all $z^*\leq z\leq z^{**}$ are suburban parcels that alternate between forest and urban uses, where z^* and z^{**} are defined by $R^u(z^*)=R^f$ and $R^u(z^{**})+\rho=R^f$. The suburban region is half forested but has no core forest benefits because no forest parcel is adjacent to another forest parcel. When neighbor preferences for open space are valuable, forest parcels exude a positive externality on urban parcels due to the proximity of such parcels to open space. Thus, when neighbor preferences exist, if agent A locates next to agent B, then A imposes a negative externality on B by depriving them of what was previously open space. As a consequence, parcels are placed in an urban use in the equilibrium landscape that should, in an optimal landscape, be left as forest. The primary difference between the equilibrium and optimal landscapes is that urban developers internalize their externalities in the optimal landscape by including their neighbor's loss of open space benefits as a cost. Thus, the urban area is too large in the equilibrium landscape and the suburban area is too small. Optimally, the set of parcels $U_N^* \in \{z : z < z_N^*\}$ should be urban, the set of parcels $S_N^* \in \{z : z_N^* \le z \le z^{**}\}$ should be suburban, and the set $F_N^* \in \{z : z > z^{**}\}$ should be forested. Of particular importance in Turner's analysis is that in-fill development is not optimal.

The presence of core benefits can significantly impact the optimal landscape configuration with neighbor preferences. Proposition 4 presents the optimal landscape with neighbor preferences and core benefits. In this landscape forest parcels exude a positive externality to both neighboring urban parcels and neighboring forest parcels.

Proposition 4: *Consider a landscape where benefits from core forests are positive and where urban landowners have neighbor preferences.* L_{NC}^{**} *is the optimal social landscape with the following characteristics:*

1. *If ρ>B,* L_{NC}^{**} *consists of a contiguous urban region* U_{NC}^*, *a suburban region* $S_{NC}^* \neq \phi$ *where forest and urban uses are fragmented, and a contiguous forest region* F_{NC}^*, *where* $U_{NC}^* = U_N^*$, $S_{NC}^* \subset S_N^*$, *and* $F_{NC}^* \supset F_N^*$.
2. *If ρ<B (ρ=B),* L_{NC}^{**} *consists of a contiguous urban region* U_{NC}^*, *a contiguous forest region* F_{NC}^*, *and no suburban region* $S_{NC}^* = \phi$, *where* $U_{NC}^* \subset U_N^*$ $(U_{NC}^* = U_N^*)$, S_{NC}^* *is a null set, and* $F_{NC}^* \supset F_N^*$.

There are two primary points to emphasize from proposition 4. First, whether suburban development is optimal depends critically on the relative magnitude of ρ and B. If ρ>B, then the open space benefit exceeds the value of one core forest parcel and the optimal landscape will include an urban, suburban, and a forested region, where fragmentation is optimal in the suburban region. Note that for at least one suburban parcel to be optimal then urban returns at the closest suburban parcel to the optimal city edge must exceed[12] R^f+2B. The value of two core parcels is the point of comparison here because wildlife benefits generated by converting the furthest suburban parcel from the optimal city edge to forest are equal to 2B. If $\rho \leq B$, then benefits from one core parcel exceed the open space benefits. In this case it is not optimal to have a suburban region, and therefore any level of fragmentation is sub-optimal. In addition, if ρ is strictly less than B, then the equilibrium city boundary is too far from the CBD, similar to the finding in the central city with amenities model. When $\rho < B$ then it will not be optimal to have a suburban region and thus core benefits can be achieved by moving the optimal city boundary closer to the CBD. The size of the optimal forest region is never smaller than the equilibrium forest region and the size of the optimal urban region is never larger than the equilibrium urban region. Proposition 5 presents the optimal incentive policy for the central city with neighbor preferences model.

Proposition 5: *Consider a landscape where benefits from core forests are positive and where urban landowners have neighbor preferences. The following policy will achieve the optimal landscape* L_{NC}^{**}*:*

1. *If $\rho \leq B$, impose a uniform impact fee (subsidy) of B on all developers (forest landowners).*
2. *If $\rho > B$, impose an impact fee (subsidy) of 2B on all leapfrog developers (core forest owners) and an impact fee (subsidy) of ρ on in-fill developers (non-core forest owners).*

The design of the optimal incentive policy is conditional on the relative magnitude of ρ and B. If $\rho \leq B$ a simple Pigouvian incentive policy is optimal. The incentive could be a spatially-uniform fee or subsidy equal to B, and urban development will only occur on parcel z if $R^u(z) > R^f+B$. It will never be optimal for a landowner to develop a suburban parcel under such a policy and the optimal landscape will be achieved. In contrast, if $\rho > B$ a simple Pigouvian incentive policy no longer works. The optimal policy will have to internalize the positive externalities of forest on

[12] If $\rho > B$, then urban returns on this parcel will exceed R^f+2B (see appendix for proof).

both neighboring urban and forest parcels. The fee of ρ is equal to the open space benefits to urban uses while the fee of 2B represents the wildlife benefits generated by the furthest suburban parcel from the CBD being converted to forest. This spatially-varying policy will result in the optimal landscape.

An important point to emphasize after considering these alternative models of urban developments is that spatial heterogeneity in land quality greatly influences the optimality of fragmentation in land use and the choice of policy incentives. When land quality is not very heterogeneous, such as in a simple central city model with no amenities, then fragmentation is never optimal and simple Pigouvian incentives can be used to achieve the optimal landscape. However, as land quality becomes more heterogeneous, the likelihood of fragmentation being optimal increases. In addition, simple Pigouvian incentive policies may no longer lead to the optimal landscape and the spatial properties of the optimal incentive policy become more complex as land quality becomes more spatially heterogeneous. An agglomeration bonus is one such policy approach (Smith and Shogren 2002). Our results highlight how the design of an efficient agglomeration bonus must account for spatial heterogeneity in land quality.

5. Conclusions

This paper has developed a spatially-explicit model of land use to examine optimal landscape configuration and policy design when wildlife habitat fragmentation affects the social value of land-use. The optimal spatial configuration of forest depends on the spatial distribution of land quality, and therefore we develop optimal policies for reducing fragmentation that explicitly account for land quality information. Since land quality for urban and agricultural land use is influenced by different factors, policy insights are developed for the cases of forest fragmentation caused by urban development and by agriculture. In particular, we assume urban land quality is a function of observable distances to cities and amenities while agricultural land quality is a function of soil quality and other unobserved parcel-specific attributes.

In the case of forest fragmentation caused by agriculture, we derive the optimal amount of forest restoration when land quality information is incomplete and the regulator doesn't know the spatial location of restored forestland a priori. Results indicate two possibilities: convert all agricultural land to forest or convert nothing to forest. This corner solution is driven by the spatial relationships giving rise to fragmentation and the uncertainty as to the exact location of restored forestland. In particular, as the probability of every parcel being forest increases, the probability of every parcel being adjacent to other forest parcels increases at an increasing rate. The net social benefits of the optimal reforestation strategy are shown to vary significantly across landscapes with different amounts of forest, fragmentation, and opportunity costs of conversion. This variation in net social benefits gives rise to targeting rules to guide conservation efforts across multiple landscapes with differing degrees of landscape heterogeneity. In general, efforts to reduce fragmentation should be targeted to the most fragmented landscapes with an aggregate share of forest equal to a threshold, defined by the ratio of the opportunity cost of conversion to the social value of core forest. In addition, a fragmentation policy will yield higher welfare gains if targeted towards landscapes with lower opportunity costs of conversion.

When urban development is the primary cause of fragmentation, the aggregate amount of forestland is higher on the optimal landscape than on the equilibrium landscape under all assumptions of land quality. However, the spatial clustering of land use will not always yield the highest social welfare, as some level of fragmentation may be optimal. While fragmentation is never optimal on simple landscapes such as predicted in central city models, spatial heterogeneity in amenities or household preferences for open space can lead to an optimal level of fragmentation. Under the simple central city model a spatially uniform incentive policy (e.g. a development impact fee) can achieve the optimal landscape because only the location of the city edge is not optimal. However, a uniform policy does not necessarily achieve the optimal landscape in the presence of spatial heterogeneity in amenities or household preferences for open space. When an exogenous amenity exists outside the city boundary, a policy which punishes the first leapfrog developer outside the city will achieve the optimal landscape. When urban land quality is also a function of neighboring uses, the optimal policy will offer varying incentives to developers depending on whether they engage in ‘in-fill’ or ‘leapfrog’ development. These results arise because urban development generates a larger increase in fragmentation if it occurs outside the city boundary rather than at the city edge.

References

Albers H.J. 1996. “Modeling Ecological Constraints on Tropical Forest Management: Spatial Interdependence, Irreversibility, and Uncertainty.” *Journal of Environmental Economics and Management* 30, 73-94.

Armsworth, P.R., B.E. Kendall, and F.W. Davis. 2004. “An Introduction to Biodiversity Concepts for Environmental Economists.” *Resource and Energy Economics,* 26: 115-136.

Askins, R.A. 2002. *Restoring North America's Birds.* Yale University Press, New Haven, CT.

Capozza, D.R., and R.W. Helsley. 1989. “The Fundamentals of Land Prices and Urban Growth.” *Journal of Urban Economics,* 26: 295-306.

Deacon, R.T, Kolstad, C.D., Kneese, A.V., Brookshire, D.S., Scrogin, D., Fisher, A.C, Ward, M., Smith, V.K., and J. Wilen. 1998. “Research Trends and Opportunities in Environmental and Resource Economics,” *Environmental and Resource Economics,* 11(3-4): 383-397.

Faaborg, J. 2002. *Saving Migrant Birds: Developing Strategies for the Future*. University of Texas Press, Austin, TX.

Gardner, R. H., B.T. Milne, M.G. Turner and R.V. O'Neill. 1987. “Neutral Models for the Analysis of Broad-Scale Landscape Pattern.” *Landscape Ecology*, 1(1):19-28.

Hof, J. and M. Bevers. 2002. *Spatial Optimization in Ecological Applications.* Columbia University Press, New York, NY.

Hof, J., and M.G. Raphael. 1997. “Optimization of Habitat Placement: A Case Study of the Northern Spotted Owl in the Olympic Peninsula.” *Ecological Applications*, 7(4): 1160-1169.

Mills, D.E. 1981. “Growth, Speculation, and Sprawl in a Monocentric City.” *Journal of Urban Economics,* 10: 201-226.

Parker, D.C. 2000. “Edge Effect Externalities: Theoretical and Empirical Implications of Spatial Heterogeneity.” Unpublished PhD Dissertation, University of California, Davis.

Paton, P.W.C. 1994. “The Effect of Edge on Avian Nest Success: How Strong is the Evidence?” *Conservation Biology*, 8: 17-26.

Plantinga, A.J. 1996. “The Effect of Agricultural Policies on Land Use and Environmental Quality.” *American Journal of Agricultural Economics*, 78: 1082-1091.

Ritters, K.H., Wickham, J.D, O'Neill, R.V., Jones, K.B., Smith, E.R., Coulston, J.W., Wade, T.G., and J.H. Smith. 2002. “Fragmentation of Continental United States Forests.” *Ecosystems*, 5: 815-822.

Robbins, C.S., Dawson, D.K., and B.A. Dowell. 1989. "Habitat Area Requirements of Breeding Forest Birds of the Middle Atlantic States." *Wildlife Monographs,* 103: 1-34.

Robinson, S.K., F.R. Thompson, T.M. Donovan, D.R. Whitehead, and J. Faaborg. 1995. "Regional Forest Fragmentation and the Nesting Success of Migratory Birds." *Science,* 267(5206): 1987-1990.

Saak. A.E. 2004. "Equilibrium and Efficient Land-Use Arrangements under Spatial Externality on a Lattice." *Working Paper 04-WP 376,* Center for Agricultural and Rural Development, Iowa State University.

Smith, R.B.W., and J.F. Shogren. 2002. "Voluntary Incentive Design for Endangered Species Protection." *Journal of Environmental Economics and Management*, 43(2): 169-187.

Swallow, S.K., Talukdar, P., and D.N. Wear. 1997. "Spatial and Temporal Specialization in Forest Ecosystem Management under Sole Ownership." *American Journal of Agricultural Economics*, 79:311-326.

Temple, S.A., and J.R. Cary. 1988. "Modeling Dynamics of Habitat-Interior Bird Populations in Fragmented Landscapes." *Conservation Biology,* 2(4): 340-357.

Turner, M.A. 2004. "Landscape Preferences and Patterns of Residential Development." Forthcoming in *Journal of Urban Economics.*

Van Horn, M.A., R.M. Gentry, and J. Faaborg. 1995. "Patterns of pairing success of the Ovenbird within Missouri Forest Fragments." *Auk*, 112: 98-106.

Walsh, R.P. 2004. "Endogenous Open Space Amenities in a Locational Equilibrium." *Working Paper No. 04-03*, Center for Economic Analysis, University of Colorado.

Wu, J. and A.J. Plantinga. 2003. "Open Space Policies and Urban Spatial Structure." *Journal of Environmental Economics and Management* 46(2): 288-309.

Figure 1 – Net Benefits of the Optimal Landscape (β_o=1)

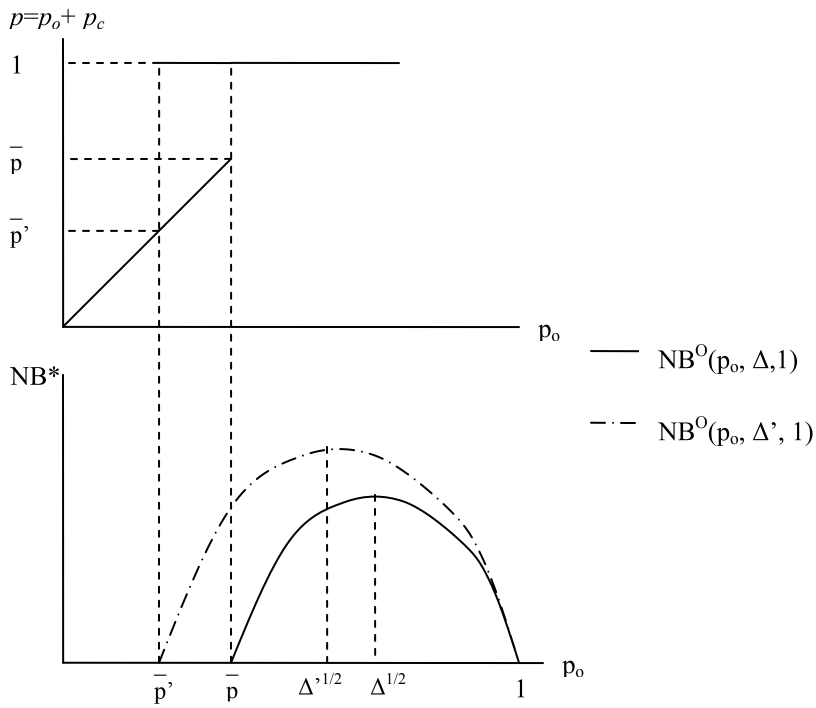


Figure 2 – Iso-Net Benefit Curves (Initial Forest (p_o) vs. Initial Fragmentation (β_o))

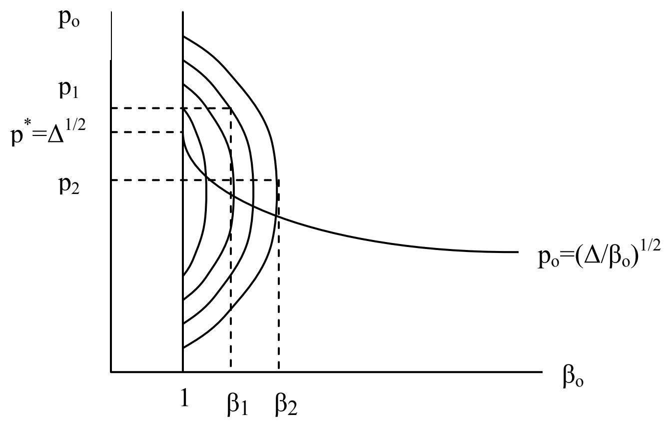


Figure 3 – Simulated Net Benefit Function (two dimensions)

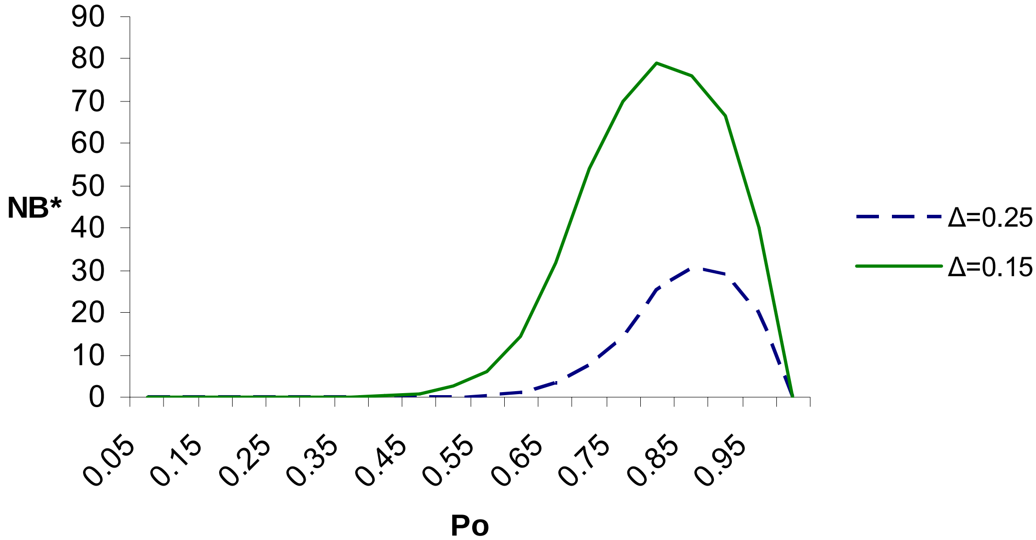
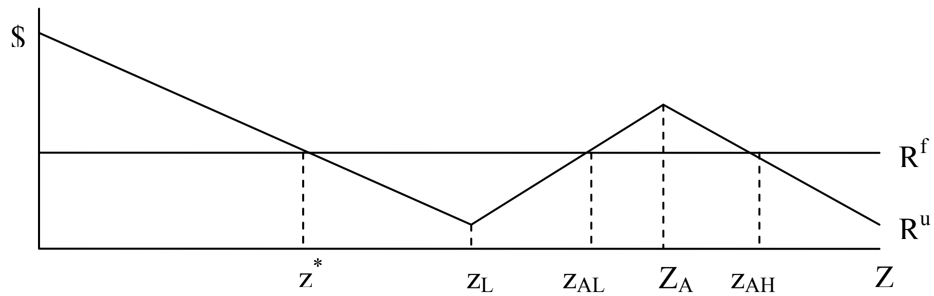
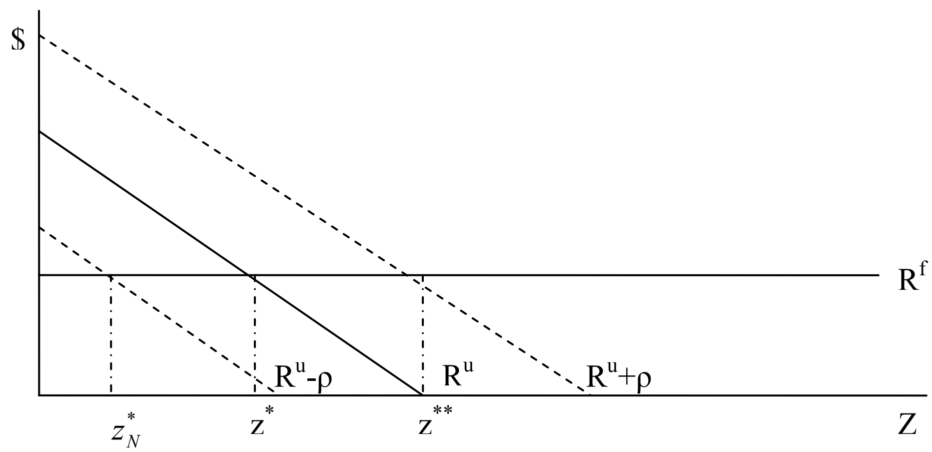


Figure 4 – Market Returns to Land

a. Central City with Amenity



b. Open Space Preferences



Appendix: Proofs

Proof of Lemma*:* If L is fragmented with configuration L', then

Max TC(L') = { N_f –3 if δ_N=1
{ N_f -4 if δ_N<1

Therefore, TC(L) > max TC(L')**.**

Proof of Proposition 1:

First, we prove that equation (4) is convex in p^c. If β_o=1, the initial landscape is random and $\partial^2 EB^O / \partial p_c^{\,2} = 6(Bp_c + p_o) > 0$. If $\beta_o \neq 1$ then the initial landscape is non-random. To prove that (4) is convex in p^c when $\beta_o \neq 1$, subdivide the non-random landscape into S random sub-landscapes such that the following properties hold: 1) there are i=1,…,S sub-landscapes; 2) each sub-landscape i has s_i percent of the initial landscape L; 3) p_o^i denotes the probability of low quality land (e.g. forest) on sub-landscape i; 4) $\sum_{i=1}^{S} s_i p_o^i = p_o$; 5) expected core benefits from a parcel of land on sub-landscape i is equal to $B{p_o^i}^3$. The core benefits on the landscape will equal $B\sum_{i=1}^{S} s_i {p_o^i}^3 = B\beta_o {p_o}^3$. If we increase the probability that every parcel on the landscape is forest by p_c, then $\sum_{i=1}^{S} \left\{ s_i p_o^i + \alpha_i p_c \right\} = p_o + p_c$, where $\alpha_i = (1 - p_o^i) \Big/ \sum_{i=1}^{S} s_i (1 - p_o^i)$. Therefore, the probability of a forested parcel on sub-landscape i after conversion is equal to $p^i = p_o^i + (1/s_i)\alpha_i p_c$, and expected core benefits from the entire landscape can be written as follows: $EB = BE[\beta(\beta_o, p_o, p_c, \gamma)] \cdot (p_o + p_c)^3 = B\sum_{i=1}^{S} s_i (p_o^i + (1/s_i)\alpha_i p_c)^3$, and

$$\partial^2 EB \big/ \partial p_c^{\,2} = B\sum_{i=1}^{S} s_i 6[p_o^i + (1/s_i)\alpha_i p_c]((1/s_i)\alpha_i)^2 > 0.$$ Therefore, (4) is convex in p_c.

Since (4) is convex in p_c we can only have a corner solution to (4): p_c =0 or p_c =1-p_o. If p_c =1-p_o then β=1. The point at which it is optimal to switch from p_c =0 to p_c =1-p_o can be derived by examining the point p_o=p_L at which the expected benefits from solution p_c =1-p_o exceed the expected benefits from solution p_c =0. This can be expressed by examining when the following equation equals zero:

$$NB^* = EB^*(p_c = 1 - p_o) - EB^*(p_c = 0) = B[1 - \beta_o {p_o}^3] - (R_H^a - R_H^f)(1 - p_o)$$

First, note that when p_o=1, β_o=1 by assumption, and NB^*=0. Second, note that $\partial^2 NB^* \big/ \partial p_o^{\,2} = -6\beta_o p_o \le 0$, because $p_o \geq 0$ and $\beta_o \geq 0$ by assumption. Therefore, NB^* is always concave in the relevant range $p_o \geq 0$ and there can be at most two positive values of p_o for which NB^*=0, including p_o=1. Thus, $\overline{p} = \min\{1, \overline{p}^*\}$ is the implicit solution to NB^*=0.

Using implicit differentiation on NB^*=0 we can derive $\partial \overline{p} \big/ \partial \beta_o = \overline{p}^3 / 3(\Delta - \beta_o \overline{p}^2)$. In order to sign this derivative note that NB^* is concave in p_o and maximized when $\beta_o {p_o}^2 = \Delta$. Therefore, Δ>

$\beta_o{}^3 p_L{}^2$ and $\partial \bar{p} / \partial \beta_o > 0$. Also, using implicit differentiation on NB*=0 we can derive $\partial p_L / \partial \Delta = (\bar{p} - 1) / (\beta_o \bar{p}^2 - \Delta)$. Since we already showed that $\Delta > \beta_o \bar{p}^2$, then $\partial \bar{p} / \partial \Delta > 0 \quad \forall \quad \bar{p} < 1$.

Proof of Proposition 2:

1. By definition, $R^u(z)>R^f$ at all locations $z \le z^*$ and $z_{AL} \le z \le z_{AH}$, thus profit maximizing landowners will place these lands in urban uses and the rest in forest.

2. Suppose $R^u(z_A,0) \le R^f + 3B$ and it is not optimal for all locations $z>z^*$ to be forested. Then since $R^u(z_A,0) > R^u(z,0)$ $\forall$ $z>z^*$, a configuration L' that consists of all parcels $z<z^{**}$ and parcel z_A in an urban use and all other parcels in forested use should have a higher total welfare than L^{**}. However, converting the parcel at location z_A to forest creates core benefits of 3B, and since $R^u(z_A,0) < R^f + 3B$ by assumption, a Pareto improvement could be had by converting the parcel at location z_A to forest. Thus, if the parcel at location z_A should be forested, then so should all $z>z^*$.

If $R^u(z_A,0) > R^f + 3B$, all locations $z \le z^{**}$ and $z^{**}_{AL} \le z \le z^{**}_{AH}$ are in urban use U, and all locations $z^{**} < z < z^{**}_{AL}$ and $z^{**}_{AH} < z$ are in forest use F, where $R^u(z^{**}, |z^{**} - Z_A|) = R^u(z^{**}_{AL}, |z^{**}_{AL} - Z_A|) = R^u(z^{**}_{AH}, |z^{**}_{AH} - Z_A|) = R^f + B$. Now, suppose there was some other L' which created social benefits greater than L^{**}. Since $R^u(z_A,0) > R^f + 3B$ and the central city is located at z=0 (δ_0=0), then L' will be fragmented. Since δ_0=0 by assumption, the closest forest parcel to i=0 (δ_i') will generate forest benefits of R^f+B, because δ_{i-1}'=0, δ'_{i+j}=1. Likewise, since the parcel at z_A will be in urban then the closest forest parcel $z<z_A$ will generate forest benefits R^f+B and the closest forest parcel $z>z_A$ will also generate forest benefits R^f+B. Therefore any L' in which some $z<z^{**}$, or some $z^{**}_{AL} \le z \le z^{**}_{AH}$ is forested would have lower welfare than L^{**}.

3. Since $\frac{\partial R^u}{\partial z} \le 0$ and $\frac{\partial R^u}{\partial |z - Z_A|} \le 0$, then $z^{**}<z^*$, $z_{AL} > z^{**}_{AL}$, and $z_{AH} < z^{**}_{AH}$ then L^{**} must contain more forest than L^*. Therefore, since the landscape is of fixed length and has only two uses, $U^{**} \subset U^*$ and $F^* \subset F^{**}$.

Proof of Proposition 3:

The policy in proposition 3 would result in the following optimization problem for each landowner:

a. Max $\delta_i(R^f+B) + (1- \delta_i)R^u(z)$ for parcels adjacent to an urban parcel.
b. Max $\delta_i(R^f) + (1- \delta_i)(R^u(z)-3B)$ for parcels not adjacent to an urban parcel.

This setup would result in the following Kuhn-Tucker conditions to be forested:

Forest if $R^f+B>R^u(z)$ for parcels adjacent to an urban parcel.
Forest if $R^f+3B>R^u(z)$ for parcels not adjacent to an urban parcel.

Since the CBD is urban, the parcel developing next to the CBD will face the first optimization problem above. All subsequent developers then have an incentive to locate next to the original urban parcels. Since $R^u(z)>R^f+B$ for all $z \le z^{**}$, then all $z \le z^{**}$ will be in an urban use, where $R^u(z^{**}, |z^{**} - z_A|) = R^f + B$. If $R^u(z_A,0) < R^f + 3B$, then no parcels $z>z^{**}$ will be developed, because the Kuhn-Tucker necessary condition for urban development will never be satisfied since max $R^u(q(z)) = R^u(z_A, 0)$ when $z > z^{**}$. If $R^u(z_A, 0) > R^f + 3B$, then the Kuhn-Tucker necessary condition for urban development will be satisfied for at least parcel z_A, and thus parcel z_A will be developed. If parcel z_A gets developed, then all landowners $z > z^*$ would be better off facing maximization problem a than problem b, and would then choose to locate next to the existing urban parcels at the amenity. Therefore, all $z_{AL}^{**} \le z \le z_{AH}^{**}$ will have urban returns exceeding forest returns and all locations $z^{**} < z < z_{AL}^{**}$ and $z_{AH}^{**} < z$ will have forest returns exceed urban returns, where $R^u(z^{**}, |z^{**} - Z_A|) = R^u(z_{AL}^{**}, |z_{AL}^{**} - Z_A|) = R^u(z_{AH}^{**}, |z_{AH}^{**} - Z_A|) = R^f + B$. Thus, L^{**} will be achieved.

Proof of Proposition 4:

1. ρ>B

If ρ>B the forested region F_{NC}^* consists of all locations $z > z_{NC}^{**}$ which are forested; the suburban region S_{NC}^* consists of all locations $z_{NC}^* \le z \le z_{NC}^{**}$ which alternate between urban and forest uses; and the urban region U_{NC}^* consists of all locations $z < z_{NC}^*$ which are urban, where $R^u(z_{NC}^{**}) + \rho - 2B = R^u(z_{NC}^*) - \rho = R^f$.

If ρ>B, then 2ρ>2B and $R^f+2\rho>R^f+2B$. Note that $R^u(z_{NC}^*)-\rho=R^f$ by assumption. Therefore, after substitution, $R^u(z_{NC}^*)+\rho>R^f+2B$.

Suppose L^{**} does not satisfy the conditions above. Then at least one of the following must be true:

a. There must be some $z' > z_{NC}^{**}$ which should be urban. Conversion of one parcel z' to urban would generate maximum net benefits of $R^u(z')+\rho-R^f-2B$, which is negative because $R^f+2B>R^u(z') + \rho$ by assumption.

b. There must be some $z_{NC}^* \le z' \le z'' \le z_{NC}^{**}$ such that z' and z'' are either adjacent urban plots or adjacent forest plots. First, consider the case when there are adjacent urban plots. If z' is converted to forest, then net benefits are $R^f+\rho-R^u(z')$, which is greater than zero because $R^u(z')- \rho<R^f$ by assumption. Second, consider the case where there are adjacent forest plots. If z' is converted to urban, then minimum net benefits are $R^u(z')+ \rho-R^f-2B$, which is greater than zero because $R^u(z')+ \rho>R^f+2B$ by assumption.

c. There must be some $z' < z_{NC}^*$ that should remain in forest. Conversion of one parcel z' to forest would generate no core benefits and would thus generate net benefits of $R^f-R^u(z')$, which is less than zero by assumption. Conversion of two parcels z' and z'', such that z'' =z' + 2 would ensure that parcel z'+1 was suburban. Net benefits in this case would be $2R^f+\rho-R^u(z')-R^u(z'')$. However, $R^u(z')- \rho>R^u(z'')- \rho>R^f$ by assumption, and thus $R^u(z')+R^u(z'')>2R^f+ \rho$ and net benefits of creating this suburban parcel would be negative.

$z_{NC}^* = z^*$ by inspection, therefore $U_N^* = U_{NC}^*$. Likewise, $z_{NC}^* \le z \le z_{NC}^{**}$ is a smaller region than $z_N^* \le z \le z^{**}$, and therefore $S_N^* \supset S_{NC}^*$. Lastly, $F_N^* \subset F_{NC}^*$ because $U_N^* = U_{NC}^*$ and $S_N^* \supset S_{NC}^*$.

2. ρ≤B

If ρ≤B then the forested region F_{NC}^{*} consists of all locations $z > z_{NC}^{**}$ which are forested; the suburban region S_{NC}^{*} is a null set; and the urban region U_{NC}^{*} consists of all $z \leq z_{NC}^{**}$ which are urban, where $R^{u}(z_{NC}^{**}) = R^{f} + B$.

If ρ≤B, then 2ρ≤2B and R^f+2ρ≤R^f+2B. Note that $R^u(z_{NC}^{*})$-ρ=R^f by assumption. Therefore, after substitution, $R^u(z_{NC}^{*})$+ρ≤R^f+2B.

Suppose L^{**} does not satisfy the conditions above. Then at least one of the following must be true:

a. There must be some $z' > z_{NC}^{**}$ which should be urban. Conversion of one parcel z' to urban would generate maximum net benefits of R^u(z')+ρ-R^f-2B, which is negative because R^f+2B>R^u(z') + ρ by assumption.

b. There must be some $z' < z_{NC}^{**}$ that should remain in forest. Conversion of one parcel z' to forest would generate maximum net benefits of R^f+B-R^u(z'), which is less than zero by assumption. Conversion of two parcels z' and z'', such that z'' =z' + 2 would ensure that parcel z'+1 was suburban. Net benefits in this case would be 2R^f+ρ-R^u(z')-R^u(z''). However, R^u(z')- ρ>R^u(z'')- ρ>R^f by assumption, and thus R^u(z')+R^u(z'')>2R^f+ ρ and net benefits of creating this suburban parcel would be negative.

$z_{NC}^{*} < z^{*}$ by inspection, therefore $U_{N}^{*} \supset U_{NC}^{*}$. Likewise, $z_{NC}^{**} = z_{NC}^{*}$ and therefore S_{NC}^{*} is an empty set. Lastly, $F_{N}^{*} \subset F_{NC}^{*}$ because $U_{N}^{*} \supset U_{NC}^{*}$ and S_{NC}^{*} is an empty set.

Proof of Proposition 5:

1. Assume ρ≤B. Then all landowners face the following optimization problems:

Max $\delta_i(R^f+B) + (1-\delta_i)R^u(z)$ if at least one neighbor is urban

This setup would result in the following Kuhn-Tucker conditions to be forest:

Forest if R^f+B>R^u(z) if at least one neighbor is urban

Note that $R^{u}(z^{*}) = R^{u}(z^{**}) + \rho = R^{u}(z_{N}^{*}) - \rho = R^{f}$ by assumption, and that $R^{u}(z\ ) + \rho > R^{f}$ for z^*<z<z^{**}, which is the privately optimal suburban region (e.g. the only region for which ρ>0). However since ρ≤B, then R^f+B>R^u(z)+ρ for all z^*<z<z^{**}, since R^u(z)<R^f for all z>z^*. Therefore, the policy ensures that the suburban region will be a null set, which corresponds with L_{NC}^{**}.

Each landowner will face the above optimization problem all z≤z^* since R^u(z)>R^f in this range. Therefore, the urban forest boundary will occur where R^f+B=R^u(z), which by assumption occurs where z=z_{NC}^{**}. Therefore, L_{NC}^{**} is achieved.

2. Assume ρ>B. Then all landowners face the following optimization problems:

a. Max $\delta_i R^f + (1-\delta_i)(R^u(z)+\rho-2B)$ if the parcel is a leapfrogger.

b. Max $\delta_i R^f + (1-\delta_i)(R^u(z)-\rho)$ if the parcel is an in-fill.

This setup would result in the following Kuhn-Tucker conditions to be forest:

Forest if $R^f > R^u(z) + \rho - 2B$ if the parcel is a leapfrogger.

Forest if $R^f > R^u(z) - \rho$ if the parcel is an in-fill.

Note that $R^u(z^*) = R^u(z^{**}) + \rho = R^u(z_N^*) - \rho = R^f$ by assumption, and that $R^u(z\ \ ) + \rho > R^f$ for $z^* < z < z^{**}$, which is the privately optimal suburban region (e.g. the only region for which $\rho > 0$). So all parcels $z < z^*$ will then face optimization problem b, and the city boundary will be found where $R^f = R^u(z) - \rho$, which occurs at $z = z_{NC}^*$. This corresponds with the socially optimal urban boundary. Each leapfrogging parcel will face optimization problem b, and the suburban-forest boundary will be found where $R^f = R^u(z) + \rho - 2B$, which occurs at $z = z_{NC}^{**}$. This corresponds with the socially optimal suburban-forest boundary and L_{NC}^{**} is achieved.