Urban Deforestation and Urban Development

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Maria A. Cunha-e-Sá* , Sofia F. Franco*, and Renato Rosa

NOVA School of Business and Economics, Universidade Nova de Lisboa

NOVA School of Business and Economics, Universidade Nova de Lisboa

FEEM, Italy

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* Mailing Address: Campus de Campolide P-1099-032, Lisboa, Portugal. Emails: mcunhasa@novasbe.pt, sfranco@novasbe.pt. Phone Number: 351-213801600.

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Abstract

This paper has developed a model of a single forest owner operating with perfect foresight in a dynamic open-city environment that allows for switching between alternative competing land uses (forest and urban use) at some point in the future. The model also incorporates external values of an even-aged standing forest in addition to the value of timber when it is harvested. Timber is exploited based on a multiple rotation model a la Faustmann with clear-cut harvesting. In contrast to previous models, our alternative land use to forest land is endogenous. Within this framework, we study the problem of the private owner as well as that of the social planner, when choosing the time to harvest, the time to convert land and the intensity of development. We also examine the extent to which the two-way linkage between urban development and forest management practices (timber production and provision of forest amenities) contributes to economic efficiency and improvements in non-market forest benefits. Finally, we consider policy options available to a regulator seeking to achieve improvements in efficiency including anti-sprawl policies (impact fees and density controls) and forest policies such a yield tax. Numerical simulations illustrate our analytical results.

Keywords: Deforestation, Urban Development, Forest Management Practices, Anti-Sprawl Policies, Yield Taxes

1 Introduction

Urban forests can play a major role in climate regulation by reducing levels of carbon dioxide and other greenhouse gases (GHG) in the atmosphere (Nowak and Crane (2002) [12]). Trees reduce atmospheric carbon dioxide (CO2) through carbon sequestration and reducing GHG emissions by conserving energy used for space heating and cooling. Forests also provide a range of other ecological goods and services such as biodiversity and watershed protection and amenity benefits (recreation and scenic beauty).

Deforestation and suburban sprawl have substantially changed and fragmented our landscape. Almost 1 million acre of private forestland were lost to development each year from 1992 to 1997, with many important timber-producing states in the US —California, Florida, Georgia, North Carolina, and

Washington— experiencing the greatest losses (Natural Resources Conservation Service (2001)). Projections suggest that another 26 million acres will be lost to development by 2030 (Alig and Plantinga (2004) [1]). Such disturbance of the land can change the atmospheric concentration of CO2 as well as affect climate. Conversion of land from forest to urban uses is now associated with a greater average increase in minimum and maximum temperatures than rural land conversions (Halle et al. (2008) [5]). Environmental costs of suburban sprawl also include air pollution from increases in traffic congestion and losses of open space at the urban fringe (Kahn (2000) [8]).

When private forestland is developed, the market and nonmarket benefits it provides can be reduced or lost altogether. Market values for forestland are important to understanding financial issues affecting forestry, such as returns to timber production and development. Nonmarket values are important because they benefit society. Because nonmarket (social) benefits generally are not accounted for in market prices for land, it is up to public and private institutions to ensure that they are provided in sufficient quantity.

While the increasing economic importance of open space and forest amenities (Leggett and Bockstael (2000) [10], Tyrvainen and Miettinen (2000) [**?**], Irwin (2002) [7]) and the implications of nontimber benefits for harvesting within the traditional Faustmann framework (Hartman (1976) [6], Strang (1983), Max and Lehman (1988) [11], Englin and Klan (1990) [4]) are now well understood, the feedback effects between urban development and forest land changes are not.

In general, theoretical models of forest management practices do not account explicitly for the potential conversion of forest land to urban use over time. And, models of urban development (Brueckner (1990) [2], Capozza and Helsley (1989) [3], Turnbull (2002 [15], 2005 [16])) treat the alternative land use (agriculture or forest) as exogenous and do not examine endogenous interactions between forest management and development decisions.

However, the development of a framework to more fully exploit the interplay between urban development and deforestation may further reinforce the workings of emission reduction programs if co-benefits from land-based mitigation (e.g., carbon sequestration) are realized. The purpose of this paper is thus to offer a first step towards such framework. We also ask the following questions: What is the implication of forest land conversion over time for forest management practices? How do forest management activities affect the pace of urban development? Do anti-sprawl policies affect forest management practices and deforestation? What is the impact of timber tax policies on the pace of urban development?

Building on the framework of Capozza and Helsley (1989) [3] and Englin and Klan (1990) [4], we develop a model of a single forest owner operating with perfect foresight in a dynamic open-city environment that allows for switching between competing land uses at some point in the future. The model incorporates external values of an even-aged standing forest in addition to the value of timber when it is harvested. Timber is exploited based on a multiple rotation model à la Faustmann with clear-cut harvesting. Forest conversion reduces the service flow of the standing forest, but this opportunity cost is not reflected in the landowner's development decision. Land, housing and input markets are competitive. Land conversion to urban use entails an exogenous cost.

With this setup, we study the problem of the private owner as well as that of the social planner, when choosing the time to harvest, the time to convert land and the intensity of development. We also examine the extent to which the two-way linkage between urban development and forest management practices (timber production and provision of forest amenities) contributes to economic efficiency and improvements in non-market forest benefits. Finally, we consider policy options available to a regulator seeking to achieve improvements in efficiency including anti-sprawl policies (impact fees and density controls) and forest policies such a yield tax. Numerical simulations illustrate our analytical results and examine further the optimal rotation length, the optimal time to switch between land uses and the maximized returns to land use with switching.

Our analysis reveals several interesting findings. Private development can be more rapid than the development that a social planner would carry out. Higher opportunity rents along the equilibrium growth path slow development of the forested land. The source of the slope of our marginal benefit of waiting to develop is nevertheless forest management practices and not demanded density, as our development costs do not depend on structural density. For higher utility or transportation costs along the equilibrium growth path, development pace also slows down. For higher income along the equilibrium trajectory, development pace accelerates. Because nontimber amenities are not taken into account, the forest owner fails to account for the environmental costs of development, which include current nontimber benefits and future nontimber benefits from forest land due to irreversibility of development. As a result, forest land conversion may occur sooner than what is socially optimal. The forest landowner also does not take into account nontimber benefits when making harvesting decisions, which leads to inefficient rotation cycles.

We also find that the interdependence of irreversible urban development and forest amenities generates an option value that arises even in the absence of uncertainty. The size of this option value depends on the balance between the stream of forest externalities up to the harvest time (for each rotation) and current externalities. The sign of the option value depends on the shape of the externalities function. The interplay between the rotation and conversion dates also depends on the shape of the forest externality function. If urban trees provide less externalities as they grow older, the earlier the land is converted, the greater the incentive to reduce the rotation date in order to anticipate revenues from timber and to increase the benefits from non-timber externalities.

In contrast, if externalities grow with the age of the tree, the impact on the optimal rotation date depends on what effect dominates, timber or non-timber benefits. To increase benefits from timber exploitation, trees should be cut earlier, while to increase the production of non-timber externalities, it is optimal to postpone harvest. If it is the case where non-timber externalities are very strong, then the urban area can grow inwards.

Finally, we show that the optimal pace of land development can be implemented as a private solution through impact fees that internalize the present value of forest amenities and irreversibility costs of development. Development fees represent an additional cost of development and will in general slow the development pace. Efficiency can also be improved with a density restriction. Density restrictions affect urban development by reducing the value of land in urban use. These land use policies also affect rotation date decisions given the interdependency between conversion and rotation dates.

The paper is organized as follows. Section 2 provides the assumptions of an economic model that represents clear-cutting decisions for a single even-aged stand in the presence of an endoegnous alternative land use. In Section 3, we solve the problem of the social planner and present the socially optimal rotation date and conversion date. Section 4 examines the unregulated equilibrium, that is, the problem of the private forest landowner. In Section 5, discusses the policy implications, and, finally, Section 6 offers conclusions. Technical derivations and Figures are presented in the Appendix.

2 The Analytical Model

This section presents the assumptions of the analytical model. Building on the framework of Capozza and Helsley (1989) [3] and Englin and Klan (1990) [4], this section develops a model of a single, price-taking forest owner operating with perfect foresight in a dynamic open-city environment that allows for switching between competing land uses at some point in the future. The model also incorporates multiple rotations and external values of a standing forest in addition to the value of timber when it is harvested. Urban development once undertaken is assumed to be irreversible.

2.1 Assumptions

Assume that a private forest landowner has one even-aged forest stand located x miles from a central business district (CBD), an that this is the current best use of his land. The forest provides a flow of valuable services while standing in addition to the value of timber when it is harvested. Timber is exploited based on a multiple rotation model *à la* Faustmann. There are two land use options for this land: maintain it as forest or convert it to urban use. Forest conversion reduces the service flow of the standing forest, but this opportunity cost is not reflected in the landowner's development decision. In addition, the forest owner also does not take into account non-timber benefits in timber rotation decisions. Land, housing and input markets are competitive markets.

2.1.1 Forest Land Rent

We define joint production of benefits from the forest as the sum of timber and non-timber benefits. If trees are planted at $t = 0$ and harvested at $t = T$, then t represents the age of the forest and T is both the length of the rotation cycle $[0, T]$ and the harvesting age or rotation date. At harvesting moments, the forest owner immediately plants the next age class. The sequence of jump points, jT, with $j = 1, 2, ..., K$, $K \leq \infty$, determines the stand rotation or harvesting periods. All rotation cycles, have the same length T .

Timber Benefits

Timber prices, p, and harvesting and replanting costs, c are assumed to be constant over time. Following the Faustmann-Hartman framework, replanting activities follow immediately after harvest. Let $v(T)$ represent the volume of commercially valuable timber biomass on a forest stand over the rotation age jT, which is assumed to be a strictly concave function. The present value at time 0 of the financial reward from harvesting the stand at jT is given by:

$$[pv(T) - c]e^{-rjT}, j = 1, 2, ..., K \tag{1}$$

where r is the discount rate and $pv(T)-c$ is the value of timber net of harvesting and replanting costs, which is constant over rotation cycles.

Non-Timber Benefits

As the harvest is clear-cut, non-timber services are a function of the age of the trees. Let $F(t)$ denote the value of the amenity and environmental services flowing from the standing forest of age t. A value of $\frac{dF(t)}{dt} > 0$ is generally assumed, indicating that a well established forest provides more non-timber benefits than a young forest. However, this assumption has been challenged by Englin and Klan (1990) [4] and Swallow et al. (1990) [14] who argue that non-timber benefits may follow any time path, depending on the externalities considered. In the analysis that follows, the only restriction placed on $F(t)$ is differentiability. The present value of amenity services from the forest stand under a single harvest cycle of length T is given by:

$$\int_0^T F(t)e^{-rt}dt \tag{2}$$

Multiple-Rotation Forest

In the case of several harvests, the present value of a multiple-rotation forest is given by the sum of the net present value of harvest revenue and the present value of amenity services over all rotations:

$$\left[\sum_{j=1}^{K} e^{-rjT}\right](pv(T) - c) + \left[\sum_{j=1}^{K} e^{-r(j-1)T}\right]\int_0^T F(t)e^{-rt}dt \tag{3}$$

2.1.2 Urban Land Rent

When the forest is harvested, the landowner decides whether to keep the land in forest use or convert it to urban use. Once the stand has been converted to urban use it will be maintained under this use forever. Conversion to urban use entails a cost of D per unit of land. T_D represents the conversion date, which satisfies $(j-1)T < T_D < jT$, with $j = 2, ..., K$, $K \leq \infty$. The latter assumption implies that conversion of land into urban use can occur within a rotation cycle or at the rotation date. For example, if $j = 2$, timber is harvested at the end of the first rotation period, $t = T$, and is harvested again at $t = T_D$, $T < T_D < 2T$, when land is converted into urban use. Note that when $j = 1$, conversion occurs at T_D and not even one rotation cycle is completed. If the rotation date and the conversion date coincide then, $t = T = T_D$. A similar reasoning can be used to any other value of j.

Housing Rent Function

A representative urban resident enjoys utility from housing (q) and a composite consumption good (g). Households preferences are represented by a strictly quasi-concave utility function $U(g, q)$. For simplicity we set the price of the composite good equal to1 and housing demand is also fixed at one unit. The household budget constraint is given by $g + b = y(t) - z(t)x$, where x denotes distance to the CBD, $z(t)$ commuting costs per mile at time t, b is the rental price of housing and $y(t)$ denotes income earned at time t.

Housing bid rent is determined via the open-city assumption, under which the time path of utility is given by an exogenous function $U(t)$. Substituting for g using the budget constraint, the representative urban resident achieves utility $\overline{U(t)}$ when b satisfies the equation:

$$U(y(t) - b - z(t)x, 1) = \overline{U(t)} \tag{4}$$

Equation (4) implies that in equilibrium, utility must be identical regardless where a urban resident lives, otherwise, some urban residents will have an incentive to move. Equation (4) also implicitly defines the housing bid rent function as:

$$b(t,x) = b(y(t) - z(t)x, 1, \overline{U(t)}) \tag{5}$$

Equation (5) describes the maximum rent per unit floor area that a household is willing to pay at distance x from the CBD if it is to receive a given level of utility $\overline{U(t)}$.

A key assumption is that y, k and $\overline{U(t)}$ vary over time in a way that ensures that $b_t > 0$, so that housing bid rents rise over time. This requires that disposable income $y(t) - z(t)x$ is increasing sufficiently rapidly (or falling sufficiently slowly) relative to utility.[1] Moreover the housing bid rent is a decreasing function of distance from the CBD, $b_x = -z(t) < 0$.

Urban Land Rent Function

Houses are immutable and do not depreciate once constructed. Housing floor space is produced with capital and land according to a strictly concave, constant returns to scale production function. The intensive form of the production function is written $h(S)$, where S is capital per unit of land, referred to as structural density, and h satisfies h[redacted] > 0 and h[redacted] < 0. Conversion to urban use entails a cost of D per unit of land, which we assume to be constant over time.[2] At each point in time, t, the landowner chooses the amount of structural density S to maximize the gross profit per unit of land at location x, while taking into account (4):

$$b(y(t) - z(t)x, 1, \overline{U(t)})h(S) \tag{6}$$

[1] Differentiating (4) with respect to t and rearranging yields $b_t = [y_t - z_t x] - \frac{\overline{U}_t}{U_g}$.

[2] Conversion costs could be modelled as a convex function, $D(S)$, with $D^{/} > 0$ and $D^{//} \geq 0$. The assumption $D^{//} = 0$ here reduces notation clutter and changes none of the results.

S is chosen to maximize (6), satisfying the first-order condition:

$$b(y(t) - z(t)x, 1, \overline{U(t)})h_S = 0 \tag{7}$$

The density condition (7) requires that more density should be added up to the point where the value of incremental gross profit from greater density equals zero. The solution to (7) gives structural density as a function of t and x, $S(t,x) = S(y(t) - z(t)x, 1, \overline{U(t)})$.

Finally, urban land rent, denoted $R(t,x)$, is equal to profit per unit of land:

$$R(t,x) = b(y(t) - z(t)x, 1, \overline{U(t)})h(S(t,x)) \tag{8}$$

By the envelope theorem, the derivatives of the urban land rent function $R(t,x)$ are given by:

$$\begin{aligned} \frac{dR}{dt} &= b_t h > 0 \\ \frac{dR}{dx} &= b_x h < 0 \end{aligned} \tag{9}$$

Differentiating (7), yields the derivatives of structural density with respect to time (t) and distance (x) as:

$$\begin{aligned} \frac{dS}{dt} &= -b_t h_S / b h_{SS} > 0 \\ \frac{dS}{dx} &= -b_x h_S / b h_{SS} < 0 \end{aligned} \tag{10}$$

Thus, urban land rent ($R(t,x)$) and structural density ($S(t,x)$) are decreasing with distance from the CBD and rising over time.

If the landowner has perfect foresight, the value at time 0 of converted land at location x equals the present value of anticipated urban land rents net the present value of conversion costs:

$$\int_{T_D}^{\infty} R(t,x)e^{-rt}dt - De^{-rT_D} \tag{11}$$

3 Optimal Conversion Date and Rotation Date

We first examine the problem of a social planner. Subsection 3.1 sets up the maximization problem for the social planner and subsection 3.2 derives the first-order conditions for the socially optimal choice of $T > 0$ and $T_D > 0$, given a K. [3] Subsection 3.3 examines how endogenous forest management decisions and pace of urban development influence each other. We also discuss how market and policy failures, such as environmental externalities, may create a bias towards excessive deforestation and excessive urban development and dicuss the policy implications. All mathematical derivations are provided in the Appendix.

3.1 The Social Planner Problem

The goal of a social planner is to choose the rotation date (T) and conversion date (T_D) to maximize the present value of land at location x, assuming that forest is the current best use for that plot. As before, the problem is solved in two steps. First, conditional on the number of rotation cycles (K), and for each K, $V(T, T_D \mid K)$ is maximized. Then, the optimal solution will be associated to the value of K for which $V(.)$ is maximum.

The present value of land is given by the sum of land rent while in forest use which includes the value of non-timber benefits from the standing forest and the timber value for the stand over multiple rotations and the land rent once land is converted to urban use less the cost of converting the parcel (see the Appendix for details):

[3] The second-order conditions for a pair $(T, T_D) > 0$ to be a local maximum are given by: $V_{TT} < 0$, $V_{T_D T_D} < 0$ and $V_{TT}V_{T_D T_D} - \left[V_{TT_D}\right]^2 > 0$. All mathematical derivations are presented in the Appendix.

$$V(T,T_D \quad | \quad K) = \underbrace{e^{-rT_D}(pv(T_D - KT) - c) + e^{-rT}(pv(T) - c)\frac{1 - e^{-rKT}}{1 - e^{-rT}}}_{I} \tag{12}$$

$$\underbrace{+e^{-rKT}\int_0^{T_D - KT} F(t)e^{-rt}dt + \frac{1 - e^{-rKT}}{1 - e^{-rT}}\int_0^{T} F(t)e^{-rt}dt +}_{II}$$

$$\underbrace{+\int_{T_D}^{\infty} R(t,x)e^{-rt}dt - De^{-rT_D}}_{III}$$

Term I in (12) is the present value at time 0 of the net revenues from timber exploitation at the end of each rotation. Term II is the present value of non-timber benefits from a standing forest up to the date of conversion. Term III is the present value at time 0 of future urban rents from the date of conversion onward net the present value of conversion costs at time T_D. Note that nontimber values, $F(t)$, and timber stock, $v(t)$, are both a function of the age of the trees. The age of the trees is identified as the calendar time minus the time at planting, that is, $t = \widetilde{T} - jT$, where $\widetilde{T} \in [jT, ..., T_D, ..., (j+1)T]$, where $j = 1, ..., K$. Once T and T_D are chosen, the social planner chooses the K for which $V(T, T_D, K)$ is maximum.[4]

3.2 *The Social Optimum*

Socially Optimal Conversion Date

Differentiating (12) with respect to T_D and rearranging yields the first order

[4]Note that in the above problem it is required that $KT \leq T_D < (K+1)T$. Since the maximization problem is performed for each K, T_D can only be within the range defined by the interval above. We may then rewrite that inequality as follows: $T_D = (K+\mu)T$, where $0 \leq \mu < 1$. Thus, the problem can be separated in two problems, that is, for $\mu = 0$, and for $0 < \mu < 1$. In the first case, the problem is only a function of one variable, T, for each K. The second problem can be stated as a Lagrangean maximization problem with respect to μ, T , and λ, the shadow price associated with the constraint $\mu < 1$. Ultimately, the problem as presented in the text can be shown to be equivalent to these two problems, as long as the solution is interior, that is, $KT < T_D < (K+1)T$. See the Appendix for details.

condition for the socially optimal conversion date as:

$$R(T_D, x) = rD + F(T_D - KT) + pv_t(T_D - KT) - r\left[pv(T_D - KT) - c\right] \quad (13)$$

Condition (13) requires that the forest owner wait until the annualized cost of development, which is the opportunity cost of the capital invested in converting the land, rD, plus the opportunity cost of forest land equals land rent from developing the land, $R(T_D, x)$. The opportunity cost of forest land consists of the environmental value during the period $(F(T_D - KT))$ plus the value of the timber growth over the period $(pv_t(T_D - KT))$ net the capital returns form investing the returns from harvested timber at time T_D, $(r\left[pv(T_D - KT) - c\right])$.
[5]

Land is converted to urban use only when the urban land rent (left-hand side of (13) is no less than the opportunity cost of development (right-hand side of (13)). If $T_D \to \infty$, then land is kept in forest use forever, as well as if it is optimal never to harvest $T \to \infty$. [6]

Socially Optimal Rotation Date

Differentiating (12) with respect to T and rearranging yields the first order condition for the socially optimal rotation period as:[7]

[5] The value of some non-timber benefits (e.g. recreational benefits) and other values such as watershed production, carbon storage and nonuse benefits such as option and existence values may depend on distance to the CBD, so that we would have $F(t, x)$. However, to simplify the discussion, in the following we assume that non-timber benefits do not depend on distance to the CBD and analyze only the case of $F(t)$.

[6] Note that $T_D \to \infty$ implies that $R(T_D, x) - rD < pv_t(T_D - KT) + F(T_D - KT) - r\left[pv(T_D - KT) - c\right]$.

[7] See Appendix.

$$
\begin{aligned}
pv_t((K+1)T-KT) \quad &= \quad \frac{r}{1-e^{-rT}}\left[pv((K+1)T-KT)-c\right]+\left[\frac{r}{1-e^{-rT}}\int_0^{(K+1)T-KT}F(t)e^{-rt}dt-F(\right. \\
&+\frac{rK}{1-e^{-rKT}}\left[\frac{pv_t(T_D-KT)(1-e^{-rT})e^{r(K+1)T}e^{-rT_D}}{r}-(pv((K+1)T-KT)\right. \\
&+\frac{rK}{1-e^{-rKT}}\left[\frac{F(T_D-KT)(1-e^{-rT})e^{r(K+1)T}}{r}-\int_0^{T_D-KT}F(t)e^{-rt}dt\right]e^{-rKT} \\
&+\frac{rK}{1-e^{-rKT}}\left[\int_0^{T_D-KT}F(t)e^{-rt}dt-\int_0^{(K+1)T-KT}F(t)e^{-rt}dt\right]e^{-r(K-1)T}
\end{aligned}
$$

Expression (14) can be interpreted as an optimal harvesting condition for the present model which includes multiple rotation cycles, non-timber externalities, an endogenous alternative land use and forest land conversion to urban use at some point in the future. Interpretation of this formula follows conventional lines, weighting the marginal gain from postponing the harvest one cycle against the marginal loss of postponement. However, because in our model it is possible to harvest the stand within a rotation cycle if land is converted to urban use, our optimal harvesting condition can be interpreted as a Faustmann-Hartman like equation that includes new elements, associated with the disturbance of the switch to urban use at time T_D.

The left-hand side of (14) is the marginal benefit of delaying the harvest. It consists of the increase in the value of timber if the clear-cutting of the stand is delayed one period.

The right-hand side of (14) is the opportunity cost of delaying the harvest and consists of five terms.The first two terms represent the costs of holding the trees. The first term is the income that could be earned if revenue from cutting the stand were invested at an interest rate r. It accounts for the interest rate on the numerator and for the multiple rotation aspect of any version of the Faustman formula on the denominator. The second term represents the "externality balance" found in the conventional Haustmann-Hartman framework (Hartman (1976) [6], Englin and Klan [4], Koskela and Ollikainen (2001) [9]), which compares the value of current non-timber benefits $(F((K+1)T - KT))$ versus a discounted value representing the future non-timber benefits associated with the growth of the next generation of trees after felling $(\frac{r}{1-e^{-rT}} \int_0^{(K+1)T-KT} F(t)e^{-rt}dt)$. The sign of this externality balance depends on the shape of the non-timber benefits function.

Finally, the third, forth and fifth terms on the right-hand side of (14) represent the opportunity cost of postponing future forest timber (third term) and non-timber (forth and fifth terms) benefits, if conversion to urban use is delayed by one instant. That is, the last tree terms represent the costs of holding the land in forest use. These additional terms state that the possibility of converting forest land to urban use at time $T_D < (K+1)T$ affects the decision on when to harvest the timber, that is, the optimal rotation date. These terms also state that the appropriate correction to the Faustmann-Hartmann equation when the forest owner switches to an alternative land use at some point in the future T_D is the present value of the net balance of timber and non-timber benefits associated with a standing forest for the planning horizon running from KT to $T_D < (K+1)T$.

At the optimal rotation age, the extra earnings from waiting one more period must equal the cost of holding the trees and the land in forest use.[8]

3.3 Pace of Urban Development

In this subsection we examine the pace of urban development with the aid of (13). Condition (13) implicitly defines the boundary between forest and urban use at time T_D, $\overline{x}(T_D, T)$. Thus, at $\overline{x}(T_D, T)$, the annualized forest land value

[8] *Forest Preservation* $(T \to \infty, T_D \to \infty, \partial V(T, T_D)/\partial T > 0$ and $\partial V(T, T_D)/\partial T_D < 0)$
If it is the case that non-timber benefits are sufficiently great and/or the value of the alternative use $(R(T_D, x))$ is very small (with $T_D \to \infty$) such that the following condition is satisfied[9]

equals the urban use opportunity cost:

$$F(T_D - KT) + pv_t(T_D - KT) - r\left[pv(T_D - KT) - c\right] = R(T_D, x) - rD \quad (24)$$

Socially Optimal Pace of Urban Development

To examine how the boundary of the urban area changes over time, we differentiate (24) with respect to T_D to obtain:

$$\frac{d\overline{x}}{dT_D} = \frac{-R_t + \{F_t(T_D - KT) + p\left[v_{tt}(T_D - KT) - rv_t(T_D - KT)\right]\}\left[1 - K\frac{dT}{dT_D}\right]}{R_x} >=< 0 \quad (25)$$

$$\frac{\left[R(T_D, x) - rD\right](1 - e^{-rT})e^{r(K+1)T}}{r} + \quad (18)$$

$$+\left[pv(T_D - KT) - c\right](1 - e^{-rT})e^{r(K+1)T} - \quad (19)$$

$$-(pv(T) - c) - \quad (20)$$

$$-\frac{pv_t(T_D - KT)(1 - e^{-rT_D})(1 - e^{-rT})e^{r(K+1)T}}{r} - \quad (21)$$

$$-\left[(1 - e^{rT})\int_0^{T_D - KT} F(t)e^{-rt}dt + \int_0^T F(t)e^{-rt}dt\right] \quad (22)$$

$$< \quad 0 \quad (23)$$

then the value of the forest increases the farther the harvest date is pushed into the future, and it is quite possible that it is optimal never to harvest.From (13) we get that $F(T_D - KT) = R(T_D, x) - rD - pv_t(T_D - KT) + r\left[pv(T_D - KT) - c\right]$. Inserting this equation into the forth term of (14) and noting that $T = (K+1)T - KT$ while manipulating the last three terms of equation (14) yields (**??**).

If $\frac{\partial V(.)}{\partial T} > 0$ then the optimal rotation age approaches infinity and preserving the existing forest for nontimber forest benefits provides the greatest land value. The reason is because the returns to natural forest management would be greater than the returns to plantation timber production and/or urban use. Of course, this assumes that mature trees would provide the greatest non-timber benefits and thus no effort is needed for replanting the stand for nontimber benefits only. In this case, it follows that:

$$V(0 < T < \infty, 0 < T_D < \infty) < V(T \to \infty, T_D \to \infty)$$

Joint Management of Forest with no Switching ($0 < T < \infty$, $T_D \to \infty$, $\partial V(T, T_D)/\partial T = 0$ and $\partial V(T, T_D)/\partial T_D > 0$)

In this case, there is an optimal T that ensures that the marginal benefits from managing the land for timber and nontimber benefits equals the marginal costs of holding the timber and land for sucessive rotations. The land would thus be kept in perpetuity in forest use like in the conventional Faustmann-Hartman model:

$$V(0 < T < \infty, 0 < T_D < \infty) < V(0 < T < \infty, T_D \to \infty)$$

with $R_t = \left[y_t - z_t x - \frac{\overline{U}_t}{U_g}\right] h > 0$. Moreover, whether the urban area expands onwards or inwards (towards the CBD) over time also depends on the interplay between rotation date and convertion date ($\frac{dT}{dT_D}$) (see the Appendix for further details):

$$\frac{dT}{dT_D} = \frac{-V_{TT_D}}{V_{TT}} = \frac{-rKpv_t(T_D - KT) + Kpv_{tt}(T_D - KT) + KF_t(T_D - KT)}{V_{TT}} >=< 0 \tag{26}$$

By (strict) concavity of $V(.)$, the denominator of (26), V_{TT}, is negative. By strict concavity of $v(t)$, the first two terms of the numerator, V_{TT_D}, are negative, while the sign of the third term depends on how nontimber benefits are related to the age of the trees. If the production of externalities is independent from the age of the trees, $F_t(.) = 0$, the optimal rotation period is the same as Faustmann's. In this case, only the present value of the land per hectare increases in the presence of externalities, without affecting the optimal rotation period, and$\frac{dT}{dT_D} > 0$.

If externalities grow with the age of the tree ($F_t(.) > 0$), the impact on the optimal rotation date depends on what effect dominates, timber or non-timber benefits from a standing forest. To increase benefits from timber exploitation trees should be cut earlier, while to increase the production of non-timber externalities, it is optimal to postpone harvest. If it is the case that non-timber externalities are very strong, dominating the timber components, then $\frac{dT}{dT_D}$ can be negative**.**

If trees provide less externalities as they grow older, that is, $F_t(.) < 0$, $\frac{dT}{dT_D}$ is positive. Therefore, the earlier the land is converted, the greater the incentive to reduce the rotation date in order to anticipate revenues from timber and to increase the benefits from non-timber externalities. As a result, the provision of externalities reinforce the effect from timber.

In order to interpret these results, we need to impose more structure on F.

Assuming that F is concave, then a high value for F_t corresponds to younger trees, that is, a low t, while a low value corresponds to older trees, that is, a large t. Moreover, the sign of $\frac{dT}{dT_D}$ is evaluated at $t = T_D - KT$, as it is clear from (26). In other words, what matters is what occurs in the interval between the time period at which the last rotation cycle ends and the time of conversion T_D. So, if $F_t(.) > 0$ and strong enough to dominate the timber terms, by concavity of $F(.)$ trees are young, so when T_D increases it is optimal to decrease T in order to enlarge that interval as much as possible to have older trees when they are cut for the last time, that is, when the land is irreversibly converted into urban land, T_D. This explains why $\frac{dT}{dT_D} < 0$ in this case. In contrast, if $F_t(.) > 0$ but not strong enough to dominate the timber terms, then trees are older. Therefore, if T_D increases, in order to shorten the interval, T has to increase. Therefore, trees will be younger when they are cut for the last time, before the plot is irreversibly converted to urban use, at T_D, thus, maximizing the benefits from timber exploitation. In fact, in this case, the benefits from timber exploitation dominate those from non-timber externalities.

In alternative, we could assume that F is convex. In that case, a low $F_t(.) > 0$ is associated with younger trees, while a large $F_t(.) > 0$ is associated to older trees. We could argue similarly, as the results do not change.[10] Finally, trees may provide less externalities as they grow older, that is, $F_t(.) < 0$. In this case, $\frac{dT}{dT_D}$ is always positive. Independently of the age of the trees, as T_D increases, it is optimal to shorten the interval before cutting for the last time implying that trees will be younger. Recall that benefits from non-timber exploitation reinforce benefits from timber exploitation.

There are several insights from examining equation (25). First, given that $R_x < 0$, equation (25) states that, *ceteris paribus*, rising non-timber benefits

[10] Likewise, if trees are old, then it optimal to enlarge the interval by decreasing T in order to take advantage of older trees. If trees are young, then it is optimal to shorten the interval by increasing T, in order to have younger trees.

level (F_t) will slow down the pace of land development, while rising urban residents' disposable income ($y_t - z_t x$) will increase the pace of land development.

Second, if it is the case where $p\,[rv_t(T_D - KT) - v_{tt}(T_D - KT)] = F_t$, the urban area expands onwards (from the CBD) over time due to the increase over time in urban land rents (R_t), as in Brueckner (1990) [2]. In fact, in this case, $\frac{dT}{dT_D} = 0$, and $\frac{d\overline{x}}{dT_D} = \frac{-R_t}{R_x} > 0$. Note also that when non-timber externalities are very strong, dominating the timber terms, $\frac{dT}{dT_D}$ will be negative and the urban area may grow inwards.

Thus, a key insight from our model is that changes over time in the opportunity cost of urban land affect development patterns and leapfrog development may occur at sites where the environmental and amenity services of forests are rising over time or when the marginal benefits from managing the land for timber and non-timber benefits outweights the marginal benefits from converting that plot of land to urban use.

Structural Density and Pace of Urban Development

Further insight into the optimal pace of urban development can be gained by examining (24) in the context of related models. Condition (24) shows that the optimal conversion or developing time is where the marginal benefit of developing at t equals the marginal cost. Differentiating (24) with respect to time (t) yields:

$$-prv_t(T_D - KT) + pv_{tt}(T_D - KT) + F_t(T_D - KT) = R_t(T_D, x) \tag{27}$$

The left-hand side of (27) represents the slope of the marginal benefit of waiting to develop, evaluated at $t = T_D - KT$, while the right-hand side represents the slope of the marginal cost of waiting to convert land into urban use, which can also be written as follows:

$$R_t(T_D, x) = \frac{dS}{dT_D}\frac{bh_{SS}h}{h_S} + \frac{(V_{T_DT})^2}{V_{TT}} \tag{28}$$

Thus, from (28) and (26) the impact of a marginal change in the optimal conversion date on the structural density, $\frac{dS}{dT_D}$, is given by:

$$\frac{dS}{dT_D} = -\frac{h_S(R_t + R_x \frac{d\bar{x}}{dT_D})}{bh_{SS}h} = \frac{h_S\left[-\frac{(V_{T_DT})^2}{V_{TT}} - p\{rv_t(T_D - KT) - v_{tt}(T_D - KT)\} + F_t(T_D - KT)\right]}{bh_{SS}h} \tag{29a}$$

with $h_{SS} < 0$, $b, h,$and $R_t > 0$. Because the sign of $\frac{d\bar{x}}{dT_D}$is ambiguous a priori, we cannot determine the impact of conversion date on structural density. Note from (29a) that the sign of $\frac{dS}{dT_D}$ depends on how nontimber benefits are related to the age of the trees $(F_t(.))$.

In contrast to the case where the opportunity cost of developed land (for example agricultural rent or forestry rent) is exogenous, the slope of our marginal benefit of waiting is not given by the slope of demanded density. When the opportunity cost of developed land is exogenous and constant over time, as in Turnbull (2005), the marginal benefit of waiting to develop a plot of land is upward (downward) sloped when the demanded density is rising (falling) over time. This occurs when the current best use has a lower (higher) structural density than a future best use. As the development time is postponed, the best use for that time entails greater (lower) structural density and hence the curve depicting development time and the best use at that time is upward (downward) sloped.

In our framework, the marginal benefit of waiting can also be upward or downward sloping. Note that the sign of the slope of the marginal benefit is given by the numerator of $\frac{dT}{dT_D}$. Therefore, $\frac{dT}{dT_D} > 0$ implies that the slope of the marginal benefit is negative, and vice-versa if $\frac{dT}{dT_D} < 0$. However, the underlying source of the slope of our marginal benefit of waiting is not demanded density but the return of land in its current use (forest) over time, as development costs are constant. As a result, our marginal benefit of waiting is only influenced by forest management practices (timber exploitation and nontimber amenities provision). Depending on the sign of this new term and on the magnitudes of the different components of the marginal benefit of waiting, we may have cases where the marginal benefit of waiting to develop is downward sloped when the demanded density is rising over time.[11] This obviously will have impact on the way regulations affect the use of land.

On the other hand, the forgone urban land rents represent the marginal cost of waiting. Since the demand for urban land is growing over time, this (annualized) return is rising over time and the marginal cost of delaying conversion is upward sloped in general. Any change over time in $\overline{U}(t)$, $z(t)$ and $y(t)$ changes housing bid rents and thus, urban land rents and the marginal cost of waiting.

The most profitable time to develop is thus when the marginal benefit and marginal cost of waiting are equal. Higher opportunity rents along the equilibrium growth path $(F(T_D - KT) + pv_t(T_D - KT) - r\left[pv(T_D - KT) - c\right])$ would slow development of the forested land so that the urban area is smaller at each point in time. For higher utility or transportation costs along the equilibrium growth path development pace also slows down ($\frac{\partial T_D}{\partial \overline{U}(t)} > 0$, $\frac{\partial T_D}{\partial z(t)} > 0$). For higher income along the equilibrium trajectory, development pace acelerates ($\frac{\partial T_D}{\partial y(t)} < 0$).

[11] Suppose that the cost of developing the land $(D(S))$ rises with greater structural density. In this case, our development timing condition is given by: $rD(S) + F(T_D - KT) + pv_t(T_D - KT) - r\left[pv(T_D - KT) - c\right] = R(T_D, x)$, where the left-hand side is the marginal benefit of waiting. Differentiating the marginal benefit yields: $rD_s S_t(T_D) + pv_{tt}(T_D - KT) + F_t(T_D - KT) - prv_t(T_D - KT)$, which in the case of Turnbull (2005) **??** takes the sign of S_t since the opportunity cost of developed land is exogenous and constant over time. However, in our framework the opportunity cost of land is endogenous, and changes over time according to $(pv_{tt}(T_D - KT) + F_t(T_D - KT) - prv_t(T_D - KT))$. Thus, the marginal benefit of delaying development depends not only on demanded density but also on the return of the opportunity cost of developed land.

4 *The Unregulated Equilibrium*

The unregulated equilibrium is examined next. In contrast to the social planner, the private forest landowner chooses the rotation date T and conversion date T_D to maximize the present value of land at location x, (12) , conditional on the number of rotation cycles (K), without taking into account the non-timber benefits of a standing forest (Term II equals zero).

Private Optimal Conversion Date

The first-order condition for the private optimal time of development, $T_D > 0$, given a K, is:

$$R(T_D, x) = rD + pv_t(T_D - KT) - r\left[pv(T_D - KT) - c\right] \tag{30}$$

A comparison of (30) with (13) shows that the private forest landowner does not take into account the environmental and amenity services from a standing forest when making his development decision ($F(T_D - KT) = 0$). For a given K and T, land is thus developed earlier than when it is socially optimal. Moreover, (30) also reveals that the pattern of land development under free market is inefficient because the boundary of the developed zone under the free market is suboptimal. As a result, the private forest landowner not only develops more than is optimal from a social perspective but is also more responsive to changes in economic conditions such as urban residents's disposable income.

Private Optimal Rotation Date

The first-order condition for the private optimal rotation time, $T > 0$, given a K, is:

$$\begin{aligned} pv_t((K+1)T - KT) &= \frac{r}{1 - e^{-rT}}\left[pv((K+1)T - KT) - c\right] + \\ &+ \frac{rK}{1 - e^{-rKT}}\left[\frac{pv_t(T_D - KT)(1 - e^{-rT})e^{r(K+1)T}e^{-rT_D}}{r} - (pv((K+1)T - KT)\right. \end{aligned}$$

A comparison of (31) with (14) shows that the forest owner's failure to account for all standing values also leads to a divergence between public and private rotation periods. For a given T_D and K, depending on the nature of the externalities (sign of F_t), the private rotation length can be lower or higher than the socially optimal one.

Moreover, the optimal adjustment of the harvesting time to a marginal change in the development time, evaluated at $t = T_D - KT$, which is given by:

$$\frac{dT}{dT_D} = \frac{-V_{TT_D}}{V_{TT}} = \frac{-rKpv_t(T_D - KT) + Kpv_{tt}(T_D - KT)}{V_{TT}} > 0 \qquad (33)$$

is always positive because of convexity of $v(.)$ and $V(.)$. This implies that the rotation and development decisions reinforce each other in the unregulated market. Thus, anything which decreases (increases) the development timing will shorten (lengthen) the optimal rotation. Recall that if T_D increases, in order to shorten the interval, T has to increase. Therefore, when trees are harvested at conversion time they are younger. This is in contrast to the social planner's case, in which the corresponding impact was ambiguous, depending on the balance between timber and the provision of environmental amenities.

Absent government policy, the private choices of T and T_D are thus inefficient because no market exists for services provided by the standing forest. A key policy insight from our results is that if we expect the benefits from urban forests to continue to be highly valued in the future, then government intervention may be required to create appropriate incentives for private landowners to preserve forest land today, even if alternative land use options, such as urban use, currently offer higher private present value returns.[12] In particular, the so-

[12] Alig and Plantinga (2004) [1] estimate the average present value of future returns of land in timber production for 473 counties in the southeastern United States at $415 per acre, compared to its value in residential housing at $36,216—land with a developed value nearly 90 times higher than its forest value. Developed values in the Pacific Northwest Westside are estimated at 111 times higher than forest values. This financial land-use hierarchy means that private forestry returns alone are unlikely to keep some land in forest when development is an option.

cial optimum involves two objectives, that is, to adjust both the conversion time and the rotation period. To achieve those targets, and implement the efficient solution, policy intervention is required.

Private Optimal Structural Density

Differentiating (30) with respect to time, t,yields:

$$R_t(T_D, x) = -rpv_t(T_D - KT) + pv_{tt}(T_D - KT) \tag{34}$$

The left-hand side of (34) is the slope of the marginal cost of waiting, which is positively sloped.

The right-hand side of (34) is the slope of the marginal benefit of waiting, which is always negatively sloped. Remember that the slope of the marginal social benefit of waiting can be either positive or negative depending on whether $\frac{dT}{dT_D} > 0$ or $\frac{dT}{dT_D} < 0$. The intuition underlying these results was explained in Section 3.

When $\frac{dT}{dT_D} > 0$, two cases may occur. Either $F_t > 0$ but it does not dominate the negative timber terms, or $F_t < 0$, reinforcing them. When comparing the slope of the marginal social benefit of waiting to that of the private one in absolute terms, we conclude that while in the former case the social one is lower, in the latter case it is higher, exchanging the relative positions (see Figs. 1a) and 2a)). Therefore, while in the former case the social planner solution is characterized by a larger T_D, and hence a larger T, in the latter case it is the opposite.

When $\frac{dT}{dT_D} < 0$, implying that $F_t > 0$ and strong enough to dominate the negative timber terms, the slope of the social marginal benefit is positive, while that for the private forest landowner is always negative. As a result, if forest amenities are strong enough, it is optimal from a social perspective to increase the optimal rotation which is traded-off against an earlier development time.

Given the marginal cost of waiting, depending on the relative positions of the marginal benefit curves, different outcomes may emerge. (see Figs. 3a), 4a)).

On the other hand, using (9) and (10), we obtain:

$$\frac{dS}{dt} = \frac{-R_t h_S}{h h_{SS} b} > 0$$

implying that the demanded density is rising over time. Therefore, the optimal structural density at T_D can be obtained from $S(T_D)$. From Section 3, we have that $S(T_D, \overline{x}(T_D)) = S(T_D) = S(y(T_D) - z(T_D)\overline{x}(T_D), 1, \overline{U}(T_D))$.

Finally, the marginal benefit of waiting to develop is negatively sloped while the structural density is positively sloped. This was never the case in Turnbull where the opportunity cost of the current land use is exogenous.

5 Policy Implications

Both governments and private conservation organizations intervene to correct "market failures" associated with loss of forestland as open space. Public policies and programs arise from the political process when enough voters become sufficiently concerned about open space lost to development (Wolfram (1981) [18]). This section explores the issue of how to design appropriate incentive schemes to induce the private forest landowner to make socially optimal decisions. We start by first exploring two kinds of price-based policies: a one time impact fee assessed at the time of development and a yield or unit tax on harvesting. We then examine how land-use regulations can also affect forest land preservation and forest management practices. Although land-use regulations usually are not enacted solely to protect open space, they all have open space implications and often garner widespread support among voters in rapidly growing places. Thus, we also examine a quantity-based instrument in the form of a zoning regulation that establishes a cap on the floor-area-ratio (FAR) density.

Each policy option is specified below.

Impact Fees

The land use planner can use a one time impact fee to affect both the pace of urban development and the forest rotation length. This fee or tax represents an additional cost of development to the private forest landowner and will in general slow the development pace. Because there is an interaction between the conversion date and the rotation date, an impact fee has also an indirect impact on the forest rotation length.

Let θ be the impact fee levied as a lump-sum tax. The first-order condition for the private forest landowner with respect to the conversion date T_D is now given by:

$$R(T_D, x) = r(D + \theta) + pv_t(T_D - KT) - r\left[pv(T_D - KT) - c\right] \tag{35}$$

Note that the first-order condition with respect to T is the same as before. A comparison of (30) with (35) shows that the private development timing condition is now modified only by the addition of the annualized development fee, $r\theta$, to the right hand side. This development fee increases the marginal benefit of waiting, thereby slowing the development pace.

By differentiating the system of first-order conditions with respect to T, T_D, and θ, and applying Cramer's rule, we get the impact that a marginal change in the impact fee level has on the conversion and rotation dates:

$$\frac{dT}{d\theta} = \frac{rV_{TT_D}}{D} > 0 \tag{36}$$

$$\frac{dT_D}{d\theta} = \frac{-rV_{TT}}{D} > 0 \tag{37}$$

where $D > 0$ and $V_{TT} < 0$ given strict concavity of $V(.)$. Also, $V_{TT_D} > 0$.

Equations (36) and (37) show that an impact fee discourages both deforestation and encourage longer rotations. Therefore, whenever it is optimal from a social perspective to increase both the rotation date and the conversion date, such an impact fee may implement the optimum. To determine the optimal impact fee, the social planner needs several pieces of information, including the amount of forest amenities and timber benefits lost per unit of development and over time. While timber information might be easy to get, information on nontimber benefits may be hard to get. In pratice, local governments can rely on zoning ordinances to regulate land use.

Fig. 1a) shows the marginal cost of waiting as well as the two marginal benefit curves, private and social. By concavity of $v(.)$, the slope of the private marginal benefit is negative. The slope of the social marginal benefit curve is negative, but lower in absolute value because $F_t > 0$, though not dominating. So, from a social perspective T_D should increase, as well as T. Note that in the presence of the impact fee, the private marginal benefit of waiting in Fig. 1a, for each T_D, and K, increases with T, that is, moves upwards, by concavity of $v(.)$, eventually crossing the marginal cost of waiting at the social optimum development time. Similarly, if $F_t < 0$, while keeping $\frac{dT}{dT_D} > 0$, a one-time lump-sum subsidy at the development time would give the appropriate incentive to implement the optimum (see Fig. 2a)).

If, as in Fig 4a), $F_t > 0$ and dominates, such that $\frac{dT}{dT_D} < 0$, in order to develop earlier, the optimal rotation period has to increase in order to increase the age of the trees at the development time, thus, taking advantage of the benefits generated by older trees. However, as the private landowners would decrease optimally the rotation period, the optimal solution from a social perspective cannot be implemented just with an impact fee. So, no interior solution exists in this case.

Yield Tax

Suppose that the land use planner levies a yield or a unit tax on harvesting. Let δ be the yield tax rate. The first-order conditions of the private forest owner are now given by:

$$R(T_D, x) = rD + pv_t(T_D - KT)(1-\delta) - r\left[pv(T_D - KT)(1-\delta) - c\right] \quad (38)$$

$$pv_t((K+1)T - KT)(1-\delta) = \frac{r}{1-e^{-rT}}\left[pv((K+1)T - KT)(1-\delta) - c\right] + \quad (39)$$

$$+\frac{rK}{1-e^{-rKT}}\left[\frac{pv_t(T_D - KT)(1-\delta)(1-e^{-rT})e^{r(K+1)T}e^{-rT_D}}{r} - (pv((K+1)T - KT)(1-\delta) - c)\right]e^{-rKT} \quad (40)$$

Differentiating the system of first-order conditions above yields the the impact of the yield tax on the private rotation age T and on the private development time, T_D as:

$$\frac{dT}{d\delta} = \frac{V_{T_D T_D}[G] - V_{TT_D}(pv_t(T_D - KT) - rpv(T_D - KT))}{D} \quad (41)$$

$$\frac{dT_D}{d\delta} = \frac{-V_{TT_D}[G] + V_{TT}(pv_t(T_D - KT) - rpv(T_D - KT))}{D} \quad (42)$$

where

$$G = (-e^{-T_D}K + e^{-rT}\sum)pv_t(T_D - KT) - \frac{re^{-rT}}{1-e^{-rT}}pv(T)\left[\frac{1-e^{-rKT}}{1-e^{-rT}} - Ke^{-rKT}\right] < 0$$

with $V_{TT_D} > 0, (pv_t(T_D - KT) - rpv(T_D - KT) > 0$, while $V_{TT} < 0$, $V_{T_D T_D} < 0$, and $D > 0$ by concavity. [13] . Note nevertheless that $\frac{dT}{d\delta}$ and $\frac{dT_D}{d\delta}$ must have the same sign since the private $\frac{dT}{dT_D}$ is always positive (see **??**). However,

[13] D represent the second-order Hessian of $V(.)$, which is positive by strict concavity. See Appendix.

the sign of (41) and (42) depends on the sign of its numerator, which cannot be unambiguosly obtained from the analytical model. As a result, we cannot determine a priori the impact of an yield tax on the rotation and conversion dates. In our simulations we examine the alternative cases that can emerge in the persence of an yield tax.

Zoning Regulation

Zoning regulation is perhaps the most commonly use approach to regulate land use in the United States. In this paper, we examine the impact of a floor-to-area ratio (FAR) restriction, that is, strutural density is regulated as a maximum allowed density. In this case, the zoning restriction will impose the social optimum for T_D, such that the optimal structural density is implemented when developing at the best use for that time period. Therefore, by imposing that constraint on the problem, the private landowner will solve for the corresponding optimal rotation period. Thus, the first-order conditions are similar to those shown above, in the unregulated case, that is, (31), and (34), evaluated at the social optimal development time.

Again, we also consider two cases: $\frac{dT}{dT_D} > 0$, and $\frac{dT}{dT_D} < 0$.

As $\frac{dT}{dT_D} > 0$ for the private landowner, if it is optimal to postpone the optimal development time from a social perspective, then, it has to be also optimal from a social perspective to increase the optimal rotation period. Hence, if $\frac{dT}{dT_D} > 0$ from a social perspective, and assuming that $F_t > 0$, the regulator may intervene by imposing a zoning regulation on the floor-area-ratio, in particular, by constraining the structural density to be the one associated to the optimal social conversion time T_D. Recall that the optimal social conversion time is greater than the private one, and that the demanded density is positively sloped, implying that the best use for that time entails greater structural density. Therefore, by forcing to postpone development from the private planned time T_D to T_D^* determines that, when the forested land is developed, it will be for a use with greater structural density than it would otherwise have been without intervention (see Fig 1a). At the same time the optimal rotation period will also increase, increasing the marginal benefit of waiting for each T_D, which moves the marginal private benefit curve upwards. Therefore, this instrument may be enough to implement the efficient solution from a social perspective. As well, this intervention will implement the optimal pattern of land development as the boundary of the developed zone will be the optimal from the social perspective, that is, $\overline{x}(T_D^*)$. See Fig. 1a).

If $F_t < 0$, while keeping $\frac{dT}{dT_D} > 0$, a similar case to the previous one is obtained, except that the marginal benefit curves have their relative positions reversed. Therefore, a zoning regulation imposing lower structural density than it would otherwise have been without intervention, will decrease the optimal rotation period, moving down the private marginal benefit curve. Eventually, the optimal solution will be implemented. See Fig. 2a).

In contrast, if$\frac{dT}{dT_D} < 0$, it is not possible to achieve the optimum, at least within the set of interior solutions. See Figs. 4a), and 4b).

6 Conclusions

This paper has developed a model of a single forest owner operating with perfect foresight in a dynamic open-city environment that allows for switching between alternative competing land uses (forest and urban use) at some point in the future. The model also incorporates external values of an even-aged standing forest in addition to the value of timber when it is harvested. Timber is exploited based on a multiple rotation model à la Faustmann with clear-cut harvesting. In contrast to previous models, our alternative land use to forest land (urban) is also endogenous.

Within this framework, we have examined the private and socially optimal rotation age and time of development of the forest land as well as the interplay between the conversion date and the rotation date. We found that changes over time in the opportunity cost of urban land affect development patterns and leapfrog development may occur at sites where the environmental services provided by forests are significant and increasing over time or when the marginal benefits from managing the land for timber and non-timber benefits outweigh the marginal benefits from converting that plot of land to urban use. Moreover, as the opportunity cost of the current use of the private land is endogenous, the private owner responds to changes in incentives by adjusting forest management practices as well as the development time. The interplay between the rotation and conversion dates depends nevertheless on the shape of the forest externality function. If urban trees provide less externalities as they grow older, the earlier the land is converted, the greater the incentive to reduce the rotation date in order to anticipate revenues from timber and to increase the benefits from non-timber externalities. In contrast, if externalities grow with the age of the tree, the impact on the optimal rotation date depends on what effect dominates, timber or non-timber benefits. To increase benefits from timber exploitation, trees should be cut earlier, while to increase the production of non-timber externalities, it is optimal to postpone harvest. If it is the case where non-timber externalities are very strong, then the urban area can grow inwards. Finally, we also show that the slope of the marginal benefit of waiting to develop may also depend on forest management practices, and not only on the structural density, in contrast to previous results in the literature, with implications for policymakers.

In the absence of government intervention, the forest owner considers only the cash flows from harvesting and selling timber and urban land rents when managing his forest. As a result, his forest management practices as well as his time of conversion are not socially optimal, resulting in too much deforestation and urban sprawl. Thus, we also examined in this paper the ability of anti-sprawl policies (FAR restrictions and impact fees) and harvesting taxes (yield taxes) to incentivize the private forest owner to increase forest land and lengthen rotations whenever older trees provide the highest externalities, both steps which may help mitigate climate change and achieve other significant local environmental benefits, such as improved water quality, recreational activities, species habitat and biodiversity.

We show that the optimal pace of land development can be implemented as a private solution through impact fees that internalize the present value of forest amenities and irreversibility costs of development. Development fees represent an additional cost of development and will in general slow the development pace. Efficiency can also be improved with a density restriction. Density restrictions affect urban development by reducing the value of land in urban use. These land use policies also affect rotation date decisions given the interdependency between conversion and rotation dates.

A key policy insight from our paper is that if we expect the benefits from urban forests to continue to be highly valued in the future, then government intervention may be required to create appropriate incentives for private landowners to preserve forest land today, even if alternative land use options, such as urban use, currently offer higher private present value returns. However, policy makers should take into account the interdependencies between alternative land uses when setting these incentives. The reason is because these interdependencies create feedback effects, which affect private landowners' decisions. Another implication is that urban land use policies can also be used to achieve forest goals since they may create incentives not to switch to an alternative land use and by affecting the value of the outside option these policies can also affect harvest decisions.

Appendix

Social Planner's Problem:

The social planner's problem as stated in (12) can be separated in two problems, for each K:

1) In the case $\mu = 0$. This implies that $T_D = KT$. Therefore, when trees are harvested, the amount of timber is given by $v(T)$, and the problem of the social planner, as stated in (12), simplifies significantly, as it has only one variable, T, for each K, and the first and the third terms in (12) are eliminated.

2) In the case $0 < \mu < 1$, we may write the following Lagrangean maximization problem:

$Max\ L(\mu, T, \lambda \mid K) = V(T, T_D \mid K) + \lambda[1 - \mu]$

First-order conditions:

$$\begin{array}{lll} \frac{\partial L}{\partial T} = \frac{\partial V}{\partial T} \leq 0 & T \geq 0 & \frac{\partial L}{\partial T} T = 0 \\ \frac{\partial L}{\partial b} = \frac{\partial V}{\partial b} - \lambda = 0 & \mu > 0 & \frac{\partial L}{\partial \mu} \mu = 0 \\ \frac{\partial L}{\partial \lambda} = 1 - \mu > 0 & \lambda \geq 0 & \frac{\partial L}{\partial \lambda} \lambda = 0 \end{array}$$

Since $\mu < 1$, then $\lambda = 0$. For an interior solution of μ, this implies that $\frac{\partial V}{\partial b} = 0$.

Therefore, if there is a solution that satisfies 1) or 2), then it is the solution of the problem. We can show that the problem is similar to the one that we solve in the paper, as long as the interior solution exists. As long as there is a solution for some K, the problem has a solution. If, for different values of K, one of the two the above problems has a solution, the solution of the problem will be given by the value of K for which $V(.)$ is maximized.

Total Differential of the the First-order Conditions of Social Planner Problem (12):

In order to study the social planner's optimal harvesting timing-conversion timing-density choice problem, we differentiate totally the system consisting of the first-order conditions of the above problem, (14), (13), with respect to T, and T_D, as well as with respect to the parameters of the model, p, and c.

Note that the first-order condition with respect to T,(14) in the body text, can also be written as follows:

$$\frac{\partial V(.)}{\partial T} = -e^{-rT_D}K(pv_t(T_D-KT)-KF(T_D-KT)e^{-rT_D}-rKe^{-rKT}\int_0^{T_D-KT}F(t)e^{-rt}dt-$$

$$-\frac{re^{-rT}}{1-e^{-rT}}(pv(T)-c)\left[\frac{1-e^{-rKT}}{1-e^{-rT}}-Ke^{-rKT}\right]+\frac{rKe^{-rKT}}{1-e^{-rT}}\int_0^T F(t)e^{-rt}dt+$$

$$-\frac{(1-e^{-rKT})e^{-rT}}{1-e^{-rT}}\left[-F(T)+\frac{r}{1-e^{-rT}}\int_0^T F(t)e^{-rt}dt\right]+$$

$$+e^{-rT}pv_t(T)\frac{1-e^{-rKT}}{1-e^{-rT}}=0 \tag{43}$$

By total differentiating the system of the two first-order conditions, we obtain a system of two equations.

The first equation is obtained by differentiating totally (13), that is,

$$\{rKpv_t(T_D-KT)-Kpv_{tt}(T_D-KT)-KF_t(T_D-KT)\}dT+$$

$$+\{-rpv_t(T_D-KT)+pv_{tt}(T_D-KT)+F_t(T_D-KT)-R_t-R_x\frac{d\overline{x}}{dT_D}\}dT_D+$$

$$+\{-rv(T_D-KT)+v_t(T_D-KT)\}dp+rdc=0 \tag{44}$$

The second equation of the corresponding system of equations is obtained by differentiating totally (14), and is given as follows

$$\{e^{-rT}pv_{tt}(T)\frac{1-e^{-rKT}}{1-e^{-rT}}+e^{-rT}pv_t(T)\left[B\right]-\frac{re^{-rT}}{1-e^{-rT}}pv_t(T)\left[C\right]$$

$$+\frac{r^2 e^{-rT}}{(1-e^{-rT})^2}(pv(T)-c)\,[A]+$$

$$+e^{-rT_D}K^2pv_{tt}(T_D-KT)+[E]\}dT-\{K(-rpv_t(T_D-KT)+pv_{tt}(T_D-KT)+F_t(T_D-KT))\}dT_D+$$

$$+\{e^{-rT}v_t(T)\frac{1-e^{-rKT}}{1-e^{-rT}}-\frac{re^{-rT}}{1-e^{-rT}}v(T)\,[C]-$$

$$-e^{-rT_D}Kv_t(T_D-KT)\}dp+\{\frac{re^{-rT}}{1-e^{-rT}}\,[C]\}dc=0 \qquad (45)$$

where $A=\sum -Ke^{-rKT}-K^2e^{-rKT}(1-e^{-rT})-\frac{(K+1)e^{-rKT}-e^{-rKT}Ke^{-rT}-e^{-rT}}{1-e^{-rT}}$
$=\frac{-K^2e^{-rT(K+3)}+3K^2e^{-rT(K+2)}+e^{-2rT}-2e^{-rT(1+K)}-3K^2e^{-rT(1+K)}+Ke^{-rT(K+2)}-e^{-rT}+e^{-rKT}-Ke^{-rT(1+K)}+K^2e^{-rKT}}{-e^{-2rT}+2e^{-rT}-1}$

$B=-\sum r+\frac{\partial\sum}{\partial T}=-\frac{(1-e^{-rKT})r}{1-e^{-rT}}+\frac{rKe^{-rKT}(1-e^{-rT})-re^{-rT}(1-e^{-rKT})}{(1-e^{-rT})^2}=$
$-r\frac{1-e^{-rKT}-Ke^{-rKT}+Ke^{-rT(K+1)}}{(-1+e^{-rT})^2}$

$C=\sum -Ke^{-rKT}=\frac{(1-e^{-rKT})}{1-e^{-rT}}-Ke^{-rKT}=\frac{-1+e^{-rKT}+Ke^{-rKT}-Ke^{-rT(1+K)}}{-1+e^{-rT}}$

and $E=e^{-rT_D}K^2v_{tt}(T_D-KT)+K^2F_t(T_D-KT)e^{-rT_D}+$
$+r^2K^2e^{-rKT}\int_0^{T_D-KT}F(t)e^{-rt}dt+rK^2F(T_D-KT)e^{-rT_D}+$
$+\frac{-r^2K^2e^{-rKT}(1-e^{-rT})-r^2e^{-rT}Ke^{-rKT}}{(1-e^{-rT})^2}\int_0^T F(t)e^{-rt}dt+\frac{rKe^{--rKT}}{1-e^{-rT}}F(T)e^{-rT}+$
$+e^{-rT}\left[F(T)-\frac{r}{1-e^{-rT}}\int_0^T F(t)e^{-rt}dt\right][\frac{\partial\sum}{\partial T}-\sum r]+$
$+\sum e^{-rT}[F_t(T)+\frac{r^2e^{-rT}}{(1-e^{-rT})^2}\int_0^T F(t)e^{-rt}dt-\frac{r}{1-e^{-rT}}F(T)e^{-rT}].$

where $\sum=\frac{1-e^{-rKT}}{1-e^{-rT}}$.

We may also write the above system as follows:

$$V_{T_DT}dT+V_{T_DT_D}dT_D+V_{T_Dp}dp+V_{T_Dc}dc=0$$

$$V_{TT}dT+V_{TT_D}dT_D+V_{Tp}dp+V_{Tc}dc=0$$

By strict concavity of $V(.)$ we have that $V_{TT} < 0$, $V_{T_D T_D} < 0$, and $D = V_{T_D T_D} V_{TT} - (V_{TT_D})^2 > 0$.

Assuming that the price of timber, p, the cost of replanting, c, and the discount rate, r, are fixed, we first study the impact of a change in the optimal development time on the boundary of the developed zone, $\overline{x}$. Hence, after dividing the system by dT_D, from (45) we obtain $\frac{dT}{dT_D}$, that is, the optimal adjustment of harvesting time with respect to a marginal change in the optimal conversion time. Inserting this result in (44), we are finally able to derive the impact of a marginal change in the optimal timing of conversion on the boundary.

We now show these results. From (45) we have:

$$\frac{dT}{dT_D} = \frac{-V_{TT_D}}{V_{TT}} = \frac{-rKpv_t(T_D - KT) + Kpv_{tt}(T_D - KT) + KF_t(T_D - KT)}{V_{TT}} \tag{46a}$$

This condition is the same as (26) in the body text.

We could obtain similar conditions for the unregulated problem, by ignoring non-timber benefits.

To study the effect of the impact fee and the yield tax we proceed similarly, that is, by differentiating the above system with respect to the corresponding policy instruments.

References

[1] Alig, R and A. Plantinga, "Future Forestland Area: Impacts from Population Growth and Other Factors that Affect Land Values", *Journal of Forestry*, 102 (8): 19-24(6), 2004.

[2] Brueckner, J.K., "Growth Controls and Land Values in an Open City", *Land Economics*, 66 (3): 237-248, 1990.

[3] Capozza D. and R. Helsley, "The Fundamentals ofLand Prices and Urban Growth", *Journal of Urban Economics*, 26, 295-306, 2009.

[4] Englin, J., and M. Klan, "Optimal Taxation: Timber and Externalities", *Journal of Environmental Economics and Management* 18, 263-275, 2000.

[5] Halle, R. C., K. P. Gallo, and T. R. Loveland, "Influences of specific land use/land cover conversions on climatological normals of near-surface temperature", *Journal of Geophysical Research*, 113, D14113, 9 PP, 2008.

[6] Hartman, R., "The Harvesting Decision when a Standing Forest has Value", *Economic Inquiry* 14, 52-58, 1976.

[7] Irwin, E.G., "The effects of open space on residential property values", *Land Economics*, 78 (4), 465-480, 2002.

[8] Kahn, M., "The environmental impact of suburbanization", *Journal of Policy Analysis and Management*, 19 (4), 569-586, 2000.

[9] Koskela, E. and M. Ollikainen, "Forest Taxation and Rotation Age under Private Amenity Valuation: New Results", *Journal of Environmental Economics and Management* 42, 374-384, 2001.

[10] Leggett, C., and N. Bockstael, "Evidence of the Effects of Water Quality on Residential Land Prices" *Journal of Environmental Economics and Management* 39, 121–144, 2000.

[11] Max, W., and D. Lehman, "A Behavioral Model of Timber Supply", *Journal of Environmental Economics and Management* 15, 77-86, 1988.

[12] Nowak, D. J., and D. E. Crane, "Carbon storage and sequestration by urban trees in the USA", *Environmental Pollution* 116:381-389, 2002.

[13] Strang, W., "On the Optimal Harvesting Decision", *Economic Inquiry* 21, 401-423, 1983.

[14] Swallow, Stephen K., Peter J. Parks, and David N. Wear, "Policy-relevant nonconvexities in the production of multiple forest benefits," *Journal of Environmental Economics and Management*, Elsevier, vol. 19(3), pages 264-280, November, 1990.

[15] Turnbull, G., "Land Development under the Threat of Taking", *Southern Economic Journal* 69, 468-501, 2002.

[16] Turnbull, G., "The Investment Incentive Effects of Land Use Regulations", *The Journal of Real Estate Finance and Economics 31:4, 357-395, 2005.*

[17] Tyrvainen, L., and A. Miettinen, "Property Prices and Urban Forest Amenities", *Journal of Environmental Economics and Management* 39, 205-223, 2002.

[18] Wolfram, G., "The Sale of Development Rights and Zoning in the Preservation of Open Space: Lindahl Equilibrium and a Case Study", *Land Economics.* 57:(3), 398-412, 1981.

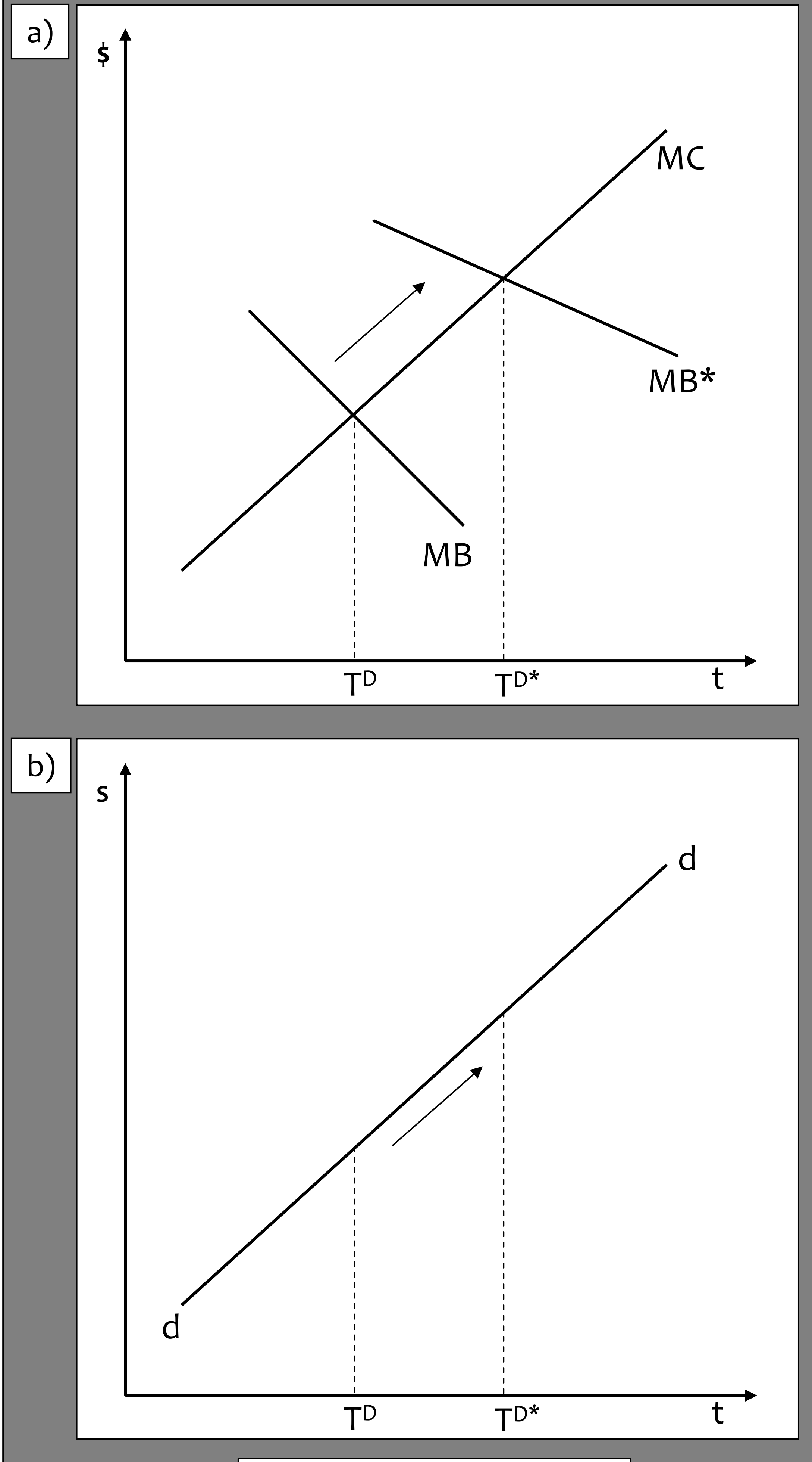

Figure 1: $\partial T^D / \partial T > 0$ with $F_t > 0$

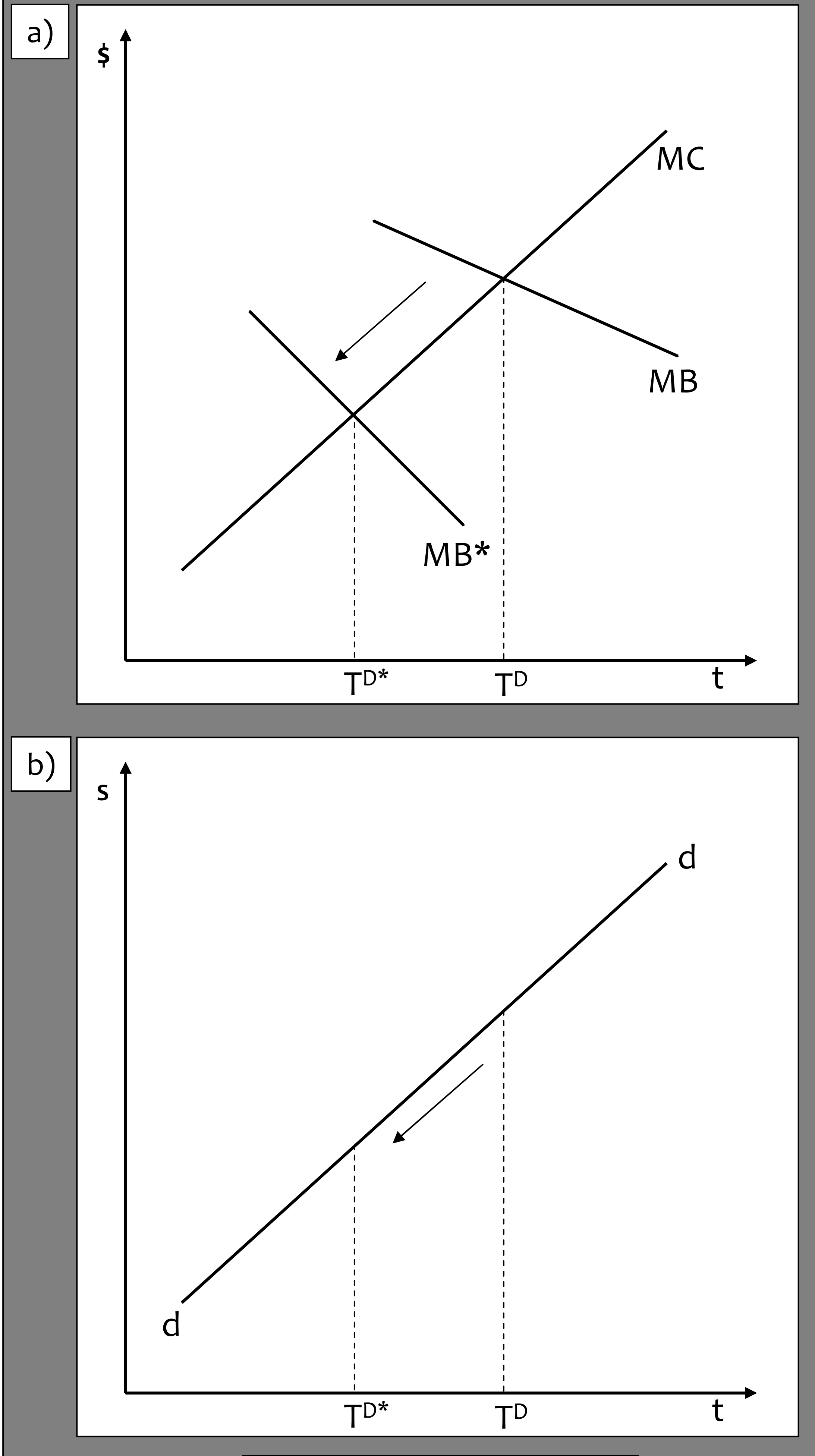

Figure 2: $\partial T^{D} / \partial T > 0$ with $F_t < 0$

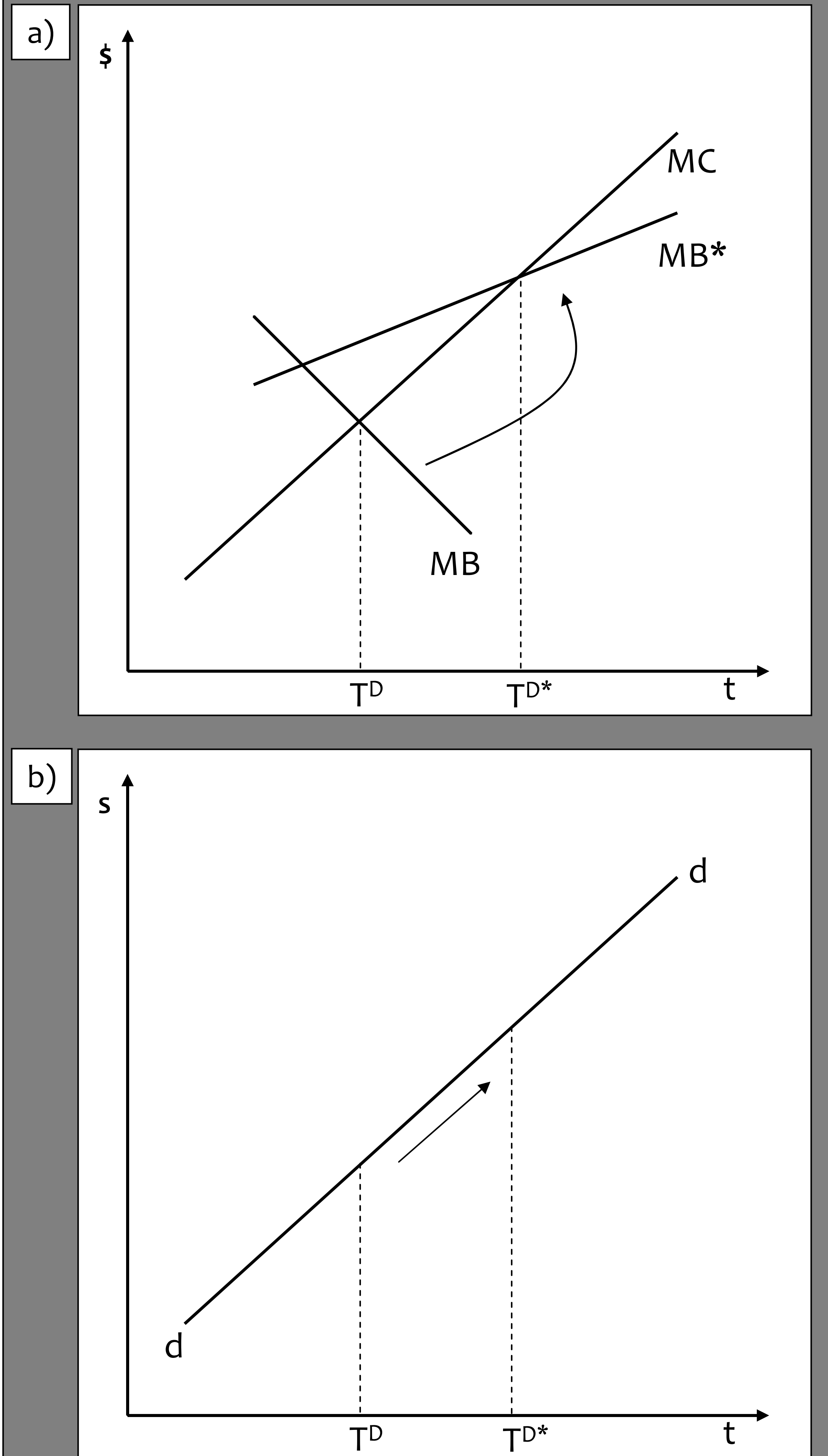

Figure 3: $\partial T^D / \partial T < 0$ (requires $F_t > 0$, no solution)

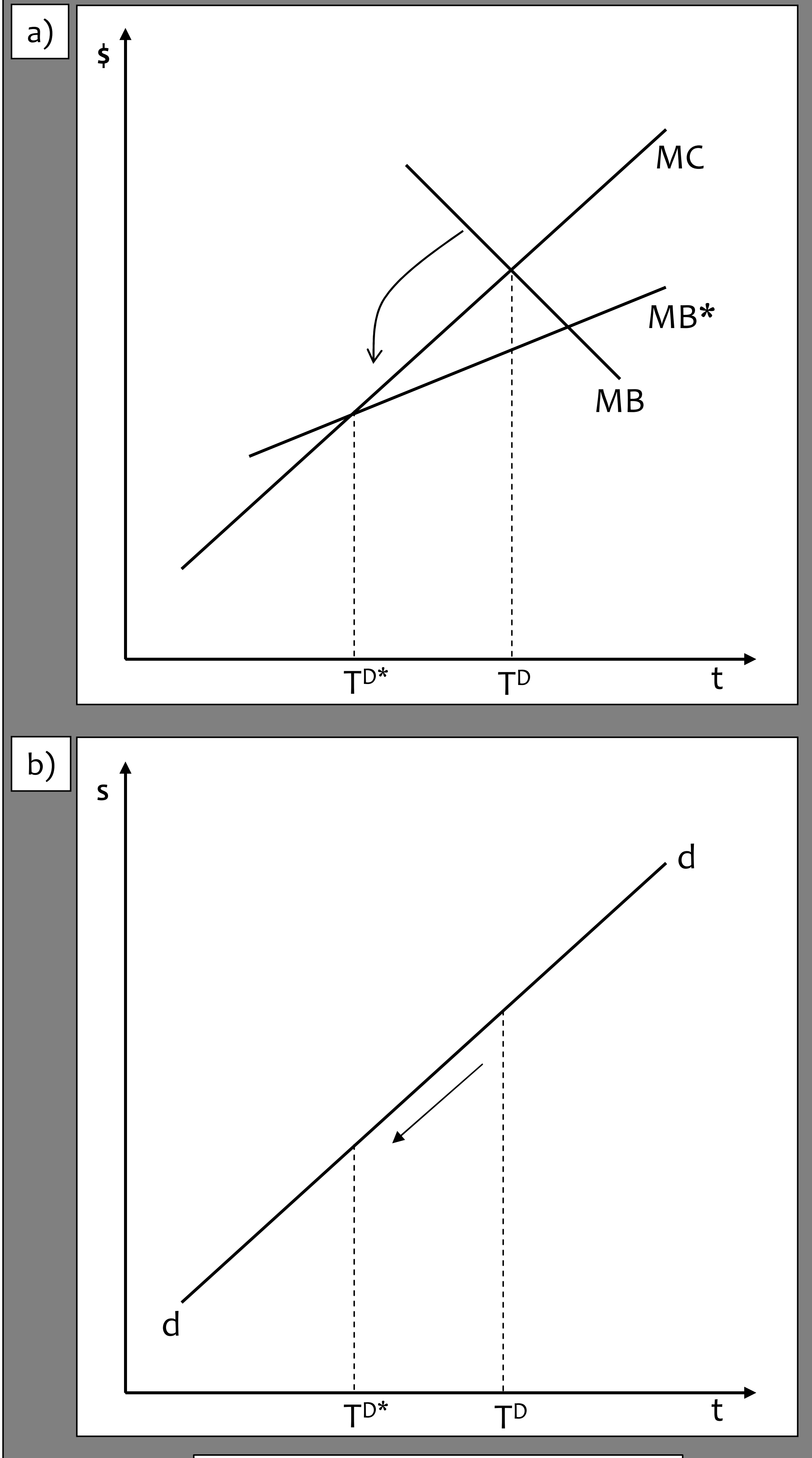

Figure 4: $\partial T^D / \partial T < 0$ (requires $F_t > 0$)