The dynamics of deforestation and reforestation in a developing economy

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Abstract

Forest transition theory is often used to describe the long term evolution of forest cover in a country as it develops, yet previous theoretical work has considered only net forest cover change when describing deforestation. However, little work exists describing the dynamics involved in forest cover change, particularly the relationship between reductions in primary native forests commonly associated with deforestation and concomitant reforestation and establishment of secondary forest plantations. In this paper we examine this distinction and formulate a new forest transition hypothesis. Our approach recognizes that primary and secondary forests are imperfect substitutes in terms of ecosystem services, but also costs associated with securing tenure. The latter is important given the property rights insecurities that have led to deforestation in many tropical countries. Our model allows a study of both the length of a forest transition and the speed at which net forest depletion eventually ends in the long run. Understanding the forest transition as we describe it could be important for future climate change mitigation policies.

Keywords: *forest transition, land uses, development, deforestation, reforestation*

JEL classification: O11, O13, Q23, Q56, Q57

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1 Introduction

Deforestation is responsible for a significant amount of the world's CO_2 emissions and represents one of the most serious threats to biodiversity preservation. In the long run, after deforestation has reached levels high enough, it is possible that net forest cover in a country could stop decreasing, and inherent in this idea is a point in time where forest cover starts to increase (Mather, 1992). Obviously such a point has already been reached in developed countries where previous large native forests were harvested during the industrial revolution. These forests have now been replaced with secondary managed forests. Clearly, many tropical developing countries have not reached such a turning point where managed forests replace primary forest cover. While some developed countries such as France and the United States experienced this transition a few centuries ago, it is a current challenge for tropical developing economies which may still be very far from reaching the transition point. While most of the deforestation literature has focused only on replacement of primary forests with non-forest land uses, to understand the forest transition one must also understand that net forest cover is composed of two distinct forest stocks: primary native (i.e. natural old-growth forests) and secondary forests (i.e. plantations established through reforestation). During development, the former decreases while the latter increases. Since primary and secondary forests are not perfect substitutes, in terms of carbon storage, biodiversity and livelihoods, and costs of securing tenure, integrating this specification within the forest transition framework is an important consideration.

In this paper, we model the transition between primary forest depletion and secondary forest growth in a given economy. Our model highlights the economic features under which a transition is possible and its consequences on climate change and biodiversity. Our approach allows an analysis of the turning point that represents the minimum value of net forest cover (or highest level of deforestation) in the long run. We also analytically solve for the speed at which an economy reaches the turning point.

The following section presents a detailed discussion of the forest transition and highlights the importance of completing the theory by accounting for the two dynamics that actually compose net forest cover change. The model is developed in section 3, while conditions of a turning point are shown in section 4. In section 5 we study land uses in the steady state. The last section concludes with a policy discussion.

2 The Forest Transition theory: towards a more complete framework

The Forest Transition (FT) hypothesis states that the forest stock of a country changes in a predictable way along a development path, following different phases. Initially, forests are abundant and un-harvested since access to rents is limited. Then, as population growth and infrastructure increases, a major phase of deforestation occurs. Agricultural rents are higher than forest rents on frontier land units, and land is therefore converted to meet food, income and energy demand. Finally, a phase of stagnation and reforestation takes place, and eventually the net deforestation rate turns from positive to either zero or negative. This is the turning point in the FT literature.

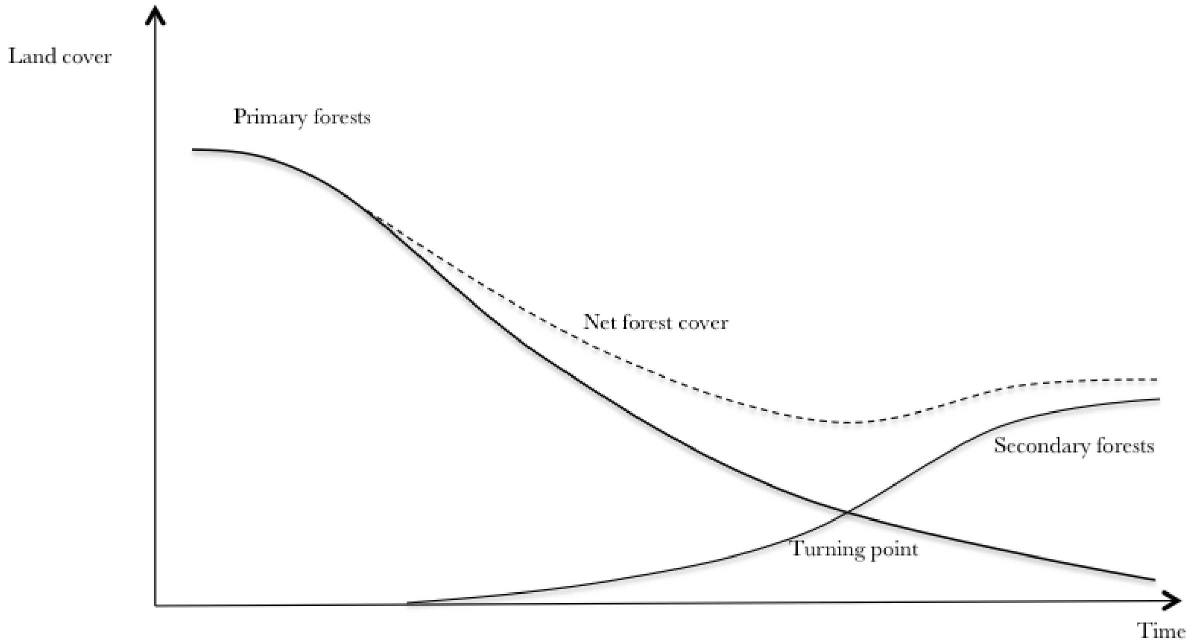
Based on observations of developed nations, Rudel et al. (2005) explained the occurrence of the turning point using either an economic development or a forest scarcity interpretation. The economic development interpretation states that the capital stock formed during agricultural land expansion is reinvested in new, more profitable sectors that do not require intensive use of forests[1]. Industry-based production increases along with a creation of new urban jobs with higher wages that attract farmers from frontiers to urban areas. Some previously cropped lands therefore return to forest. During this period, governments, who may have become more responsive to ecological and climatic problems, may implement reforestation programs. The Fig. 1 illustrates this usual representation of the forest transition and the turning point, along with the expected path of net forest cover through time.

The scarcity interpretation argues that the relative scarcity of land held in forests serves to increase forest harvesting prices while at the same time leading to potentially high environmental issues due to lack of forest cover[2]. In order to benefit from the high forest rents and control environmental degradation, large-scale plantations are then implemented. The net deforestation rate turns to null or negative, the turning point occurs. Additionally, globalization can favor the end of deforestation (i.e. a turning point) by trading ecological ideologies, new patterns of demand, or by developing tourism (Lambin and Meyfroidt, 2010). Also, through the study of 15 developing countries over 1990-2010, Wolfersberger, Delacote and Garcia (2013) found that the institutional quality also promoted the occurrence of this turning point.

[1]Considering the intensive use of forest includes agricultural activities, since forest and agriculture often compete for the use of land.

[2]For instance, during the 1980s, China has faced desertification, flooding and soil degradation, which had been attributed to deforestation (Mather, 2007).

Figure 1: The Forest Transition



Previous work that considers the dynamics of long term forest conversion is sparse and has focused mainly on the first deforestation phase in Fig. 1. Hartwick et al. (2001) studied the allocation of land uses between forest and agriculture, along with development in a small open economy allowing for the possibility of re-timbering of lands, but the forest transition was not examined. Barbier et al. (2005) used an optimal control model to examine how lobbying can influence the long-term conversion rate of forests. Using a similar approach, Ollivier (2012) investigated the effect of REDD+ transfer schemes on long-term land conversion. With the exception of Hartwick et al. (2001), this work has only considered replacement of primary forest with non-forest uses and no possibility of reforestation.

The absence of forest plantations in discussions of long term deforestation is not consistent with empirical studies showing that, during development, natural old-growth and secondary forests follow two opposite motions that establish an existence of a turning point. Primary forests tend to decrease while secondary forests increase. Grainger (1995) first pointed out this issue, and actually refers to FT as a transition between "*two separate national land use processes*". Mather (2007) and Perz and Skole (2003), respectively, analyzed data from Amazonia and Asia (China, India and Vietnam), claiming that the FT theory required refinements since they found that the net increase of forest cover in the FT (phase 3) was largely composed of plantations. For public policy purposes, Angelsen and Rudel (2013) also highlighted the importance of going beyond the "*forest-nonforest* *dichotomy*" within the FT theory. They argued that because of differences in ecosystem services attributed to carbon storage capabilities, considering only net forest cover as a policy target would lead to protection of low carbon landscapes. The distinction between primary and secondary forests is also a major focus in climate ecology. Luyssaert et al. (2008) argued that old growth forests can store centuries worth of carbon reserves. Regarding carbon dioxide emission, it is therefore more efficient over the short and mid terms to conserve old forests rather than seek to plant new ones. Stephenson et al. (2014) also found that old-growth forests absorb more carbon than new forests despite that growth rates of new forests are higher. Concerning biodiversity, Burley (2002) showed that tropical forests are home to 50% of the known vertebrates and 60% of plant species. However, forests reestablished on non-forest land as plantations cannot lead to full recovery of all of these species, especially if some agricultural activities took place prior to reforestation. The conclusion from this literature establishes that secondary forests have a lower marginal environmental value than primary ones in terms of both carbon and biodiversity.

It follows that making a distinction between the type of forest (i.e. primary or secondary forests) is necessary since deforestation of primary forests is irreversible in the sense that they only can be replaced by secondary forests, which are imperfect substitutes in terms of the ecosystem services that can be produced from any land unit. In this work, we integrate the double dynamics of deforestation and reforestation within the FT framework, and study how it is articulated and what are the implications on development and environment.

3 The double dynamics driving the forest cover

3.1 The model

We consider a small open economy with a land endowment normalized to one unit. Initial primary and secondary forest covers are $F_0 = \overline{F}$ and $S_0 = \overline{S}$, respectively. Let $f(F_t)$ and $g(S_t)$ be the land rents under the primary (F_t) and the secondary (S_t) forests. The former includes the public good value associated with an old-standing forest (e.g. carbon stock, biodiversity benefits, soil protection, quality of water etc.) as well as the net income from selective timber harvesting. The latter includes rents from secondary forests plantations, i.e., timber harvesting and public goods value (flows of sequestered carbon, for instance). The rent functions for primary and secondary forests differ so as to reflect the imperfect substitutability of the forest stocks, be it in terms of public goods or benefits from harvesting. The rents obtained from agriculture are assumed to equal $h(1 - F_t - S_t)$.

The functions $f(.), g(.)$ and $h(.)$ are assumed to be strictly concave, that is, $f'(F_t) > 0$, $f''(F_t) < 0$; $g'(S_t)$>0, $g''(S_t)$<0); $h'(1 - F_t - S_t) > 0$, $h''(1 - F_t - S_t) < 0$. In light of the fact that rents take into consideration both timber and the public goods benefits, we consider that $f(F_t)$, $g(S_t)$ and $h(1 - F_t - S_t)$ reveal the preferences of a representative land user toward different sources of rents.

The dynamics of deforestation and of reforestation are represented by the parameters $(d_t, r_t \geq 0)$. Deforestation implies $d_t > 0$ while positive reforestation implies $r_t > 0$ for any time period. The timber harvested from cleared primary forests is sold at price p_F, and $C(d_t)$ is the cost of harvesting d_t hectares of primary forest, with $C'(d_t) > 0$ and $C''(d_t) > 0$. Accordingly, $p_F.(d_t) - C(d_t)$ represents the profit obtained from cleared primary forest.

Primary forests are considered to be pure open-access resources. The cost of securing tenure of agriculture is considered to be zero. Indeed, in most developing countries, deforestation for agricultural purposes is a way to empower landholders and to avoid expropriation. For example, Araujo et al. (2009) reported that in Brazil, landowners clear forests to assert the productive use of land and reduce expropriation risk or increase the ease of obtaining permanent title. In this context, we assume that plantations entail a land tenure cost of $\Phi_t(r_t)$ for r_t hectares of planted forest at time t, with $\frac{\partial \Phi_t}{\partial t} < 0$, $\Phi'(d_t) > 0$ and $\Phi''(d_t) > 0$. This land tenure cost represents the effort devoted to protect the forest investment, which is costlier in countries with low enforcement (Bohn and Deacon, 2000).

The representative land user agent chooses the levels of deforestation and reforestation that maximize his welfare, that is:

$$\max_{d_t, r_t} W(d_t, r_t) = \int_0^T [f(F_t) + g(S_t) + h(1 - F_t - S_t) + p_F d_t - C(d_t) - \Phi_t(r_t)] e^{-\delta t} dt \tag{1}$$

$s.t$

$$\begin{aligned}
&\dot{F}_t = -d_t \ , \\
&\dot{S}_t = r_t \ , \\
&F_0 = \bar{F} \ , \\
&S_0 = \bar{S} \ , \text{ and} \\
&d_t \geq 0 \ ; r_t \geq 0 \ \ \forall \ t \in [0, T].
\end{aligned}$$

From (1), the current value of the Hamiltonian is:

$$H = f(F_t) + g(S_t) + h(1 - F_t - S_t) + p_F.d_t - C(d_t) - \lambda_t d_t + \mu_t r_t - \Phi_t(r_t) \tag{2}$$

where λ_t and μ_t respectively denote the co-state variables associated with deforestation d_t and reforestation r_t. Applying Pontryagin's maximum principle enables us to obtain the necessary conditions for respectively the optimal paths of deforestation and reforestation. The first-order conditions with respect to d_t and r_t, are:

$$H_{d_t} = p_F - C'(d_t) - \lambda_t = 0, \text{ and} \tag{3}$$

$$H_{r_t} = -\Phi'_t(r_t) + \mu_t = 0. \tag{4}$$

From (3), we observe that if $p_F - C'(d_t) < \lambda_t$, primary forests conversion will not occur. In this case, the marginal increase in utility from harvesting is lower than the shadow price of in situ forest stock at time t. From (4), reforestation will not occur if the shadow value of secondary forests in situ μ_t is lower than the tenure costs at the margin $\Phi'_t(r_t)$. Indeed, secondary forests are established only when their net rent becomes high enough. Given that we assume a decreasing land tenure cost over time, secondary forests start growing only when the tenure cost is below a certain threshold. This is consistent with the empirical results of Bohn and Deacon (2000), who show that countries with more developed enforcement and less political instability, along with lower probability of illegal logging or expropriation, are consistent with lower plantation investment costs.

The dynamics of the co-state variables are given by:

$$\dot{\lambda}_t = \delta\lambda_t - f'(F_t) + h'(1 - F_t - S_t), \text{ and} \tag{5}$$

$$\dot{\mu}_t = \delta\mu_t - g'(S_t) + h'(1 - F_t - S_t). \tag{6}$$

The transversality conditions for this model are:

$$\lim_{t\to\infty} e^{-\delta t}\lambda_t F_t = 0, \text{ and} \tag{7}$$

$$\lim_{t\to\infty} e^{-\delta t}\mu_t S_t = 0. \tag{8}$$

From (5), the shadow price of a hectare of primary forests converted to agriculture increases with the marginal net benefit from favoring agriculture at the expense of sustainable primary forest management, $h'(1-F_t-S_t) - f'(F_t)$. It follows that this shadow price decreases as primary forests become more scarce. Deforestation thus clearly decreases as time goes by and primary forests disappear in an irreversible manner, which is consistent with the forest scarcity path. Moreover, substituting (3) into (5) indicates that deforestation decreases in time if the marginal return to forest conversion decreases.

In contrast, (6) states that the marginal cost of converting an additional land unit of agriculture into secondary forests increases with the marginal net benefit of agriculture relative to sustainable secondary forests management, $h'(1 - F_t - S_t) - g'(S_t)$. Again, using (4) into (6) indicates that reforestation increases in time if marginal land tenure costs decrease.

The optimal paths of deforestation and reforestation from (3) and (4) can be obtained as:

$$-C''(d_t)\dot{d}_t = h'(1 - F_t - S_t) - f'(F_t) + \delta[p_F - C'(d_t)], \text{ and} \quad (9)$$

$$\Phi_t''(r_t)\dot{r}_t = h'(1 - F_t - S_t) - g'(S_t) + \delta\Phi_t'(r_t). \quad (10)$$

3.2 Explicit program

Our results are illustrated by numerical simulations. We voluntarily choose scenarios of contrasted preferences in order to emphasize their consequences on FT. The simulations should therefore not be considered for their numerical results, but for the qualitative and illustrative contents they provide. The explicit form of our welfare function is:

$$W(d_t, r_t) = \int_0^T [\alpha lnF_t + \beta lnS_t + (1 - \alpha - \beta)ln(100 - F_t - S_t) + p_F.d_t - \frac{1}{2}.(d_t)^2 - \lambda_t d_t - \frac{1}{2}.(r_t)^2 + \mu_t r_t]e^{-\delta t}dt. \quad (11)$$

The cost functions $C(.)$ and $\Phi_t(.)$, respectively the costs of deforesting and securing the reforested lands, are convex and have the same form as in Hartwick et al. (2001): $C(d_t) = \frac{1}{2}.(d_t)^2$ and $\Phi(r_t) = \frac{1}{2}.(r_t)^2$.

Table 1 provides the parameters that differentiate the scenarios. Scenario 1 is the benchmark scenario, where the representative land user agent gives more weight to agriculture and is indifferent between primary and secondary forests. This is the usual way development proceeds in a country with forests.

Table 1: Simulation scenarios

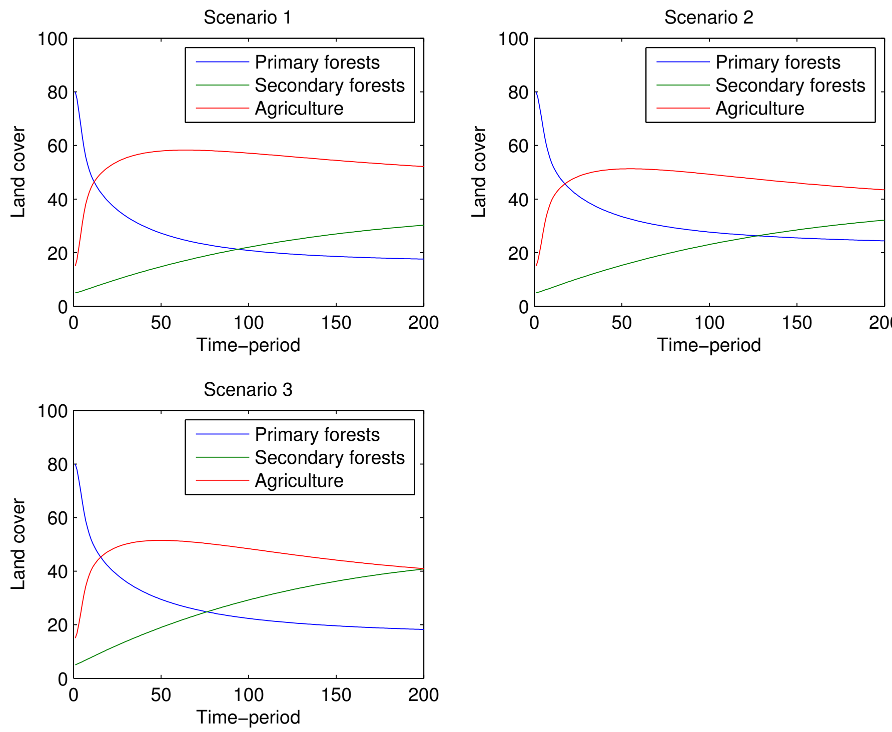
Description	Scenario	α	β	$(1-\alpha-\beta)$	Land tenure costs
Pref. for agriculture	1	0.3	0.3	0.4	$\frac{1}{2}(r_t)^2$
Pref. for prim. forests	2	0.4	0.3	0.3	$\frac{1}{2}(r_t)^2$
Pref. for sec. forests	3	0.3	0.4	0.3	$\frac{1}{2}(r_t)^2$
Increasing tenure costs	4	0.3	0.3	0.4	$(r_t)^2$
Decreasing tenure costs	5	0.3	0.3	0.4	$\frac{1}{4}(r_t)^2$

Notice that the variations of land tenure costs (scenarios 4 and 5) are built on the benchmark case (scenario 1), since it is the most likely.

3.3 Speed of deforestation and reforestation in the transition

From (9), the speed of deforestation from primary forests decreases with the rents from primary forests, increases with the preferences for agriculture (or agricultural rent), and increases with the net marginal benefit of forest conversion. Equation (10) shows that the speed of reforestation increases with preferences for secondary forests (or secondary forests rent), decreases with preferences for agriculture, and decreases with marginal land tenure costs. Fig. 2 illustrates these results.

Figure 2: Variation in land uses under different preferences



Referring to the first scenario, the agricultural area surpasses 50% of the total land area by 60 time-periods. The turning point occurs around time-period 95. While the initial stock of primary forest covers 80% of total land, it ends up at a level less than 20%.

In scenario 2 and 3, preference is given to forests. In (2), the highest rents are attributed to primary forests while (3) shows a situation where relative rents are higher in secondary forests. Unlike Scenario 1, we note that deforestation proceeds slower when rents generally favor forest. We also observe that scenario 2 leads to a longer transition than scenario 3, but ultimately results in a preservation of more primary native forest cover.

4 Resources stock

Resources stock is studied under different features. First when deforestation ceases, i.e., at the turning point. Second when economy reaches steady state. Influence of marginal rents and tenure costs on stock are also examined.

4.1 Analyzing of the turning point

As described in Section 2, the turning point is of particular importance in FT theory. At this point, net forest cover no longer decreases, and reforestation compensates for deforestation. Two characteristics of the turning point have to be considered. First, forest cover at the turning point gives an indication of the cumulative nature of deforestation during the development phase. Second, the time at which the turning point occurs indicates the length of the net deforestation (deforestation minus reforestation) phase.

The turning point takes place when the gain of secondary forests offsets the loss of primary forests, i.e.

$$\dot{d_t} = \dot{r_t}. \tag{12}$$

Using this expression with (5) and (6) yields:

$$f'(F_t) + g'(S_t) = 2h'(1 - F_t - S_t) + \delta[p_F - C'(d_t) + \Phi_t'(r_t)] \tag{13}$$

Equation 13 shows that the turning point between primary and secondary forests occurs when the double marginal return from agriculture equals the total marginal rents from all forest cover, minus the discounted profit from primary forests wood sale and the marginal cost of land tenure[3]. This result is consistent with forest scarcity path. Indeed, we see that the turning point occurs when the marginal value associated with forests equals that of converting it.

Hence, we can deduce that the forest stock at the turning point is higher when preferences and rents for primary and secondary forests are higher, and lower when timber price or preferences for agriculture are higher. This result is confirmed by our simulations. It is straightforward to see from Fig. (2) that the turning point occurs at a lower forest cover when preferences for agriculture are stronger.

[3]Notice that our result holds for $\Phi_t''(r_t) = C''(d_t) = 1$, which is in accordance with our explicit program.

4.2 Role of land use and tenure costs to the length of the transition

Two main questions arise from our analysis that are important in assessing transition length: land-uses preferences and land tenure costs.

Another interesting piece of information comes from revisiting the length of the forest transition from section 3.2. From equality (12), ceteris paribus, a slower speed of deforestation indicates a longer forest transition, in the sense that it takes longer for the deforestation rate to equal that of reforestation. The same type of reasoning can be done with reforestation: a slower pace of reforestation also indicates a longer forest transition.

We can therefore reason that the length of the forest transition increases with preferences for primary forests and decreases with the marginal benefit from primary forest conversion, since they decrease the speed of deforestation. Further, the FT length decreases with preferences for secondary forests and increases with marginal land tenure costs, which increase the speed of reforestation. Finally, the FT length may either increase or decrease with preferences for agriculture, since this increases both the pace of deforestation and decrease the pace of reforestation.

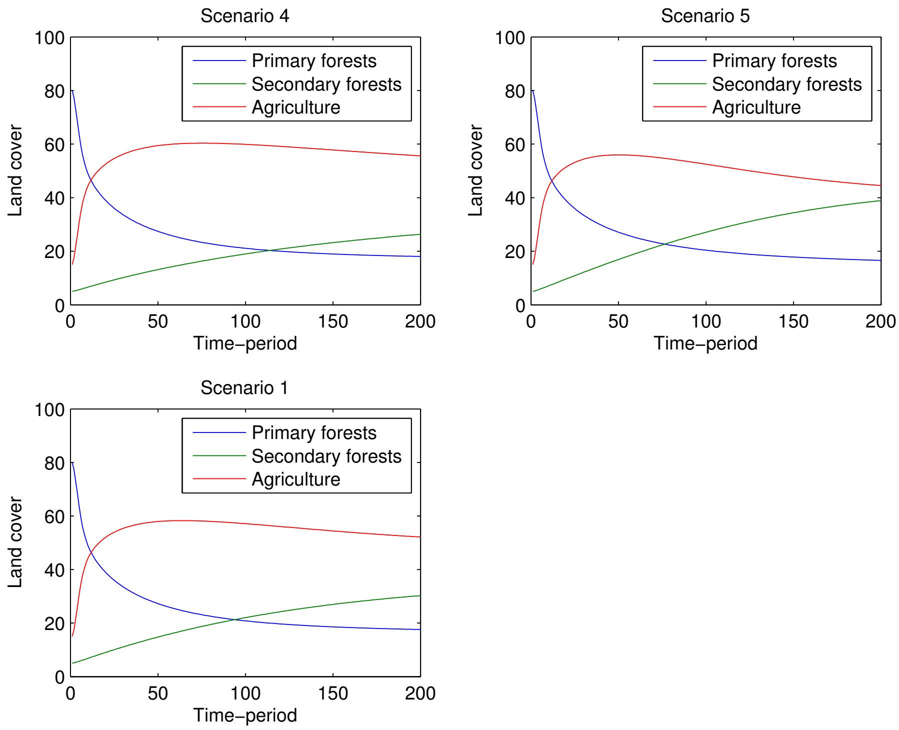
This result is visible in our simulations. Scenario 2 results in lower rate of deforestation. In the same manner, when the preferences for secondary forests are low, the reforestation rates are lower. Finally, when the preferences for agriculture are low, they tend to decrease the deforestation rate and increase the reforestation rate. The junction of these three effects produces a longer forest transition.

In contrast, scenario 3 presents a relatively short forest transition. Here, higher preferences for secondary forests enhance the pace of reforestation. Conversely, low preferences for primary forests increase the pace of deforestation. Lower agricultural preferences increase the reforestation rate and decrease the deforestation rate. In sum, a shorter forest transition is observed.

These results provide interesting insights into the cumulative nature of deforestation. Indeed, when preferences for primary forests are higher, the net deforestation phase lasts longer., yet the cumulative amount of deforestation will be smaller. Thus, having positive net rates of deforestation may not be very serious for a country: it may simply reveal that the forest transition phase will be longer, but with lower cumulative deforestation. In the same manner, high deforestation rates may suggest that the forest transition will appear more rapidly and potentially end with smaller cumulative deforestation.

The magnitude of tenure cost also influences the length of transition. Result (13) and figure 3 illustrate this.

Figure 3: Change in land tenure costs

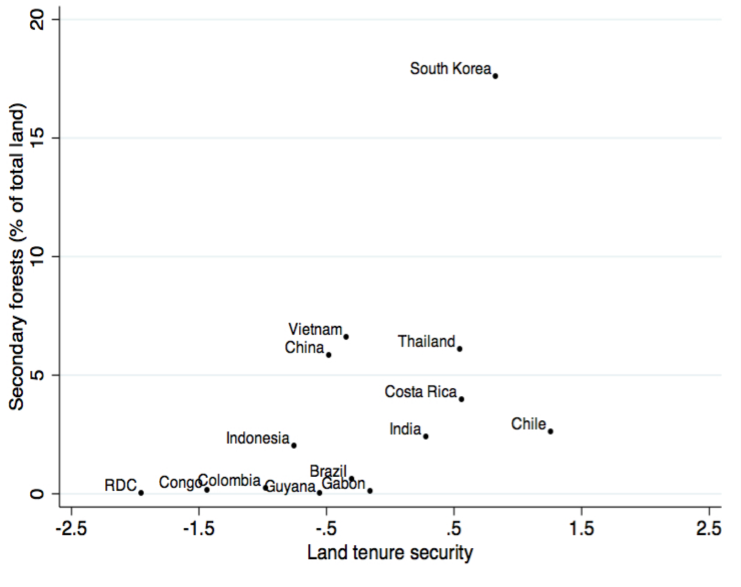


The occurrence of the turning point is clearly affected by the land tenure costs. An increase of these costs (scenario 4) delays the turnaround point in forest cover relative to the reference case (scenario 1). The turning point occurs around 20 time-periods later. On the contrary, not only does a decrease of these costs (scenario 5) significantly accelerate the occurrence of the turning point, but it appears at a time-period with higher total forest cover.

This result is particularly relevant for public policies such as REDD+. Obviously, one way to promote transitions in developing countries is to reinforce property rights and political stability in order to decrease tenure costs. Data provided by FAO and World Bank support this, as illustrated by Fig. (4).

The tenure security is here measured by the "Rule of Law" variable from the World Bank, that *"reflects perceptions of the extent to which agents have confidence in and abide by the rules of society, and in particular the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence"*. It varies within a range of $-2,5$ to $2,5$. A high score signifies low tenure costs. It is obvious that when the tenure security is very low, e.g. Congo, Colombia or Indonesia, the share of secondary forests is low as well. At the opposite, better

Figure 4: Reforestation and tenure costs in 14 countries (year 2000)



Data sources: FAO and World Bank

ranked countries such as Costa Rica, Thailand or South Korea are found to have practiced more reforestation.

Note that one must be careful when analyzing this figure since the development effects also account. For example, in the Democratic Republic of Congo (RDC) the tenure security and the share of secondary forests are both low. However, it is important to keep in mind that such a country has not yet started its major deforestation phase. This may also explain its low share of secondary forests.

All in all, in the long-term perspective, focusing on deforestation rates may be clearly misleading in terms of cumulative deforestation. What is really important is to get a clearer idea of the countries' preferences. We now provide an analysis of the steady states.

4.3 Steady state analysis

Studying the steady state is of particular interest since it is likely that a given country reaches this condition after development. For example, France experienced its turning point during the 18^{th} century, and its forest cover can be considered as stationary.

Before the stationary point is reached, clearing an additional hectare of primary forests provides $h'(1-F_t-S_t)+\delta\lambda_t$, while sustainable primary forests management gives $f'(F_t)+\dot{\lambda}_t$. Likewise, an additional hectare of secondary forests yields $g'(S_t)+\dot{\mu}_t$ while agriculture gives $h'(1-F_t-S_t)+\delta\mu_t$.

In steady state $\dot{F}_t = \dot{\lambda}_t = 0$ and $\dot{S}_t = \dot{\mu}_t = 0$. We find that the marginal benefit from converting a hectare of natural old-growth forest $\delta.p_F + h'(1 - F_\infty - S_\infty)$ equals the marginal return from sustainable primary forest management $f'(F_\infty)$.

Concerning the dynamics of the secondary forests, the steady state can be written as the equality of the marginal rents from a hectare of agriculture $h'(1 - F_\infty - S_\infty)$ and the marginal rents of a hectare of plantations $g'(S_\infty)$. The representative agent is then indifferent between allocating an additional hectare of land either to agriculture or to the secondary forests.

Equalizing the steady-states of the two types of forests by the marginal return from agriculture $h'(1 - F_\infty - S_\infty)$ yields:

$$f'(F_\infty) - \delta.p_F = g'(S_\infty) \tag{14}$$

This result shows that in the steady state, the marginal benefit from secondary forests equals that of primary forests minus the discounted sale price of timber obtained from clearing primary forests. This can be explained by the delay between the period of planting and realization of high ecosystem service benefits. This last equation implicitly describes the tradeoff between primary and secondary forests. It follows that forest composition differs when preferences lean toward primary or secondary forests. As a result, total forest cover in steady state is composed of both primary and secondary forests.

When primary forests are preferred, such as in scenario 2 and 3, primary forests represent a larger share of the forest cover in the long run. This result clearly indicates the validity and the importance of separately considering the deforestation and reforestation dynamics. Indeed, when considering preferences for forests without distinguishing between their types, one would miss this composition effect. We can argue that, despite similar total forest covers, Scenario 2 is preferable in terms of biodiversity and carbon stocks, while Scenario 3 better performs in terms of timber harvesting.

5 Implications for public policies: an application

Consider the implication of a drastic decrease of the land tenure costs. This type of reduction may come from the first phase of REDD+[4] implementation where strengthening tenure security is

[4] Reducing Emissions from Deforestation and Forest Degradation (REDD) is an effort to create a financial value for the carbon stored in forests, offering incentives for developing countries to reduce emissions from forested lands and invest in low-carbon paths to sustainable development. "REDD+" goes beyond deforestation and forest degradation, and includes the role of conservation, sustainable management of forests and enhancement of forest carbon stocks.

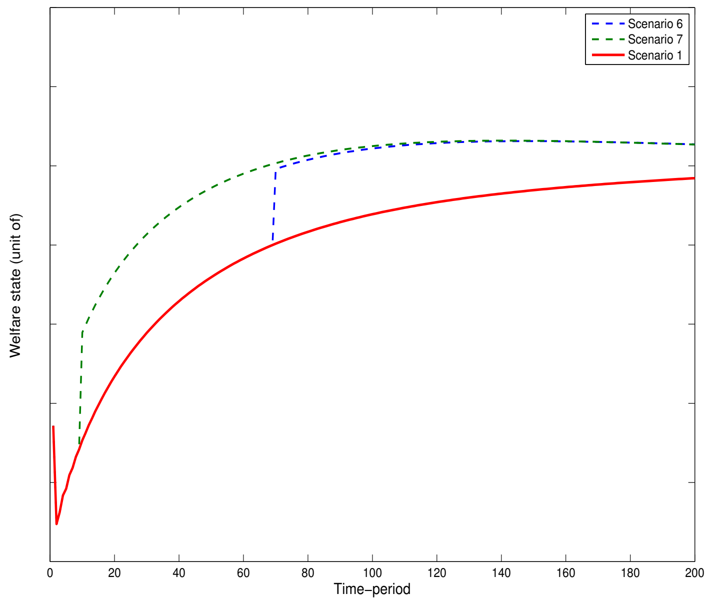
frequently mentioned as a key element before carbon redistribution. Moreover, our previous results and papers of Araujo et al. (2009); Bohn and Deacon (2000); Wolfersberger et al. (2013) confirm that public policies should be targeted on institution quality in order to fight against deforestation. For this reason, we focus on tenure costs in this application. Table 2 describes the programs.

Table 2: REDD+ scenarios

Description	Scenario	Land tenure costs	Interval	Land tenure costs	Interval
Benchmark scenario	1	$\frac{1}{2}(r_t)^2$	[0,200]	-	-
Program 1	6	$\frac{1}{2}(r_t)^2$	[0,70[	0	[70,200]
Program 2	7	$\frac{1}{2}(r_t)^2$	[0,10[	0	[10,200]

Notice that preferences α, β, and $(1-\alpha-\beta)$ are the same in the three scenarios, based on the benchmark case ($\alpha = \beta = 0.3$ and $(1-\alpha-\beta) = 0.4$). Scenario 6 is implemented at hallway of the transition, it corresponds to countries such as Brazil or Indonesia. Scenario 7 is implemented early in the transition, it corresponds to countries such as Congo or Gabon. The representative land user agent drops the tenure costs to zero by applying a REDD+ program (1 or 2). Figure 5 presents the land-use results of the different programs.

Figure 5: Variation of welfare under different REDD+ programs



Clearly, implementing a REDD+ program increases the welfare compared to "non-acting" (scenario 1). The earlier the public policy is implemented, the higher the area of welfare. This makes sense since a financial cost is removed, we can then observe a peak at this moment (time-period 10 and 70). It follows that rents from forestry provide a higher net benefit.

Assuming that the implementation of the program is costless for the representative land user agent[5], the area between the red curve and the blue and green ones represents a social cost of not protecting the forests. We see that the later the program is implemented, the higher this cost is.

6 Concluding remarks

In this paper, we analyze the double dynamics of deforestation and reforestation that induce the forest transition. Primary native forests and secondary forests have different climate and ecological characteristics. It is therefore important to go beyond the usual "forest vs. agriculture" framework when studying the land use in developing countries. It is equally important to consider the imperfect substitutability between the two types of forests. Four important results are outlined by our analysis.

The pace of deforestation and reforestation can be analyzed through the evolution of marginal rents of the forests' types relative to those of agriculture. The pace of deforestation is also determined by the marginal benefit of land conversion, while the pace of reforestation decreases with the land tenure costs.

The turning point occurs when the marginal rents from the total forest cover in situ equals those of the agricultural and commercial uses. It is higher in terms of land use when preferences for forests are higher, and lower when agricultural preferences are higher.

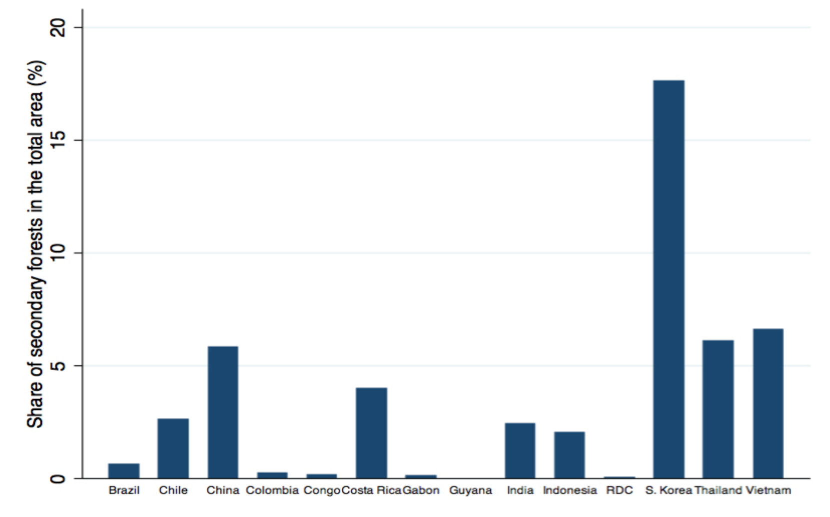
We highlighted a composition effect of the forest cover in steady state. Indeed, our model makes it possible to distinguish between primary and secondary forests. Given their different properties in terms of biodiversity and carbon storage, this result is very important. We saw that the composition of the forest stock in steady state depends on the decision maker's preferences. With a higher preference for primary forests, our results suggest that more biodiversity will be preserved over development and larger quantities of carbon will be stored.

Our model also allows to study the lengths of forest transitions. We find that the countries' net deforestation rates should be cautiously analyzed. Even if the turning point occurs further in time, it can be characterized with higher ecological properties and less cumulative deforestation.

[5]This assumption is enough realistic since REDD+ is overall a mechanism financed by North countries.

Likewise, we find that the net deforestation ends earlier in time when the countries' preferences are moving toward the secondary forests' growth. A quick look at the FAO data on secondary forests confirms these findings, which is also illustrated in Fig. 6.

Figure 6: Secondary forests in 14 countries (year 2000)



Data source: FAO

Countries experiencing a turning point are also the ones where the share of reforestation is important. The examples of China, Costa Rica, South Korea and Vietnam highlight this effect. As well, some countries considered as being close to the turning point, e.g. Chile, Thailand, have larger shares of secondary forests than countries identified as distant from the turning point, e.g. Congo, Gabon, Guyana or RDC. This reinforce our analysis on the impact of REDD+ programs on the level of welfare, from section 5.

In conclusion, in a long-term perspective, the net deforestation rates can be misleading. Accordingly, public policies should rather consider different types of forests at stake and better take into account the real motives behind the preferences for the forest cover conservation.

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References

Angelsen, A. and Rudel, T. K. (2013). Designing and implementing effective REDD+ policies: A forest transition approach. *Review of Environmental Economics and Policy*, 7(1):91–113. 2

Araujo, C., Bonjean, C. A., Combes, J.-L., Motel, P. C., and Reis, E. J. (2009). Property rights and deforestation in the brazilian amazon. *Ecological Economics*, 68(8–9):2461 – 2468. 3.1, 5

Arcand, J.-L., Guillaumont, P., and Jeanneney, S. G. (2008). Deforestation and the real exchange rate. *Journal of Development Economics*, 86(2):242 – 262.

Asner, G. P., Keller, M., Lentini, M., Merry, F., and Souza, C. (2009). Selective logging and its relation to deforestation, in amazonia and global change. *American Geophysical Union*.

Barbier, E. B., Damania, R., and Léonard, D. (2005). Corruption, trade and resource conversion. *Journal of Environmental Economics and Management*, 50(2):229–446. 2

Bohn, H. and Deacon, R. T. (2000). Ownership risk, investment, and the use of natural resources. *American Economic Review*, 90(3):526–549. 3.1, 3.1, 5

Burley, J. (2002). Forest biological diversity. *UNASYLVA-FAO*.

Grainger, A. (1995). The forest transition: An alternative approach. *Area*, 27(3):242–251. 2

Hartwick, J. M., Van Long, N., and Tian, H. (2001). Deforestation and development in a small open economy. *Journal of Environmental Economics and Management*, 41(3):235–251. 2, 3.2

Lambin, E. F. and Meyfroidt, P. (2010). Land use transitions: Socio-ecological feedback versus socio-economic change. *Land Use Policy*, 27(2):108 – 118. 2

Luyssaert, S., Sebastiaan, L., Schulze, E., Börner, A., Knohl, A., Hessenmoller, D., Law, B., Ciais, P., and Grace, J. (2008). Old-growth forests as global carbon sinks. *Nature*, 455:213–215. 2

Mather, A. S. (1992). The forest transition. *Area*, 24(4):367–379. 1

Mather, A. S. (2007). Recent asian forest transitions in relation to forest-transition theory. *International Forestry Review*, 9(1):491–502. 2, 2

Ollivier, H. (2012). Growth, deforestation and the efficiency of the REDD mechanism. *Journal of Environmental Economics and Management*, 64(3):312 – 327. 2

Perz, S. G. and Skole, D. L. (2003). Secondary forest expansion in the brazilian amazon and the refinement of forest transition theory. *Society and Natural Resources*, 16(4):277–294. 2

Rudel, T. K., Coomes, O. T., Moran, E., Achard, F., Angelsen, A., Xu, J., and Lambin, E. (2005). Forest transitions: towards a global understanding of land use change. *Global Environmental Change*, 15(1):23 – 31. 2

Simonet, G. and Wolfersberger, J. (2014). Forest transition and redd+ in developing countries: challenges for climate change mitigation. *Les Cahiers de la Chaire Economie du Climat*, Information and debates Series(29).

Stephenson, N. L., Das, A. J., Condit, R., Russo, S. E., Baker, P. J., Beckman, N. G., Coomes, D. A., Lines, E. R., Morris, W. K., Ruger, N., Alvarez, E., Blundo, C., Bunyavejchewin, S., Chuyong, G., Davies, S. J., Duque, A., Ewango, C. N., Flores, O., Franklin, J. F., Grau, H. R., Hao, Z., Harmon, M. E., Hubbell, S. P., Kenfack, D., Lin, Y., Makana, J. R., Malizia, A., Malizia, L. R., Pabst, R. J., Pongpattananurak, N., Su, S. H., Sun, F., Tan, S., Thomas, D., van Mantgem, P. J., Wang, X., Wiser, S., and Zavala, M. A. (2014). Rate of tree carbon accumulation increases continuously with tree size. *Nature*, advance online publication(1476-4687). 2

Wolfersberger, J., Delacote, P., and Garcia, S. (2013). An empirical analysis of the cumulative nature of deforestation. *Working Paper Chaire Economie du Climat*. 5