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Abstract

This paper develops a model of a forest owner operating in an open-city environment, where the rent for developed land is increasing concave in nearby preserved open space and is rising over time reflecting an upward trend in households' income. Thus, our model creates the possibility of switching from forestry to residential use at some point in the future. In addition it allows the optimal harvest length to vary over time even if stumpage prices and regeneration costs remain constant. Within this framework we examine how adjacent preserved open space and alternative development constraints affect the private landowner´s decisions.

We find that in the presence of rising income, preserved open space hastens regeneration and conversion cuts but leads to lower density development of nearby unzoned parcels due to indirect dynamic effects. We also find that both a binding development moratorium and a binding minimum-lot-size policy can postpone regeneration and conversion cut dates and thus help to protect open space even if only temporarily. However, the policies do not have the same effects on development density of converted forestland. While the former leads to high-density development, the latter encourages low-density development.

Keywords: urban growth; development moratorium; minimum lot size; open space conservation; forest management practices

JEL Classification #: Q23, R11, R14

1. Introduction

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Concern about the effects of development on private forests has risen sharply in the United States since the 1990's, when the conversion of forest land to developed uses reached a million acres per year. A total of 49.7 million acres of forest across the U.S. is now projected to be converted to urban use by 2062 (Alig et al. (2010)). Population and personal incomes growth are the primary forces driving changes in the forest landscape (Kline et al. (2004), Alig et al. (2010)).

Forest land conversion is a persistent issue for policy makers due to its negative ecological (e.g. effects on water quality and wildlife habitat) and socio-economic effects (e.g. reduction of recreation opportunities). Moreover, a significant amount of forest land undergoing development each year is used for dispersed residential development in suburban, rural and exurban areas. And, increases in housing density on or adjacent to forests can result in changes to the forest's quality and changes in forest investment (Kline et al. (2004)).

Governing agencies have attempted to lessen the negative environmental impacts of urban growth by regulating land uses on private lands and by preserving forests and open spaces. Large-lot zoning and open space acquisition are the most common implemented preservation tools at the local level in most U.S. states. Other preservation policies include growth management laws such as urban growth boundaries and development moratoria.

This naturally raises the following questions: how do population growth and increases in personal incomes affect a forester's harvesting and conversion planned decisions? What are the implications for the Faustmann harvesting strategy when conversion to an irreversible land use may occur at some point in the future? And finally, how do adjacent preserved open space and development constraint policies affect a forester's management decisions and thus, development pace and intensity?

This paper aims to build a theoretical framework for determining the optimal regeneration and conversion cut dates in the face of urban growth pressure. In particular, we develop a model of a forest owner operating in an open-city environment, where the rent for developed land is increasing concave in nearby preserved open space and is rising over time reflecting an upward trend in households' income. The primary purpose of the model is to explore how a development moratorium, minimum lot-size zoning and nearby preserved open space affect harvest cut decisions.

The traditional Faustmann setup investigates the optimal harvesting strategy for successive timber crops under the assumption that stumpages prices and regeneration costs remain constant over time and disregards the existence of any alternative use to forestry. This implies that land will be perpetually used for timber production and that rotation lengths (time between harvests) are constant over time.

Very few theoretical studies have investigated the implications for the Faustmann strategy of forestland conversion over time. To our knowledge there have been only two studies that have examined this issue (McConnell et al. (1983), Burgess and Ulph (2001)). McConnell et al. (1983) determine the "approximately" optimal harvesting strategy of a forester who maximizes the present discounted value net revenue from a single site when timber prices and regeneration costs vary exogenously and agricultural rents remain constant over time.[1] Burgess and Ulph (2001) use a forest land use option

[1] Armstrong and Philips (1989) also develop a theoretical framework to determine the optimal timing of land use change from timber production to agriculture when the parcel of land supports a productive stand of timber. In contrast to McConnell et al. (1983), the authors assume that the landowner starts with a stand of trees of a particular age (so they relax the bare land assumption) and the goal of the landowner is to

model to allow for the conversion of forest land between alternative management options over time to explain the ongoing process of deforestation in the tropics.

More specifically, McConnell et al. (1983) deal with the possibility of shifting from forestry to agriculture and vice-versa, while Burgess and Ulph (2001) focus on the switch between alternative valued tree crops over time. Therefore, none of these previous frameworks is suitable to understand current trends in forest land conversion in areas with strong urban growth pressure or to examine the impacts of anti-sprawl policies on forest management practices. Yet, both studies provide important insights on how harvesting decisions are affected when we consider evolving prices, allowing for varying optimal rotation lengths over time.

In contrast to McConnell et al. (1983) and Burgess and Ulph (2001) our alternative use to forestry is residential development, timber prices and regeneration costs are constant over time and urban rents are endogenously determined. This allows us to discuss how rising personal incomes affect forest management practices and explain the conversion of private working forests in an urban growth context.

In addition, we examine how adjacent open space and development policy restrictions affect the forester's harvest and conversion decisions. Typically, theoretical studies on the impacts of regulation on forest management practices ignore the existence of endogenous alternative uses and focus on examining how alternative forms of forestry taxation affect timber rotation dates (Englin and Klan (1990), Koskela and Ollikainen

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determine the age of timber harvest (and therefore the timing of land use conversion) under this scenario. It is also assumed that stumpage prices, regeneration costs and agriculture rent remain constant over time. Armstrong and Philips (1989) show that failure to separate forest bare land values from the productive value of standing timber can bias decisions towards immediate conversion. Yet, the authors do not examine the implications for the traditional Faustmann strategy of converting forestland into an alternative use at some point in the future or how evolving prices or policy interventions may affect forest management practices.

(1997, 2001, 2003)) and volume of tree retention (Koskela et al. (2007)). In contrast to these studies, we examine how land-use development policies in fast growing areas affect both regeneration and conversion cut dates.

Our analysis reveals several interesting findings. The fact that urban rents change over time alters the nature of the timber problem since it forces us to allow for the possibility to changes in land use from timber to residential use. Similar to McConnell et al. (1983) and Burgess and Ulph (2001), our model allows the optimal harvest length to vary over time. Yet, optimal rotation lengths are shown to be always lower than the Faustmann rotation length.

Our comparative static analysis reveals that an increase in nearby preserved open space speeds the landowner´s conversion cut time and decreases the regeneration cut date of unzoned forestland. It also increases residential bid land rents, decreases residential lot sizes and raises development density. Yet, these impacts are smaller in magnitude when households' income is rising over time. The reason is that preserved open space and waiting time are substitutes in the rent of the alternative land use to forestry.

On the one hand, for a given income level, there is a spatial dynamic amenity effect from the positive capitalization of nearby open space into residential rents, which creates an incentive to anticipate the conversion of forest land into residential use. On the other hand, because income rises over time, the value of nearby open space increases over time while the value of lot size decreases. As a result, there is also a temporal dynamic effect that pushes conversion into the future. The net effect of a marginal increase in nearby preserved open space on the conversion cut date depends on the magnitudes of these two countervailing forces. We show that while the spatial dynamic amenity effect dominates the temporal dynamic effect, the rate of forestland conversion and the rate of development density are lower when households' income rises over time, that is, when the temporal dynamic effect is taken into account.

In addition, we find that when a growth moratorium is binding, the landowner's best strategy is to convert his land to residential use as soon as it is allowed. As a result, a growth moratorium delays the conversion cut date and forested land is developed at higher densities. Since conversion and regeneration cuts are complements in our landowner's land value function, this policy will also delay the regeneration cut.

Finally, depending on the stringency level, a minimum-lot-size restriction can slow-down or stop conversion of forestland into residential use. It also increases the regeneration cut date and decreases the intensity of development of converted forested land.

The rest of the paper is organized as follows. Section 2 presents the analytical model. Section 3 describes the unregulated solution of the private landowner and discusses how the optimal harvesting strategy changes from the Faustmann formula. Section 4 examines the impacts of adjacent preserved open space and development constraints on regeneration and conversion cuts. Finally, section 5 offers conclusions.

2. Model

2.1. Assumptions

Consider a landowner who owns a parcel of bare undeveloped land of fixed size $\overline{L}$ adjacent to permanently preserved open space. Let t denote the calendar time. We assume the entire parcel of land is under commercial forestry at $t = 0$ and that it will be converted to residential use after two rotation cycles.[2] Switching from forestry to residential use is not costless since the landowner must make a significant one-time expenditure to clear clash, remove stumps etc. Denote switching costs, S, as the cost per unit of land of switching from timber production to residential use. Development is also assumed to be irreversible so that conversion of land from residential use back to forestry is economically infeasible. When land is developed to residential use, the timber benefits it provides are lost altogether. In addition, conversion to residential use implies the subdivision of the parcel into multiple residential lots.

Timber Benefits

Timber harvests can be categorized into regeneration cuts and conversion cuts. Regeneration cuts harvest the current stand and provide for regeneration of the subsequent stand. The land continues to be managed for timber production. A conversion cut harvests the current stand with no provision for regenerating a future stand. The land is no longer managed for timber production and is converted into residential use. We denote as T the rotation length of the timber stand or the age of the trees at the first harvest and $D-T$ the rotation length of the timber stand at the second harvest, where D stands for the conversion cut date.[3]

[2] An endogenous number of rotation cycles could be imposed without changing any of the paper's results. Moreover, because our interest is in the sequence of harvest dates given a number of timber harvests, rather than on the number of timber harvests itself, we assume two rotation cycles to make the problem more tractable and easier for interpretation. In addition, given discounting and the long production period in forestry, the impacts of increases in the alternative use rent are likely more important on initial rotation lengths. Even fast growing trees species are characterized by a long production period. For example, the native Eastern cottonwood - the fastest growing tree in North America- has rotations of ten years and the Eucalyptus in Northern California has rotation periods between nine and twelve years. Thus, assuming that land is converted to residential use after two rotation periods when there is strong urban growth pressure seems to us not an unrealistic assumption.

[3] A rotation length is a cutting cycle that is, the interval between harvests.

Stumpage prices (i.e. timber price net of harvest cost) (p) and planting costs (c) are constant over time and $v(t)$ represents a strictly concave production function of wood per unit of land as a function of the age of the current stand. Initial planting costs equal c_0 .

Households

Households, all of whom are identical, earn income $y(t)$ at time t. Income increases over time according to $y(t) = y(0)e^{\mu t}$, with $y(0)$ income at $t = 0$ and $\mu > 0$.

Preferences are given by a strictly quasi-concave utility function $U(l, Q, \psi O)$, where l is consumption of land, Q is consumption of a numeraire nonland good, O denotes nearby protected open space.[4] The parameter $0 \leq \psi \leq 1$ measures the degree to which benefits from nearby open space are accessible to households.

The household's budget constraint is given by $Q + lR + Z = y(t)$, where Z denotes commuting costs to the nearest urban center and R is land rent per unit of land. For simplicity, we assume that the price of the numeraire nonland good is normalized to unity.

2.2. Residential Land Rents

[4] One special form of protected open is a greenbelt, which is a large parcel of land in and around cities where urban development is totally prohibited through zoning, or public ownership, easement or development restriction. Greenbelts provide several environment benefits such as noise and air pollution abatement, climate amelioration biodiversity, watershed protection and wildlife habitats. In our analysis we assume that nearby protected open space is exogenous. This allows us to discuss in a tractable way the impacts of nearby protected areas on development decisions and forest management practices.

Substituting for Q using the budget constraint, households choose l to maximize $U(l, y(0)e^{ut} - Z - Rl, \psi O)$. The first-order condition for this problem is given by

$$MRS_{Q,l} = \frac{U_l(l, y(t) - Z - Rl, \psi O)}{U_Q(l, y(t) - Z - Rl, \psi O)} = R \tag{1}$$

where $MRS_{Q,l}$ stands for the marginal rate of substitution between the composite good and the lot size.

From (1) we obtain the uncompensated demand for land conditional on R as

$$l(y(0), \mu, Z, R, \psi, O, t) \tag{2}$$

Substituting (2) back into $U(l, y(0)e^{ut} - Z - Rl, \psi O)$ yields the indirect utility function $U(y(0), \mu, Z, R, \psi, O, t)$. Land rent is determined via the open-city assumption, under which the time path of utility is given by an exogenous function $\overline{U}(t)$. For simplicity we assume that $\overline{U}(t)$ is constant over time and equal to $\overline{U}$.[5]

$$U(y(0), \mu, Z, R, \psi, O, t) = \overline{U} \tag{3}$$

Equation (3) implicitly defines the residential bid land rent function as

$$R(y(0), \mu, Z, \psi, O, \overline{U}, t) \tag{4}$$

The residential bid land rent function (4) represents the maximum amount a household is willing to pay for a unit of land located Z miles from a CBD and a set of neighborhood characteristics (ψ, O) at time t if he is to receive utility $\overline{U}$.

[5] Considering an increasing but exogenous path for the utility, $\overline{U}(t)$, would not change any of our conclusions. In this case, $R_t = \frac{U_Q \mu y(t) - \overline{U}_t}{U_Q l}$ and an $R_t > 0$ requires that income is increasing sufficiently rapidly relative to utility.

Inserting (4) into (2), yields the optimal residential land consumption conditional on t as

$$l(y(0),\mu,Z,\psi,O,\overline{U},t) \tag{5}$$

3. The Private Landowner Behaviour

To establish a benchmark for evaluating the effects of development restrictions on forest management practices, consider first the unregulated problem.

3.1. Unregulated Equilibrium

When forestland is converted to residential use immediately after the second harvest, the landowner receives forest rents before land is developed and residential land rents after the land is converted to residential use. Thus, a landowner chooses a forest management plan $\{T, D\}$ that maximizes

$$\begin{aligned} V(T,D) &= \overline{L}\left\{-c_0 + \left[pv(T)-c\right]e^{-iT} + pv(D-T)e^{-iD}\right\} + \\ &+ \overline{L}\left\{\int_D^{+\infty} R(y(0),\mu,Z,\psi,O,\overline{U},t)e^{-it}dt - Se^{-iD}\right\} \end{aligned} \tag{6}$$

while taking into account that residential bid rents are given by (4) and that development is constrained by the parcel size, that is, $nl(y(0),\mu,Z,\psi,O,\overline{U},D) \le \overline{L}$, where n represents the number of identical residential lots of size $l(y(0),\mu,Z,\psi,O,\overline{U},D)$ and i is the relevant discount rate. For simplicity we assume that the constraint on total land availability is always binding. This implies that if the parcel is converted to residential use at $t = D$, it is developed with intensity

$$n(y(0),\mu,Z,\psi,O,\overline{U},\overline{L},D)=\frac{\overline{L}}{l(y(0),\mu,Z,\psi,O,\overline{U},D)} \tag{7}$$

Let $\{T^*,D^*\}$ represent the landowner's optimal management plan in the absence of land use regulations. After simplifying, the necessary conditions for an interior maximum at $\{T^*,D^*\}$ can be written as

$$V_T=0 \Leftrightarrow pv_t(T)+ic=ipv(T)+pv_t(D-T)e^{-i(D-T)} \tag{8}$$

$$V_D=0 \Leftrightarrow pv_t(D-T)-ipv(D-T)=R(y(0),\mu,Z,\psi,O,\overline{U},D)-iS \tag{9}$$

at $\{T^*,D^*\}$.

The second-order conditions can be expressed as

$$V_{TT}=\overline{L}e^{-iT}\left\{pv_{tt}(T)-2ipv_t(T)+i^2\left[pv(T)-c\right]\right\}+\overline{L}pv_{tt}(D-T)e^{-iD} \tag{10}$$

$$V_{DD}=\left\{pv_{tt}(D-T)-2ipv_t(D-T)+i^2pv(D-T)-R_t(D;\cdot)+i\left[R(D,\cdot)-iS\right]\right\}\overline{L}e^{-iD} \tag{11}$$

$$|H|=V_{TT}V_{DD}-V_{DT}V_{TD} \tag{12}$$

where $|H|$ represents the determinant of the Hessian matrix and by Young's theorem $V_{TD}=V_{DT}=p\left[iv_t(D-T)-v_{tt}(D-T)\right]\overline{L}e^{-iD}$. If $\{T^*,D^*\}$ is a maximum, then $V_{TT}<0$, $V_{DD}<0$ and $|H|>0$ at $\{T^*,D^*\}$ must be satisfied. Given that $v(t)$ is strictly concave it follows that $V_{TT}<0$ and $V_{DD}<0$. We assume nevertheless that condition $|H|>0$ holds so that $\{T^*,D^*\}$ is a global maximum. Given that $v(t)$ is strictly concave it also follows that $V_{DT}=V_{TD}>0$, implying that regeneration and conversion cuts are complements in the land profit function V.

Economic interpretation of the first-order conditions is as follows. Equation (8) defines the optimal condition for the first timber harvest. The left-hand side of equation

(8) is the marginal benefit from waiting one more year. The marginal benefit consists of the extra amount of money earned because of the larger stand volume from the first timber crop plus the gain from postponing the payment of planting costs. On the right-hand side is the marginal cost of waiting one more year. The cost of waiting comprises the forgone interest returns from harvesting immediately plus the foregone discounted marginal revenue product from the next harvest.

Condition (9) is the optimal conversion cut condition which says that the parcel should be converted to residential use when the net benefit of postponing conversion one year equals the net cost from postponing conversion. The net benefit includes the present value of the gain in stumpage value from added timber growth net the interests forgone from delaying second harvest timber revenues one year. The net cost represents the discounted value of residential land rent at time D net the switching costs savings that accrue from postponing the switch to residential use one year.

Note that equations (8) and (9) show that the conversion cut date decision has a direct bearing on the decision of the first regeneration cut date, that is, on the harvest age for the first crop of trees. Therefore, any policy that regulates development timing or the intensity of development will also influence forest management decisions. In addition, because preserved open space creates a positive amenity which gets capitalized into housing bid land rents, policies that preserve open space can affect the likelihood of development of nearby parcels and thus, forest management activities.

Solving (8) and (9) for $\{T^*, D^*\}$ yields the optimal first harvesting date and the optimal conversion date, respectively, as

$$T^*(y(0), \mu, Z, \psi, O, \overline{U}, S, c, p, i) \tag{13}$$

$$D^*(y(0),\mu,Z,\psi,O,\overline{U},S,c,p,i) \quad (14)$$

and the optimal rotation lengths satisfy the following condition:[6]

$$D^*-T^* \underset{<}{\overset{>}{=}} T^* \text{ if } R(.,D^*)-iS \underset{>}{\overset{<}{=}} pv_t(D^*-T^*)e^{-i(D^*-T^*)}-ic \quad (15)$$

According to (15) the optimal harvest lengths increase (decrease) over time if the opportunity cost of delaying the first harvest ($pv_t(D^*-T^*)e^{-i(D^*-T^*)}-ic$) is higher (lower) than the opportunity cost of delaying the second harvest ($R(.,D^*)-iS$). If both opportunity costs are the same, then rotation lengths do not change over time. Yet, as we will show next, this is not the Faustmann solution since the parcel does not stay in commercial forestry in perpetuity.

Finally, evaluating (4), (5) and (7) at $t = D^*$ yields the optimal residential bid land rent, the optimal residential land consumption and the optimal intensity of development at the optimal conversion date, respectively, as

$$R^*(y(0),\mu,Z,\psi,O,\overline{U},S,c,p,i) \quad (16)$$

$$l^*(y(0),\mu,Z,\psi,O,\overline{U},S,c,p,i) \quad (17)$$

$$n^*(y(0),\mu,Z,\psi,O,\overline{U},S,c,p,i,\overline{L}) \quad (18)$$

3.2. Forestry in Perpetuity versus Developable Forestland

Faustmann Model

When there is no switch from commercial forestry to residential use, the landowner chooses the regeneration cut date, T, in order to maximize the bare land value for forestry

[6] Using the first order conditions (8) and (9) and by concavity of $v(t)$ we obtain result (15).

$$V^F(T) = \overline{L}\{-c_0 + [pv(T) - c]e^{-iT} + \sum_{j=1}^{+\infty}[pv(T) - c]e^{-iT(1+j)}\}$$
$$= \overline{L}\left\{-c_0 + \frac{pv(T) - c}{e^{iT} - 1}\right\} \tag{19}$$

The solution to this problem is the well know Faustmann regeneration cut date, T^F, where T^F satisfies the following equilibrium condition:[7]

$$pv_t(T) = i(pv(T) - c) + i\frac{pv(T) - c}{e^{iT} - 1} \tag{20}$$

According to equation (20) it is optimal to cut a stand when the timber gains from delaying harvest compensate for the financial opportunity cost of leaving the trees standing plus the value lost from delaying all future rotations, captured by the rental value of the site. The Faustmann rotation is *ceteris paribus* shorter, the higher the timber price and interest rate and the lower the planting costs.[8]

We show in the appendix that

$$D^* - T^* < T^F\ ,\ T^* < T^F \text{ and } D^* < 2T^F \tag{21}$$

Thus, if there is the possibility to switch from forestry to a more valued alternative use in the future, a forest landowner will not adopt the Faustmann solution. As shown in (15) the optimal rotation lengths can be increasing, decreasing or constant over time. However, (21) shows that, no matter the case, both rotations lengths will always be shorter than Faustmann rotation lengths. Whenever urban rents are increasing over time, the landowner finds it more profitable to have shorter harvest lengths because the relative opportunity cost of later harvests will have increased.

[7] Note that we start our problem with bare ground and the fact that the interest rate, stumpage prices and site productivity are constant implies that all harvesting lengths are the same. Thus, the landowner's objective function can be written just as a function of T.

[8] For a comparative static analysis of the Faustmann model see Hartwick and Olewiler (pp. 345-347, 1998).

The choice of converting after two rotation periods

The optimality of our results so far is contingent on the number of rotations. However, if it's optimal to develop the land after two harvesting cuts then the following condition must be met:

$$\overline{L}\int_{0}^{+\infty} R(y(0),\mu,Z,\psi,O,\overline{U},t)e^{-it}dt < V^{F}(T^{F}) < V(T^{*},D^{*}) \tag{22}$$

Increasing income over time ensures that the gross returns to development are also rising over time. This in turn implies that forest land will eventually be developed at some future time, even if at time $t=0$ forestry rents per unit of land exceed the residential rent that is, $\int_{0}^{+\infty} R(y(0),\mu,Z,\psi,O,\overline{U},t)e^{-it}dt < \frac{V^{F}(T^{F})}{\overline{L}}$. Condition (22) also suggests that the value of future timber harvest plus the value of future conversion to residential use, discounted to the present, is higher than the value of an immediate land use change. We assume that the income growth rate, μ, is such that (22) is met.

4. Land Use Policies

Many local governments in the United States have responded to the excessive conversion activity in suburban and ex-urban areas by implementing policies to preserve land in farmland and forestry or by enacting regulations to slow the pace of development.

Open space conservation policies such as timber harvesting regulations, conservation easements, purchase or transfer of development rights and land taxes to fund purchases of open space have been used to preserve open space in the outskirts of cities and metropolitan areas.

Local governments have also used minimum-lot size zoning (MLZ) to retain forested areas. The reasoning is that large lots preclude use for strictly residential purposes and encourage food and fiber production on the land.[9]

In this section we examine the impacts on forest management decisions of an increase in adjacent preserved open space and of two growth management policies. The growth management policies consist of a development timing restriction in the form of a growth moratorium and a zoning ordinance through a minimum lot size requirement.

4.1 Adjacent Preserved Open Space

It is shown in the appendix that D^* and T^* are both decreasing functions of nearby protected open space, O, and therefore an increase in adjacent preserved open space speeds the landowner´s planned conversion time and decreases the planned first rotation period. Formally, we have that

$$\frac{dT^*}{dO} = \frac{-R_O^* e^{-iD^*}\bar{L}V_{TD}}{|H|} < 0, \qquad \frac{dD^*}{dO} = \frac{R_O^* e^{-iD^*}\bar{L}V_{TT}}{|H|} < 0 \tag{23}$$

where $R_O^* = \dfrac{U_O^*}{U_Q^*}\dfrac{1}{l^*} > 0$ and represents the amenity effect of an increase in nearby open space. The amenity effect represents a spatial dynamic effect that results from the positive capitalization of preserved open space into nearby residential rents, given a certain level of income (that is, given D^*). Because the amenity effect raises the value of the alternative use to forestry, it creates an incentive to anticipate the conversion cut date.

[9] For example, along with phased development inside the UGB, counties in Oregon, USA are given the authority of zoning rural lands for exclusive farm use and forest conservation outside the UGB. In addition, Oregon designates rural residential zones with 3-5 acre minimum lot sizes outside the UGB.

A remark is nevertheless in order. The total impact of a marginal change in O on the optimal conversion cut date can also be written as

$$\frac{dD^*}{dO} = \frac{D_R^* R_O^*}{1 - D_R^* R_t^*} < 0 \tag{24}$$

where $R_t^* = \frac{\mu y(0) e^{\mu D^*}}{l^*} > 0$ and $D_R^* < 0$.

Equation (24) allows us to better disentangle the dynamic effects at play when there is an increase in O. Note that if $R_t^* = 0$, the denominator of (24) decreases and the landowner plans a shorter conversion time than would be planned with $R_t^* > 0$. Moreover, the amenity effect, R_O^*, is the sole source of change in the optimal regeneration and conversion cut dates. This is also the only effect at play in spatial models of land use conversion (Wu and Plantinga (2003), Wu (2006)).[10]

On the other hand, when income increases over time, there is a temporal dynamic effect operating through the induced change in income from earlier conversion ($D_R^* R_t^*$) that partially offsets the amenity effect from an increase in O. For a given amount of nearby protected open space, a decrease in the optimal conversion cut date, D, is associated with a lower income level and lower residential bid rents. This in turn creates an incentive to push conversion into the future.

Hence, the net impact on the conversion cut date depends on the magnitudes of these two countervailing dynamic effects. The unambiguous signs of (23) and (24) suggest

[10] The short-run amenity-effect associated with large quantity of government-preserved open space attracting more development to the unrestricted portions of a community has also been identified in empirical studies (see for example Roe, Irwin, and Morrow-Jones (2004)).

nevertheless that the amenity effect is more important than the temporal dynamic income effect. Thus, the net effect of an increase in nearby preserved open space is to speed the landowner´s conversion cut time and to decrease the regeneration cut date of unzoned forestland parcels. However, our results also suggest that the timing of conversion need not be immediate as static models of land use conversion show since the rate of land use change (that is, the rate of conversion to residential use) is slower when households' income rises over time.

In addition, the increase in O will lead to changes in R^*, l^* and n^*. The total impact on optimal residential land rents can be decomposed into the amenity and the temporal dynamic effects such that

$$\frac{dR^*}{dO} = R_O^* + R_t^* \frac{dD^*}{dO} \gtrless 0 \tag{25}$$

The sign of the expression (25) is not immediately apparent since the two dynamic effects run in opposite directions. After some manipulations it is shown that the amenity effect dominates the temporal dynamic effect so that the sign of (25) is unambiguously positive.

$$\frac{dR^*}{dO} = \frac{R_O^* V_{TD}\, p\left[iv_t(T^*) - v_{tt}(T^*)\right]e^{-iT^*}\overline{L}}{|H|} > 0 \tag{26}$$

The net impact of an increase in O is thus to increase residential land rents of nearby parcels. When income is constant over time, the total impact of O on R^* is stronger and just given by the amenity effect.

Since the sign of (26) is unambiguously positive, it also follows that

$$\frac{dn^*}{dO} = -\frac{\overline{L}}{l^{*2}}\frac{dl^*}{dO} > 0 \text{ as } \frac{dl^*}{dO} = \eta\frac{dR^*}{dO} < 0 \tag{27}$$

where $\eta = \left(\frac{\partial MRS}{\partial l}\right)^{-1} < 0$ is the slope of the appropriate income-compensated (constant-utility) demand curve.[11]

The relationships in (27) show that the planned density of development is higher when nearby preserved open space increases because households tradeoff lot size for an increase in nearby preserved open space. However, the planned density of development under $\mu > 0$ is lower than the constant-income density of development, that is,

$$\left.\frac{dn^*}{dO}\right|_{\mu>0} = -\frac{\overline{L}}{l^{*2}}\eta\left[R_O^* + R_t^*\frac{dD^*}{dO}\right] < -\frac{\overline{L}}{l^{*2}}\eta R_O^* = \left.\frac{dn^*}{dO}\right|_{\mu=0} \tag{28}$$

The intuition behind (28) is as follows: on the one hand, an increase in nearby preserved open space decreases the demand of residential lot size because households close to preserved open space do not need a large plot to enjoy the benefits from open space. As a result, the number of residential subdivisions increases because more lots of smaller size fit in the parcel of size $\overline{L}$. When income is constant over time, $\mu = 0$, this represents also the total effect on the optimal intensity of development of a marginal increase in O. On the other hand when $\mu > 0$, a countervailing dynamic effect emerges. Note that when land is converted earlier, households' income level is smaller since $y_t > 0$. To the extent that an increase in O anticipates conversion then households are not willing to pay as much for the increase in O and thus, to substitute as much nearby preserved open space for residential lot size. Hence, in the presence of rising income, development intensity is actually lower when there is an increase in nearby preserved

[11] Note that η is negative given the convexity of indifference curves and *MRS* is given by the left-hand side of equation (1).

open space.[12] Our results thus show that considering only the spatial dynamic amenity effect of an open space conservation policy will bias the results on development intensity toward a more compact land use change.

The above comparative static results have an interesting policy implication. By purchasing open space in residential areas, local governments and conservation agencies may be able to protect more land from development than just the open space parcel itself. But if preserved open space is likely to skew choice towards low-density development, then conservation policies may fail to mitigate low density in urban development or urban sprawl.[13] A better understanding of the extent to which consumers are willing to substitute open space for lot size over time is therefore an essential element to designing policies that preserve open space by increasing housing density. While this issue clearly deserves further examination, it is beyond the scope of this paper.

4.2 Growth Moratorium

Suppose that an unanticipated growth control policy is imposed at time zero, $t = 0$. Moreover, this policy takes the form of a growth management timing ordinance in which

[12] Formally, the total impact of an increase in O on the optimal residential lot size can be decomposed as follows: substituting (25) into $\frac{dl^*}{dO} = \eta \frac{dR^*}{dO}$ and simplifying the expression yields $\frac{dl^*}{dO} = l_O^* + \eta R_t^* \frac{dD^*}{dO} = \underbrace{l_O^*}_{-} + \underbrace{\eta R_y^* \mu y\big|_{D^*} \frac{dD^*}{dO}}_{+}$. Therefore, when $\mu = 0$, $\frac{dl^*}{dO} = l_O^*$ as discussed earlier.

[13] Our theoretical result is consistent with the empirical findings of Lewis et al. (2009). The authors examine the effects of shoreline zoning restrictions and public conservation land on the amount and spatial configuration of land development across a fast-growing lake system in the northern forest region of Wisconsin. The overall conclusion of this study is that local open space conservation policies may reduce the rate of growth in residential development density. The underlying explanation in Lewis et al. (2009) is that open space and parcel size are complements in the land value function.

the local government announces that each parcel of undeveloped land is not allowed to be developed until date $\overline{D}$, where $D^* < \overline{D} < \infty$. After $\overline{D}$, the policy will no longer apply.

The landowner's strategy under this regulation is to choose a forest management plan in order to maximize (6) taking into account $D \geq \overline{D}$. Let $\{\hat{D}, \hat{T}\}$ represent the landowner's planned strategy in the presence of a growth moratorium. In the appendix, we show that under a binding growth moratorium

$$\hat{D} = \overline{D} > D^* \text{ and } \hat{T} > T^* \tag{29}$$

According to (29) the landowner's best strategy is to convert his land to residential use as soon as it is allowed. This implies that a growth moratorium delays the conversion cut date. In addition, this policy will also lengthen the first rotation period and thus delay the first regeneration cut. Further, the planned density of development under a growth moratorium ($\hat{n}$) is higher than the unregulated case density since demanded density for developed land is rising over time, that is,

$$\hat{n} > n^* \text{ as } \hat{l} < l^* \tag{30}$$

since $l_t = \eta R_t < 0$ and $R_t > 0$.

Next we consider how lengthening the development moratorium (when it is imposed) affects the landowner's planned strategy. The impacts of this regulation on the regeneration cut date, conversion cut date and density of development are given, respectively, by:

$$\frac{d\hat{T}}{d\overline{D}} = \frac{-\hat{V}_{T\overline{D}}}{\hat{V}_{TT}} > 0 \tag{31}$$

where $\hat{V}$ represents the maximum present value of the developable land parcel with the moratorium in place.

$$\frac{d\hat{D}}{d\overline{D}} = 1 > 0 \tag{32}$$

$$\frac{d\hat{n}}{d\overline{D}} = -\frac{\overline{L}}{\hat{l}^2}\frac{d\hat{l}}{d\overline{D}} > 0 \text{ as } \frac{d\hat{l}}{d\overline{D}} = \eta\frac{d\hat{R}}{d\overline{D}} < 0 \tag{33}$$

The above comparative statics reveal that a longer development moratorium delays the planned development pace, increases the planned regeneration cut date and increases the planned development density. In the limit, when $\overline{D} \to +\infty$, the landowner's problem becomes the traditional Faustmann case with $\overline{T} = T^F$ since land will be perpetually used for timber production.

4.3 Minimum-Lot-Size Zoning (MLZ)

Suppose now that the local government imposes at $t = 0$ a minimum-lot-size on which homes can legally be built. Under this regulation, households face a restriction establishing that $l \geq \bar{l}$ when maximizing their utility subject to their budget constraint.

If it is the case that the most profitable lot size at time $D*$ is not prohibited by law, that is, $\bar{l} < l*$, then MLZ would not be binding and the regulated and the unregulated equilibriums would be the same. On the other hand, the landowner´s parcel size puts an upper bound on the lot size that can be offered to households. If the legal minimum is above this feasible maximum (that is, $\bar{l} > \overline{L}$), bid rents are zero and the value of the alternative use to forestry is nil because that parcel cannot be developed under the current regulation. In this case, the parcel will be perpetually used for timber production and the landowner adopts the Faustmann management solution.

Next, we focus our discussion on the case where the policy constraint is binding, $\bar{l} > l^*$, and the legal minimum is below the parcel´s size, $\bar{l} < \bar{L}$. However, before proceeding further, it is convenient at this point to draw attention to an intermediate result that provides useful interpretations when examining the impacts of a binding MLZ on forest management decisions.

MLZ and Development Rent

As written, equation (4) describes rents from development at time t if there is no lot-size constrained by the government. Let $t = D^*$. Then

$$U(l, y(0)e^{uD^*} - Z - Rl, \psi O) = \overline{U} \tag{34}$$

implicitly defines residential development rent at D^* as a function of lot size

$$R(y(0)e^{uD^*}, Z, \psi O, \overline{U}, l) \tag{35}$$

where for a given D^* (that is to say a given income level $y(D^*)$)

$$\left.\frac{\partial R}{\partial l}\right|_{D^*} \quad > \quad (<) \quad 0 \quad \text{as} \quad R - \frac{U_l}{U_Q} \quad < \quad (>) \quad 0 \tag{36}$$

To understand the implications of (36), observe first that the expression $R = U_l / U_Q$ can change sign at most once (from positive to negative) as l increases. Let l' denote the critical value at which the expression changes from positive to negative. At l', $R = U_l / U_Q$. In addition, equation (35) is a continuous function on the interval $[l_1, l_2]$ where $R(l_1, D^*) > 0 > R(l_2, D^*)$. This also suggests that there is a $l'' \in [l_1, l_2]$ such that $R(l'', D^*) = 0$, implying that current income ($y(D^*)$) is not enough to afford such a large residential lot size. Thus, function (35) is bell-shaped with the logical constraint that $l > 0$.

Given (1) and the fact that $t = D^*$, the lot size that maximizes (35) is also the optimal unregulated lot size, that is, $l' = l^*$. Therefore, if the MLZ constraint is binding it must be the case that $\bar{l}$ lies above l', which implies $\bar{l} > l^*$ and

$$\left.\frac{\partial R(\cdot, D^*)}{\partial l}\right|_{l=\bar{l}} < 0 \qquad (37)$$

Two remarks are now in order. First, our result (37) shows that the unconstrained development rent is actually higher than the constrained development rent examined at $t = D^*$, $R(l^*, D^*) > R(\bar{l}, D^*)$. As we increase the stringency of zoning and move further away from the most profitable lot size at time D^*, development rent decreases and the value of developable forestland is also lower, $V(T^*, D^*, l^*) > V(T^*, D^*, \bar{l})$. However, this result assumes that the landowner will not adjust his planned cut dates in face of a MLZ constraint. Second, our result (36) holds for any value of D and therefore, in particular, for $D = D^*$. This is equivalent to saying that there will be a whole family of such profiles, each with a different optimum l', which is determined entirely by the income level at each point in time, $y(D)$. Thus, for each point in time (or income level), the shape of the function describing the relationship between development rent and lot size is the same regardless of which lot size is expected to be the most profitable in the future.

When the conversion cut date is endogenous and feeds back into households' income, development residential rent in the presence of MLZ at the conversion cut date is best described as

$$R(y(0)e^{uD(R(\bar{l}))}, Z, \psi O, \bar{U}, \bar{l}) \qquad (38)$$

Landowner's response to the MLZ

Let D^{mlz} and T^{mlz} denote the landowner's planned conversion cut date and the planned regeneration cut date under the MLZ policy. We show in the appendix that

$$\text{if } l^* < \bar{l}\text{, then } D^{mlz} > D^* \text{ and } T^{mlz} > T^* \tag{39}$$

In this case, a minimum lot size zoning policy slows down conversion of forestland into residential use and protects (even if just temporarily) open space when compared to the unregulated case. Yet, this policy also produces larger residential lots overall since $\bar{l} > l^*$ and lower-density development than would be planned without the regulation, $n^{mlz} < n^*$.

Increasing the stringency of the policy (when it is imposed and assuming that $\bar{l} < \bar{L}$ is satisfied) results into

$$\frac{dT^{mlz}}{d\bar{l}} = -\frac{\bar{L}R_{\bar{l}}e^{-iD^{mlz}}V_{TD}^{mlz}}{\left|H^{mlz}\right|} > 0 \tag{40}$$

$$\frac{dD^{mlz}}{d\bar{l}} = \frac{\bar{L}R_{\bar{l}}e^{-iD^{mlz}}V_{TT}^{mlz}}{\left|H^{mlz}\right|} > 0 \tag{41}$$

$$\frac{dn^{mlz}}{d\bar{l}} = -\frac{\bar{L}}{\bar{l}^2} < 0 \tag{42}$$

where $R_{\bar{l}} = \dfrac{\partial R(\cdot, D^{mlz})}{\partial \bar{l}}$, V^{mlz} represents the value of developable forestland under MLZ and $\left|H^{mlz}\right|$ is the determinant of the Hessian matrix under MLZ.

According to the above comparative statics, the landowner's optimal response to an increase in the binding lot-size restriction is to push the planned conversion cut date forward and postpone the planned regeneration cut date. Further, planned development density decreases since residential lot sizes are bigger under this policy and the landowner's parcel size is fixed at $\bar{L}$. If a very large lot size is imposed such that $\bar{l} > \bar{L}$, then a MLZ policy can actually stop the residential development of a parcel. In this case deforestation does not occur and the landowner will maximize the present value of timber revenues by adopting the Faustmann solution, as in (20).

We also show in the appendix that

$$\frac{dR^{mlz}}{d\bar{l}} = R_{\bar{l}} \frac{V_{TD}^{mlz}\left[ipv_t(T^{mlz}) - pv_{tt}(T^{mlz})\right]e^{-iT^{mlz}}\bar{L}}{\left|H^{mlz}\right|} \underset{<}{\overset{>}{-}} 0 \quad \text{as} \quad R_{\bar{l}} \underset{<}{\overset{>}{-}} 0 \tag{43}$$

The sign of (43) depends entirely on the sign of $R_{\bar{l}}$. Therefore, like (35), the residential development rent function (38) has an inverted-U shape. If MLZ is binding then $R_{\bar{l}} < 0$ and the total impact of increasing minimum lot-size is to decrease the return of the alternative use, that is, residential development rents.

How Do our Results Relate to Existing Empirical Results?

Our findings are consistent with a very recent paper on minimum lot size rules on development in urban fringe communities (Magliocca et al. (2012)). Magliocca et al. (2012) use a simulation economic agent-based model of land and housing markets to examine the effects of large-lot zoning on land conversion, land prices and density of new development in a hypothetical exurban area. The study shows that a 2-acre minimum lot size zoning encourage sprawl by keeping newly developing region in low-density development, whereas larger lot size requirements (for instance a 5-acre minimum lot size) result in more contained development. Lichtenberg, Tra and Hardie (2007) also found that minimum lot size zoning increased the average size of building lots and reduced the number of building lots in each subdivision, especially in subdivisions with public sewer access, confirming earlier findings that zoning reduces density (Moss (1977), Pasha (1996), McConnell, Walls and Kopits (2006)). Previous empirical studies from the agricultural economics literature (Irwin and Bockstael (2002), Carrion-Flores and Irwin (2004)) also confirm that if a lot size restriction is set high enough, a rural parcel either cannot or will not be developed for residential use.

5. Conclusions

The purpose of this paper is to provide a theoretical framework for determining the approximately optimal regeneration and conversion cut dates when urban rents vary over time. By relaxing the assumption that the return from the alternative use is constant over time, we create the possibility of switching from forestry to residential use at some point in the future. Moreover, our model allows the optimal harvest length to vary over time even if stumpage prices and regeneration costs remain constant. Within this framework, we examined how adjacent preserved open space and development constraints affect the private forester´s decisions. Because the rental value of developed land is endogenously determined we are able to disentangle several indirect dynamic effects from land use policies, which have interesting policy implications.

Our results show that an increase in nearby preserved open space speeds the landowner´s conversion cut time and decreases the regeneration cut date of unzoned forestland parcels. It also increases residential bid land rents, decreases residential lot sizes and raises development density. Yet, all those impacts are smaller in magnitude when households' income is rising over time. Moreover, when the temporal dynamic effect of land use policies is taken into account, preserved open space can actually lead to low-density development of undeveloped land in the unzoned area, even though development density is higher than density under the unregulated case.

Quantitative estimates of the relative values of residential lot size and open space are essential to making informed policy and planning decisions regarding zoning, urban growth boundaries and similar initiatives (McConnell and Walls (2005)). However, our results suggest that a better understanding of the temporal dynamic of the values attributable to open space and lot size is important to designing policies that preserve open space by increasing housing density.

We also find that both a binding development moratorium and a binding minimum-lot-size policy can postpone regeneration and conversion cut dates and thus help to protect open space even if only temporarily. However, the policies do not have the same effects on development density of converted forestland. While the former leads to high-density development, the latter encourages low-density development.

The model presented here assumes that the landowner's decisions are taken in a deterministic environment. Future work could examine how regeneration and conversion cuts change when residential rents are driven by uncertainties in the housing market. An additional stochasticity that could be modeled is policy uncertainty. In our analysis we assume that the zoning regime is fixed. However, zoning regimes may vary in the future according to a set of probabilistic expectations. Finally, while down-zoning could reduce land prices because it eliminates certain development rights, it could also increase the price of vacant land because it provides a higher level of amenity and fiscal protections to the neighborhood within which the developable parcel sits. So another avenue of research could be to develop a single unified framework that incorporates these endogenous offsetting effects of large-lot zoning on forest management practices.

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Appendix: Analytical Derivations[14]

Deriving (21)

If it is optimal to convert the parcel to residential use at time $t = D^*$, it has to be the case that rent in residential use exceeds the forestry rent forgone plus the opportunity cost of the capital needed to convert the land net the savings from not incurring planting costs

$$R(D^*,.) > i\frac{pv(T^F) - c}{e^{iT^F} - 1} + iS - ic \tag{A1}$$

From (9) and (20), while using (A1) we have that $pv_t(D^* - T^*) - ipv(D^* - T^*) > pv_t(T^F) - ipv(T^F)$ and from concavity of $v(t)$ it follows that $D^* - T^* < T^F$. This in turn implies that $pv_t(D^* - T^*)e^{-i(D^* - T^*)} > pv_t(T^F)e^{-iT^F}$. From (8) we can easily obtain $pv_t(T^*) - ipv(T^*) + ic > pv_t(T^F) - ipv(T^F) + ic$. Finally, again from concavity of $v(t)$, $T^* < T^F$. Since $D^* - T^* < T^F$ and $T^* < T^F$ it follows that $D^* < T^F + T^* < 2T^F$.

Deriving Equations (23)

Differentiating (3) with respect to *O* yields

$$R_O = \frac{U_O}{lU_Q} > 0 \tag{A2}$$

Totally differentiating (8) and (9) with respect to *T*, *D* and *O* and dividing the equations by *dO* we get

$$\begin{aligned} \overline{L}V_{TT}\frac{dT}{dO} + \overline{L}V_{TD}\frac{dD}{dO} &= -V_{TO}\overline{L} \\ \overline{L}V_{DT}\frac{dT}{dO} + \overline{L}V_{DD}\frac{dD}{dO} &= -V_{DO}\overline{L} \end{aligned} \tag{A3}$$

By applying the Cramer Rule while taking into account (A2), $V_{DO} = -R_O e^{-iD}\overline{L} < 0$, $V_{TD} > 0$, $V_{TT} < 0$, and $|H| > 0$ yields (23).

[14] A more detailed version of the analytical appendix can be made available by the authors upon request.

Deriving (26)

Differentiating (3) with respect to t yields

$$R_t = \frac{\mu y(0)e^{\mu t}}{l} > 0 \tag{A4}$$

By applying the Cramer Rule to (A3) we get $\frac{dD^*}{dO} = \frac{-V_{DO}V_{TT}}{|H|}$. Totally differentiating (3) with respect to R and O yields (25). Finally, substituting $\frac{dD^*}{dO} = \frac{-V_{DO}V_{TT}}{|H|}$, (A2) and (A4) while taking into account that $v(t)$ is concave, $V_{TD} > 0$, $|H| > 0$ and simplifying the expression, yields (26).

Deriving (27)

By differentiating (1) and (3) with respect to t, and simplifying we get

$$\frac{\partial l}{\partial t} = \frac{1}{\frac{\partial MRS}{\partial l}} \frac{dR}{dt} < 0 \text{ where } \eta = \frac{1}{\frac{\partial MRS}{\partial l}} < 0. \tag{A5}$$

Differentiating (1) and (3) with respect to O, we get

$$\frac{\partial l}{\partial O} = \eta \frac{\partial R}{\partial O} < 0. \tag{A6}$$

Totally differentiating (5) with respect to O and using $\frac{dD^*}{dO} = \frac{-V_{DO}V_{TT}}{|H|}$, (A5), (A6), and simplifying, gives

$$\frac{dl^*}{dO} = \eta R_O^* \left[1 + \frac{R_t(D^*)e^{-iD^*}\overline{L}V_{TT}}{V_{DD}V_{TT} - (V_{TD})^2} \right] = \frac{\eta R_O^* \left[(V_{DD} + R_t(D^*)e^{-iD^*}\overline{L})V_{TT} - (V_{TD})^2 \right]}{V_{DD}V_{TT} - (V_{TD})^2} =$$

$$= \frac{\eta R_O^* V_{TD}\left[-pv_{tt}(T^*) + ipv_t(T^*) \right] e^{-iT}\overline{L}}{V_{DD}V_{TT} - (V_{TD})^2} = \eta \frac{dR^*}{dO} < 0 \tag{A7}$$

Finally, totally differentiating (7) with respect to O while using (A7) we can easily obtain (27).

Deriving (29)

Evaluating (9) at $D > D^*$ and $T = T^*$, from strict concavity of $v(t)$, and (A4) evaluated at $D > D^*$, we obtain that $V_D(D,T^*) > 0$ for any $D > D^*$. Therefore, it is optimal to postpone conversion. However, from (8), if conversion is postponed, then $V_T(D,T^*) > 0$ with $D > D^*$, as the regeneration and conversion cuts are complements ($V_{DT} > 0$). Therefore, by strict concavity of $v(t)$, the regeneration cut is also optimally postponed to some $t = T > T^*$. Since $t = \overline{D} > D^*$ is the closest possible time period at which conversion is allowed, conversion will optimally occur at $\hat{D} = \overline{D} > D^*$, and the regeneration cut will take place at $\hat{T} > T^*$.

Deriving (31), (32), and (33)

Assuming the constraint $D = \overline{D}$ is binding in (8), and totally differentiating (8) with respect to T and $\overline{D}$, we get $\frac{d\hat{T}}{d\overline{D}} = \frac{-\hat{V}_{T\overline{D}}}{\hat{V}_{TT}} > 0$, where $\hat{V}_{T\overline{D}} > 0$ and $\hat{V}_{TT} < 0$ by strict concavity of the private landowner's growth moratorium problem. Also, $\frac{d\hat{D}}{d\overline{D}} = 1 > 0$.

Given (7) and (31), $\frac{d\hat{l}}{d\overline{D}} < 0$, implying that $\frac{d\hat{n}}{d\overline{D}} = -\frac{\overline{L}}{l^{*2}}\frac{d\hat{l}}{d\overline{D}} > 0$.

Derivation of (39)

From (9), we have that

$$V_D = (-R(D,...,\bar{l}) + iS - ipv(D-T) + pv_t(D-T))e^{-iD} \tag{A8}$$

which is zero at l^* for $D = D^*$ and $T = T^*$. Evaluating (A8) at $\bar{l} < \overline{L}$, where $l^* < \bar{l} < l''$, we obtain that $V_D(D^*,T^*)|_{\bar{l}} > 0$ since $R(D^*,...,\bar{l}) < R(D^*,...,l^*)$. Therefore, it is optimal to postpone conversion. Moreover from (8), as D is increased from D^*, $V_T(D,T^*)|_{\bar{l}} > 0$, as the regeneration and conversion cuts are complements ($V_{DT} > 0$). Hence, by strict concavity of $v(t)$, T has to increase from T^*. Therefore, there exists a pair $(D^{mlz}, \mathrm{T}^{mlz})$ such that $D^{mlz} > D^*$, and $T^{mlz} > T^*$, for which $V_D(D^{mlz}, T^{mlz})_{|\bar{l}} = V_T(D^{mlz}, T^{mlz})_{|\bar{l}} = 0$. Hence, $T^{mlz} > T^*$ and $D^{mlz} > D^*$.

Deriving (40) and (41)

Assuming that MLZ is binding, we may obtain the corresponding system of the first-order conditions (FOCs) of the private landowner's problem in that context. Totally differentiating the FOCs yields

$$\begin{aligned} \bar{L}V_{TT}^{mlz}dT + \bar{L}V_{TD}^{mlz}dD &= -V_{T\bar{l}}^{mlz}\bar{L}d\bar{l} \\ \bar{L}V_{DT}^{mlz}dT + \bar{L}V_{DD}^{mlz}dD &= -V_{D\bar{l}}^{mlz}\bar{L}d\bar{l} \end{aligned} \tag{A9}$$

and applying Cramer's rule to the system of equations (A9) yields

$$\frac{dT^{mlz}}{d\bar{l}} = \frac{V_{D\bar{l}}^{mlz}V_{TD}^{mlz}}{\left|H^{mlz}\right|} \quad \text{and} \quad \frac{dD^{mlz}}{d\bar{l}} = \frac{-V_{D\bar{l}}^{mlz}V_{TT}^{mlz}}{\left|H^{mlz}\right|} \tag{A10}$$

where $V_{D\bar{l}}^{mlz} = -R_{\bar{l}}e^{-iD}\bar{L}$ and $\left|H^{mlz}\right| = V_{DD}^{mlz}V_{TT}^{mlz} - \left(V_{TD}^{mlz}\right)^2 > 0$. As $\bar{l} > l^*$, $R_{\bar{l}}(\bar{l}, D^*) < 0$, as shown in (37). Thus, it follows that (40) and (41) are both positive.

Derivation of (42) and (43)

When MLZ is binding, $n^{mlz} = \frac{\bar{L}}{\bar{l}}$. Given that $l^* < \bar{l}$, it also follows that $n^* > n^{mlz}$.

Totally differentiating $n^{mlz} = \frac{\bar{L}}{\bar{l}}$ with respect to $\bar{l}$ yields (42).

By evaluating (38) at $T = T^{mlz}$ and $D = D^{mlz}$ (thus obtaining $R^{mlz}(.)$) and totally differentiating with respect to $\bar{l}$ while substituting (41) and (A4) evaluated at $\bar{l}$, we get

$$\frac{dR^{mlz}}{d\bar{l}} = R_{\bar{l}} + R_t(\bar{l}, D^{mlz})\frac{dD^{mlz}}{d\bar{l}} = R_{\bar{l}}\frac{V_{TD}^{mlz}\left[ipv_t(T^{mlz}) - pv_{tt}(T^{mlz})\right]e^{-iT^{mlz}}\bar{L}}{\left|H^{mlz}\right|} \tag{A11}$$

Finally, since $v(t)$ is concave, $\left|H^{mlz}\right| > 0$ and $V_{TD}^{mlz} > 0$, it follows that the sign of (A11) depends on the sign of $R_{\bar{l}}$. Hence, given (37), we get (43).