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GROWTH, GREEN CAPITAL AND PUBLIC POLICIES

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We study sustainable growth in an economy with natural land endowments, specifically forests, and the need for public policies to quantify the financial value of green capital, measured by forests. Exhaustible primary forests are first depleted for agriculture and production, until a switch occurs to the renewable secondary forests. The introduction of REDD+ in the economy reduces agricultural expansion, since the social planner invests in green capital, at the expense of the physical one. We show that the optimal REDD+ national strategy highly depends on the development stage of the recipient economy. In the end, we prove our findings by calibrating our model to Indonesia and illustrate recommendations for public policies.

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1 Introduction

Agriculture, forestry and other land uses (AFOLU) represent a quarter of the total anthropogenic GHG emissions in the world (IPCC, 2014). New agricultural lands take place on previously forested lands, through deforestation (Gibbs, 2010). In this context, REDD+ (Reducing Emissions from Deforestation and forest Degradation) was created to assign a financial value to the carbon stored in forests. Developing countries are financially rewarded for their efforts to reduce forests depletion that causes carbon emissions. In this paper, we model economic growth in a country with forest endowments, and envisage the application of REDD+.

The evolution of the forest cover in a country with important endowments is strongly related to economic development. Mather (1992) first formalized the description of this evolution over time, and it is known as the forest transition. On the basis of France, Hungary and USA, the author shows that the evolution of the forest cover in a country follows a U-shape. A large phase of deforestation is followed by a phase of reforestation. Each phase can last several centuries and corresponds to a specific development stage. In this paper, we refer to the first development stage as the phase where net deforestation occurs, and to the second development stage as the reforestation phase of the forest transition. The point in time where the forest cover reaches its minimum is called the turning point. This is also the point where a switch in development occurs, from the first to the second stage. For instance, France and USA respectively experienced their turning points during the XVIIIth and XIXth centuries. Nowadays, countries such as Costa Rica, China, India and Vietnam are experiencing such a transition from shrinking to expanding forest area.[1] The forest transition concept is related to the Environmental Kuznets Curve framework. The first development stage implies a high level of environmental degradation, until a point where growth slowly becomes sustainable. The forest transition follows the same trend, with first deforestation and then reforestation, as illustrated in Figure 1.

It is composed of two separated land use processes (Grainger, 1995), based on two types of forests: primary and secondary. The distinction between primary and secondary forests is a major focus, notably in climate ecology, since those two types of forest do not have the same environmental properties. Luyssaert et al. (2008) argued that old-growth forests (i.e. primary) store centuries worth of carbon reserves. On CO_2 emissions, it is thus more efficient, at least over the short and mid terms, to preserve primary forests rather than seek to plant new ones. Moreover, Stephenson et al. (2014) found that old-growth forests capture more carbon than new forests, despite the fact that new forests grow faster. This has major implications to combat climate change, and highlights a first critical feature of primary forests. Regarding biodiversity, Burley (2002) showed that old tropical forests shelter 50% of the known vertebrates, and 60% of plant species. He argues that 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

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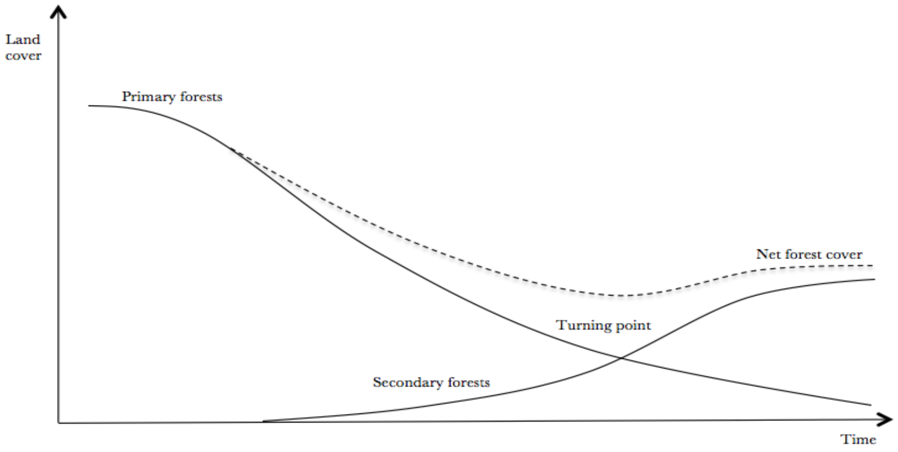
[1] For instance, please find in the Appendix an empirical illustration of the forest transition in Vietnam.

Figure 1: The forest transition



from this literature establishes that primary forests indeed have a higher marginal environmental value than secondary ones in terms of both carbon and biodiversity. Moreover, as primary forests are undisturbed forests, i.e. native species not impacted by human activity, it can be considered as a non-renewable resource. On the contrary, secondary forests are considered as a renewable resource, through natural regeneration and plantations.

It is empirically observed that because countries with forest endowments were originally covered with primary forests, this is the first stock that is depleted during economic development. Meanwhile, the stock of secondary forests grows. Once a certain level of primary forests depletion is reached, secondary forests start being harvested. The switch from one type of forest to another is important since the harvesting of primary forests is more harmful for environment. This is why we study this switching time in this paper. One may notice that this long-run evolution of the forest management corresponds to the framework of energy transition. Production is based on different stocks depending on the development stage, with first the use of exhaustible resources and then renewable ones.

To date, economists have studied development in economies with forest endowments in a variety of ways. Hartwick et al. (2001) analyzed 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. However, it does not consider the influence of a public policy to halt deforestation, nor its impact on growth. Barbier et al. (2005) used an optimal control model to examine how lobbying can influence the long-term conversion rate of forests, but not considering reforestation or REDD+. Using a similar approach, Ollivier (2012) investigated the effect of REDD+ transfer schemes on long-term land conversion and growth, but without considering reforestation. Using a land-use model, Wolfersberger et al. (2014) first introduced the distinction between primary and secondary forests within a forest transition theoretical framework, and discussed the role of land tenure costs for reforestation. None of these studies examine, like we do here, the level of growth when a country deforests and reforests, the switching time from primary to secondary forests harvesting, and the policy instruments that can be applied to forest cover change. These aspects of deforestation are critical however, in designing the optimal policies that target forest cover loss or ecosystem services, such as REDD+. Our work makes it possible to improve the understanding on the impact of different types of REDD+ programs (i.e. limiting deforestation, promoting reforestation, or both) on land use and growth in developing countries. The model we develop also considers the importance of the transition stages when implementing REDD+. In this paper, the transition stages designate a countries' position on the forest transition. Early transition stage corresponds to countries that have not started large deforestation yet, e.g. Congo, Gabon or Guyana, while late transition stage corresponds to countries close to the turning point, e.g. Chile, Mexico, Vietnam. Doing this, we provide new insights for the international discussions on the design of REDD+ national strategies that remain unclear today (Angelsen et al., 2009). To be more precise, we also calibrate our model to the Indonesian economy, as it is one of the emerging economies in which deforestation is a major issue.

Our modeling approach leans on the literature that started with Heal (1976). We determine the pace of consumption in the forest economy and we distinguish physical from green capital. The latter is represented by the stock of natural resources, that is forest in our model. The evolution of consumption is our index of economic growth in the economy, and we consider a weak sustainability criteria. In accordance with empirical observations, we find that exhaustible primary forests are first solely harvested for production, until a switch occurs and secondary renewable forests are used until the end of the transition. When introducing REDD+, as it is currently observed in several developing countries,[2] we find that the level of economic growth increases, and that the transition stage of the country plays a crucial role for the efficiency of the mechanism. We also highlight the existing tradeoff between physical and green capital. REDD+ constitutes a rent on green capital that allows the reduction of agricultural expansion. In the end, by calibrating our model to Indonesia, we show that REDD+ in this country imposes a tradeoff between the highest economic or ecological output.

The remainder of the article is organized as follows. Section 2 details the benchmark model, without public policy. We analyze the conditions of the long-run growth in the economy, the transition from depletion of primary forests to sustainable harvesting of secondary forests, and the tradeoff between physical and green capital. In Section 3, we introduce REDD+, outline its impact on land uses and growth, and highlight the importance of the different transition stages. In Section 4, we calibrate the model to Indonesia and discuss the optimal REDD+ national strategy for the country. Section 5 concludes.

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[2] In December 2013, REDD+ counted 47 country participants, with 18 in Africa, 18 in Latin America, and 11 in the Asia-Pacific region.

2 The model

Consider an economy with a land endowment normalized to one unit. Initial stock of primary forest cover is defined by $S_0 = \overline{S}$, and S_t is the stock of primary forest at time t. This stock is an exhaustible resource. Denote by X_t its deforestation rate at time t, with $X_t \geq 0$. Initial stock of secondary forest cover is given by $R_0 = \overline{R}$, and R_t is the stock of secondary forest at time t. This model assumes this resource is renewable, either through natural regeneration or plantations, with $g(R_t)$ the renewable function ($g'_R > 0, g''_{RR} < 0$). Denote by Q_t (with $Q_t \geq 0$) the deforestation rate of this forest stock, it evolves as $\dot{R}_t = g(R_t) - Q_t$. The total land area is normalized to 1, with $A_t = 1 - R_t - S_t$ the area under croplands. In the current literature on this topic only one stock of forest can be harvested. We present here, through Q_t and X_t the social planner can deforest in both primary and in secondary forests.

The production $Y(A_t, K_t, W_t)$ is composed with physical capital K_t, and land uses that encompass agricultural land expansion A_t and deforested lands $W_t = Q_t + X_t$. We assume that the production function is concave in all arguments, with $Y'_A \geq 0$, $Y'_K \geq 0$ and $Y'_W \geq 0$.

The level of production in the economy is subject to a feedback from the forest stock, given by $\delta H(R_t, S_t)$, with $H'_R \geq 0, H'_S \geq 0$ and $H''_R \leq 0, H''_S \leq 0$, and $0 < \delta < 1$.[3] This specification means that the production is positively impacted by the level of green capital in the economy, and negatively related to the level of cumulative deforestation. For instance, as a result of a variety of environmental damages (floods, desertification...) caused by long-term deforestation, China implemented major reforestation programs in the 1980s (Mather, 2007). This link between cumulative deforestation and production is also modeled in Ehui and Hertel (1989), Ehui et al. (1990), Barbier et al. (2005) and Ollivier (2012). More broadly, the presence of green capital can be associated with lower levels of pollution and climate change, and thus with a positive externality on overall production capacities (Heutel, 2012; Annicchiarico and Dio, 2015). The whole output in the economy can then be written as:

$$F(R_t, S_t, K_t, Q_t, X_t) = Y(1 - R_t - S_t, K_t, Q_t + X_t)\delta H(R_t, S_t). \tag{1}$$

The social planner solves the following optimal control problem:

$$\max_{\{C_t, Q_t, X_t\}} \int_0^\infty e^{-\rho t} u(C_t) dt \tag{2}$$

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[3] This specification gives value to the forest cover *in situ*, but does not lead to a null output even if $A_t = 1$.

Subject to the following constraints reflecting our discussion above:

$$\begin{aligned}
\dot{S}_t &= -X_t, && (3)\\
\dot{R}_t &= g(R_t) - Q_t, && (4)\\
\dot{K}_t &= F(R_t, S_t, K_t, Q_t, X_t) - C_t - \gamma Q_t - \theta X_t, && (5)\\
A_t &= 1 - S_t - R_t, && (6)\\
F(R_t, S_t, K_t, Q_t, X_t) &= Y(1 - R_t - S_t, K_t, Q_t + X_t)\delta H(R_t, S_t), && (7)
\end{aligned}$$

with $C_t \geq 0, K_t \geq 0, Q_t \geq 0, R_t \geq 0, S_t \geq 0, X_t \geq 0$ and $S(0) = S_0, K(0) = K_0, R(0) = R_0$. With C_t the amount of consumption at each time-period t, and $u(C_t)$ the utility function. The costs of harvesting primary and secondary forests are θX_t and γQ_t respectively. These costs include the technology associated with land clearing, and the cost of the settlement of croplands when conversion occurs for agriculture. We exclude capital depreciation for simplicity and without loss of generality. We impose that the utility function is at least twice continuously differentiable and has the standard properties of $u'(C) > 0$, $u''(C) < 0 \ \forall C$. We assume $u'(0) = +\infty$.

The optimization problem can be rewritten in Lagrangian form as follows:

$$\mathcal{L}_t = \mathcal{H}_t + \omega_Q Q_t + \omega_X X_t,$$

where $\mathcal{H}(t)$ is the constant value Hamiltonian and given by:

$$\mathcal{H} = U(C_t) + \lambda_t(\dot{K}_t) + \phi_t(\dot{S}_t) + \mu_t(\dot{R}_t),$$

with λ_t, ϕ_t and μ_t the shadow values of physical capital, primary and secondary forests respectively. As in Hartwick et al. (2001), Ollivier (2012) and Wolfersberger et al. (2014), the shadow values of the resources have particular significance, since total land is normalized at the unit. ϕ_t represents the relative desirability of primary forests compared to both agriculture and secondary forests. Likewise, μ_t represents the relative desirability of an additional hectare of secondary forest at the expense of both agriculture and primary forest. Using the Prontryagin's Maximum Principle we obtain the first order conditions for the optimal paths of consumption and land use. The first-order conditions with respect to C_t, X_t and Q_t are:

$$\begin{aligned}
\lambda &= U'(C_t), && (8)\\
\phi &= \lambda(F'_X - \theta) + \omega_X,\ \omega_X X_t = 0, && (9)\\
\mu &= \lambda(F'_Q - \gamma) + \omega_Q,\ \omega_Q Q_t = 0. && (10)
\end{aligned}$$

From (9) and (10), we see that primary and secondary forests are deforested only when the marginal productivities of deforestation F'_X and F'_Q exceed their marginal costs θ and γ. The dynamics of the co-state variables are given by:

$$
\begin{aligned}
-\lambda F'_K &= \dot{\lambda} - \rho\lambda, && (11)\\
-\lambda F'_S &= \dot{\phi} - \rho\phi, && (12)\\
-(\lambda F'_R + \mu g'_R) &= \dot{\mu} - \rho\mu. && (13)
\end{aligned}
$$

The transversality conditions read:

$$
\begin{aligned}
\lim_{t\to\infty} \phi(t)S(t)e^{-\rho t} &= 0,\\
\lim_{t\to\infty} \mu(t)R(t)e^{-\rho t} &= 0,\\
\lim_{t\to\infty} \lambda(t)K(t)e^{-\rho t} &= 0.
\end{aligned}
$$

From (11) one can easily verify that the discount rate ρ in the economy is equal to $F'_K + \dot{\lambda}/\lambda$. In (12) and (13), we have $F'_S = \delta(H'_S Y - Y'_S H)$ and $F'_R = \delta(H'_R Y - Y'_R H)$. Then, the marginal benefit from converting one hectare of primary forests in agriculture increases with the marginal productivity Y'_S net of the negative environmental externality H'_S. The same applies for secondary forests, with Y'_R and H'_R.

2.1 Consumption pace and resource prices

Using the first-order conditions and rearranging, we obtain the following optimal path for consumption:

$$
\frac{\dot{C}_t}{C_t} = \epsilon(F'_K - \rho). \tag{14}
$$

Above is the Keynes-Ramsey rule, which states that the growth of consumption must equalize the net return from capital, with $\epsilon = -u'(C)/Cu''(C)$ the intertemporal elasticity of substitution. The lower ϵ is, the smoother will be the consumption along the forest transition. From the first-order conditions it is also possible to express the marginal returns from capital as a function of the two types of forest:

$$
\begin{aligned}
F'_K &= \frac{\dot{F}'_X + F'_S}{(F'_X - \theta)}, \text{ and} && (15)\\
F'_K &= \frac{\dot{F}'_Q + F'_R}{(F'_Q - \gamma)} + g'_R. && (16)
\end{aligned}
$$

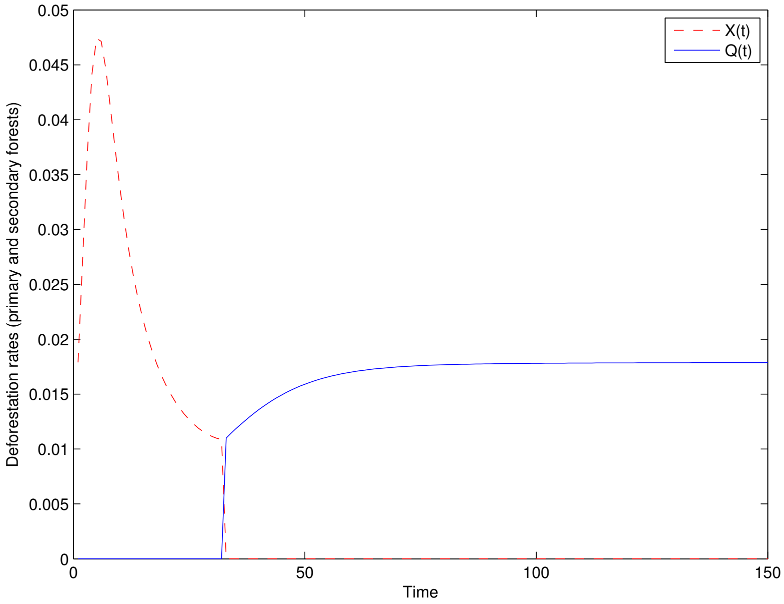
Equations (15) and (16) state that the forests prices, i.e. their marginal productivities, must increase at a rate that equals the marginal return from capital. It defines the optimal deforestation paths and corresponds to the Hotelling's rule in our production-consumption economy. In (16), we can see that the price associated with secondary forests includes the marginal growth g'_R since this resource is renewable.

2.2 From depletion to sustainable harvesting

Primary native forests are depleted during the national land use transition, and then secondary forests are used during the forest replenishment period (Grainger, 1995). In terms of production, it means that the most valuable and exhaustible forests are first harvested, before a time of sustainable production, based on forests with a lower value (secondary forests from natural regeneration or plantations). This paradigm has been observed in many developed nations, e.g. England, France, Germany, USA, and is now observable in less developed ones, e.g. China, Costa Rica, India, Vietnam. Production is then based on different stocks, depending on the development stage. It is important to understand the switch occurring in production (from primary to secondary forests), since it may help public policies to preserve a larger share of the most valuable forests that are depleted during the first development stage.

Our model enables us to study the switching time. Using the complementarity slackness conditions, we can distinguish different time-periods. First we have $X_t > 0, Q_t = 0$. It implies that $F'_X = \theta + \phi/\lambda$ and $F'_Q < \gamma + \mu/\lambda$. During this period, only primary forests are harvested. Second, assuming $X_t > 0, Q_t > 0$, implies that $\phi = \lambda(F'_X - \theta)$ and $\mu = \lambda(F'_Q - \gamma)$. It means that deforestation takes place in the two types of forest. Finally $X_t = 0, Q_t > 0$, implies $F'_Q = \gamma + \mu/\lambda$ and $F'_X < \theta + \phi/\lambda$. Here, only renewable secondary forests are harvested. Our findings are illustrated by numerical results in Figure 2. All the details on the realization of the numerical computations of this paper, including the explicit program and the parameter values, are given in Appendix A.

Figure 2: Harvesting in time



The first $(X_t > 0, Q_t = 0)$ and the second $(X_t > 0, Q_t > 0)$ time-periods can be viewed as non-sustainable, since exhaustible primary forests are harvested. The third time-period $(X_t = 0, Q_t > 0)$ corresponds to a case of a sustainable use of a renewable resource.

2.3 Steady-state analysis

In steady state, $\dot{C}_t = \dot{K}_t = \lambda = \dot{R}_t = Q_t = \mu = \dot{S}_t = X_t = \phi = 0$, $F'_X = \theta$ and $F'_Q = \gamma$. From (14), we find that the marginal productivity of capital F'_K is equal to the discount rate ρ. Likewise in steady state, from equations (15) and (16), the prices of each type of forests are equals:

$$\frac{F'_S}{(F'_X - \theta)} = \frac{F'_R}{(F'_Q - \gamma)} + g'_R. \tag{17}$$

This equality ensures a constant evolution of the land use in the economy over the long-run, as illustrated in Figure 3.

Figure 3: Land uses in the BAU scenario

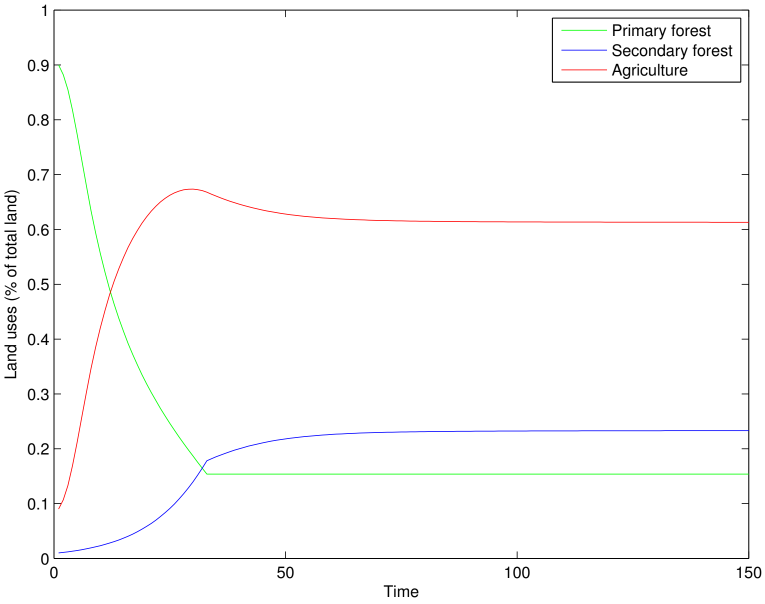


Figure 3 highlights the features of the first and the second development stages, corresponding to the phases of the forest transition, that lead to the steady state. First, land-use competition opposes primary forests and agriculture. The former are converted into croplands for income, food and energy, through X_t. Meanwhile secondary forests, R_t, take place on the least productive lands that have been abandoned, and in some parts of the country where their rents are higher than that of both primary forests and croplands. At this point, $g(R_t)$ is higher than Q_t, i.e. renewal is larger than harvesting. During the second stage primary forests, S_t, are no longer harvested $(X_t = 0)$, and the social planner starts using secondary forests $(Q_t > 0)$. At this point, the stock of agriculture

$(1-R_t-S_t)$ reaches its maximum, thanks to agricultural land expansion. This is the turning point, the total forest cover is minimum and it will not decrease anymore. Wolfersberger et al. (2014) showed that at this point, the marginal utility associated with lands under agriculture is equal to that of lands under primary and secondary forests. During the third stage, the least profitable agricultural lands return to forest (natural regeneration or plantation of secondary forests) and the total forest cover increases. Finally, the steady state is reached and secondary forests are sustainably managed ($\dot{R}_t = \dot{S}_t = 0$ and $g(R_t) = Q_t$).

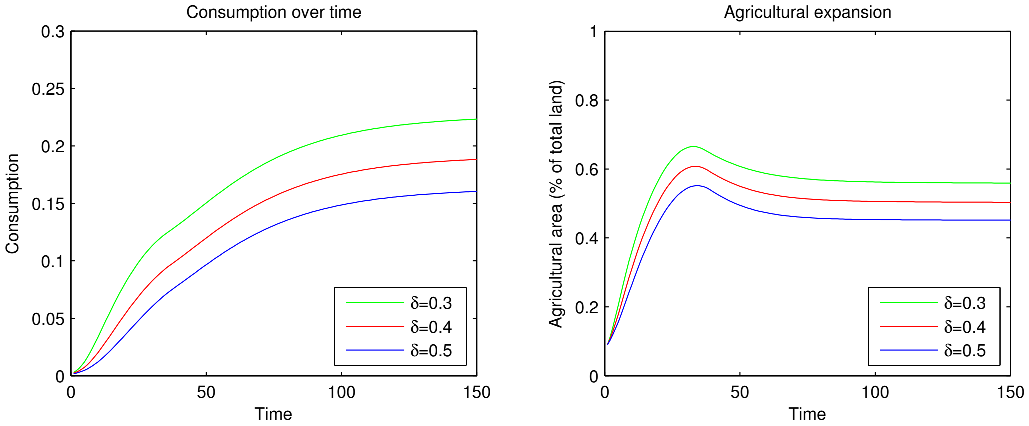
2.4 Production versus preservation

In terms of land use, the economy produces over agricultural area A_t and deforested lands W_t. In the meantime, there is a positive feedback on productivity from preserving forests, given by $\delta H(R_t, S_t)$. Then, converting more forest area allows obtaining more croplands A_t for production, but deteriorates the system of production by lowering $\delta H(R_t, S_t)$.[4] As a result, a tradeoff between production and preservation takes place.

Let us investigate this tradeoff using the results from the general form of the model. From (12), we can write: $\dot{\phi} = \rho\phi - \lambda F'_S$. The variation of the shadow value associated with the conversion of an additional hectare of primary forest $\dot{\phi}$, increases with the net marginal productivity of the land deforested, given by ϕ, but decreases with the positive externality of primary forest on production F'_S. The same applies for the secondary forest, using the equation (13).

In Figure 4, we illustrate the tradeoff existing between production and preservation. To do this, we use the parameter δ that weights the feedback from green capital on productivity in the economy.[5]

Figure 4: Consumption, Agriculture and feedback green capital



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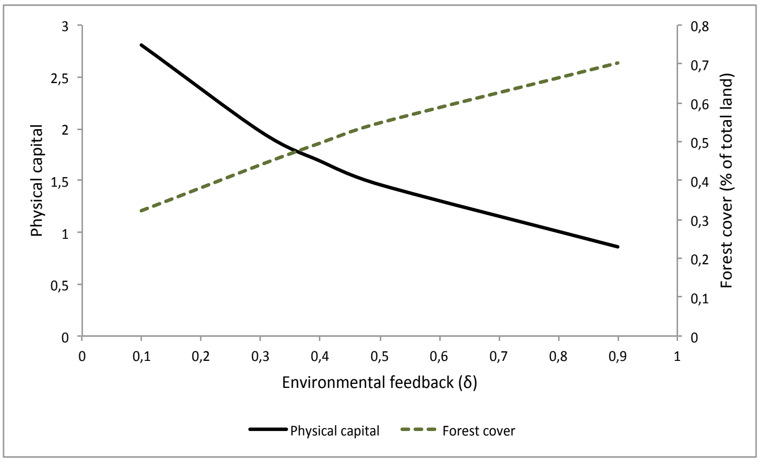
[4] This deterioration is given by the different environmental damages associated with deforestation, such as carbon emissions, losses in soil and water quality, decrease of biodiversity, less precipitation, natural disasters etc.

[5] Appendix A details the explicit form of the production function $F(.)$.

The higher the effect of the environmental feedback is, the more the tradeoff is in favor of forests. Indeed, the total agricultural expansion is lower during a country's development when this country is more dependent on green capital. This result from our model is in accordance with empirical facts and highlights the role of forests in maintaining a sustainable level of production in the economy. This unavoidable preservation of the forests induces a lower level of consumption.

Our analysis thus shows the complementarity that exists between environmental preservation (here forests) and production. It is important for an economy with large initial forest endowments to save a share of those endowments in order to ensure a sustainable level of production. The forests constitute a green capital. However, we observe that this particular type of capital is not financially rewarded since consumption is lowered when more forests are saved. There is thus a tradeoff opposing physical and green capital, as highlighted in Figure 5.

Figure 5: The relationship between physical and green capital



The green capital is given by the stock of total forest cover. We can see that the comprehensive level of wealth in the economy, represented by the accumulation of physical capital, is decreasing in green capital. This effect is identified as a result of reduced production caused by the variation of dependence on deforestation. As detailed above, a higher δ means a higher sensibility to the environmental damages caused by forests depletion.

In all, looking at consumption and capital accumulation, we can deduce that there is at present no financial incentive to protect forests. For this reason, we now investigate the potential role of public policies such as REDD+ which can quantify the value of green capital.

3 Introduction of REDD+

The aim of REDD+ is to reduce deforestation by assigning a financial value to the carbon sequestrated in tropical forests. The developing economy maximizes its level of consumption over time by converting forests into agriculture. The environmental damages caused by deforestation on production are taken into account through the feedback $\delta H(R_t, S_t)$. However, the impact on global climate change is not internalized by the developing country. For this reason, the international community offers a transfer aiming at the reduction of deforestation.

In order to ensure REDD+ is effective, tropical forest countries must define a plan of actions at the national scale, known as "national REDD+ strategy". Among others, the objectives are to coordinate local projects, to define spatial planning policies and to avoid leakage effects. However, as of today, countries' national strategies are still under discussions and remain unclear (Angelsen et al., 2009). Our work endeavors to clarify these and to bring results that may help designing the implementation of programs at the national scale.

A major added value of our model is that it makes it possible to study the impact of different types of REDD+ programs. More precisely, we can consider actions either on the dynamics of primary or secondary forests. Actions on the dynamics of primary forests aim at reducing forest losses, e.g. protected areas, forest conservation. These are known as Reduced Emissions from Deforestation (RED) programs. Actions on the dynamics of secondary forests aims at increasing the forest stock, e.g. plantations, rehabilitation, sustainable management. These are known as Afforestation/Reforestation (AR) programs. For comparison purposes, we also include a mixed program in our analysis, based on both RED and AR activities. It corresponds to a situation in which the country's national strategy is not clearly oriented on a single objective, i.e. protecting primary forests or promoting reforestation of secondary forests.

As we focus on the tradeoff between the accumulation of physical capital and the effort to either reduce deforestation or increase reforestation, we do not consider the consequences of Northern countries' investing in the South.

3.1 Assigning value to the resource in situ

Consider an incentive scheme by which the international community offers a transfer T to a country in order to reward the preservation of the forest area. The conservation of the forest cover, without distinction between forest types, is the first option (FC). The second and the third options are respectively the preservation of the primary forest (RED), and the reforestation of the secondary one (AR). The three programs, together with the Business-As-Usual (BAU), are summarized in Table 1. BAU refers to the case in which REDD+ is not implemented. The financial transfer T, funded by the international community to reduce deforestation, feeds the capital of the recipient economy, and is applied over the whole transition. The implementation of a public policy at different transition stages is considered later in this paper.

The parameter υ is the rate of transfer per unit of preserved forest area.[6] Basically, in facts, the transfers $T(.)$ correspond to the improvement of institutions, the education of local people to

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[6] Local projects might consider different values of υ, reflecting the ecological value of the targeted forest. We do not consider it here, in order to be able to compare the programs.

Table 1: Public policies on forests stock

Description	Scenario	Additional capital gains
Business-As-Usual	BAU	-
Protecting the total forest cover	FC	$T(S_t, R_t) = \upsilon\frac{1}{2}(R_t + S_t)$
Rewarding the preservation of primary forests	RED	$T(S_t) = \upsilon S_t$
Promoting the establishment of secondary forests	AR	$T(R_t) = \upsilon R_t$

sustainable forestry practices, the implementation of a Measurement, Reporting and Verification (MRV) system, etc. As our model does not aim at studying some specific REDD+ measures at a microeconomic scale, when aggregating, the incentive schemes are similar to a global payment related to the effort of preserving forest cover.

Let us now illustrate the analytical results by providing the solutions of the RED program, $T(S_t)$. We choose this one because it concerns the most valuable forests. Also, given the form of the different transfers $T(.)$, the results are also valid for the two other programs, FC and AR.[7] The social planner still maximizes its level of consumption as:

$$\max_{\{C_t, Q_t, X_t\}} \int_0^\infty e^{-\rho t} u(C_t) dt, \tag{18}$$

Subject to the following constraints:

$$\begin{aligned}
\dot{S}_t &= -X_t, & (19)\\
\dot{R}_t &= g(R_t) - Q_t, & (20)\\
\dot{K}_t &= F(R_t, S_t, K_t, Q_t, X_t) - C_t - \gamma Q_t - \theta X_t + T(S_t), & (21)\\
A_t &= 1 - S_t - R_t, & (22)\\
F(R_t, S_t, K_t, Q_t, X_t) &= Y(1 - R_t - S_t, K_t, Q_t + X_t)\delta H(R_t, S_t), & (23)
\end{aligned}$$

with $C_t \geq 0, K_t \geq 0, Q_t \geq 0, R_t \geq 0, S_t \geq 0, X_t \geq 0$ and $S(0) = S_0, K(0) = K_0, R(0) = R_0$.

While other first-order-conditions and the transversality conditions stay unchanged, (12) becomes:

$$\dot{\phi} = \rho\phi - \lambda(F'_S + T'_S). \tag{24}$$

From (24), it is interesting to see that now, the shadow price of the conversion of one hectare of primary forests decreases with the marginal benefit from the REDD+ transfer T'_S. Consumption pace can now be written as:

$$\frac{\dot{C}_t}{C_t} = \epsilon\left(\frac{\dot{F}'_X + F'_S + T'_S}{(F'_X - \theta)} - \rho\right). \tag{25}$$

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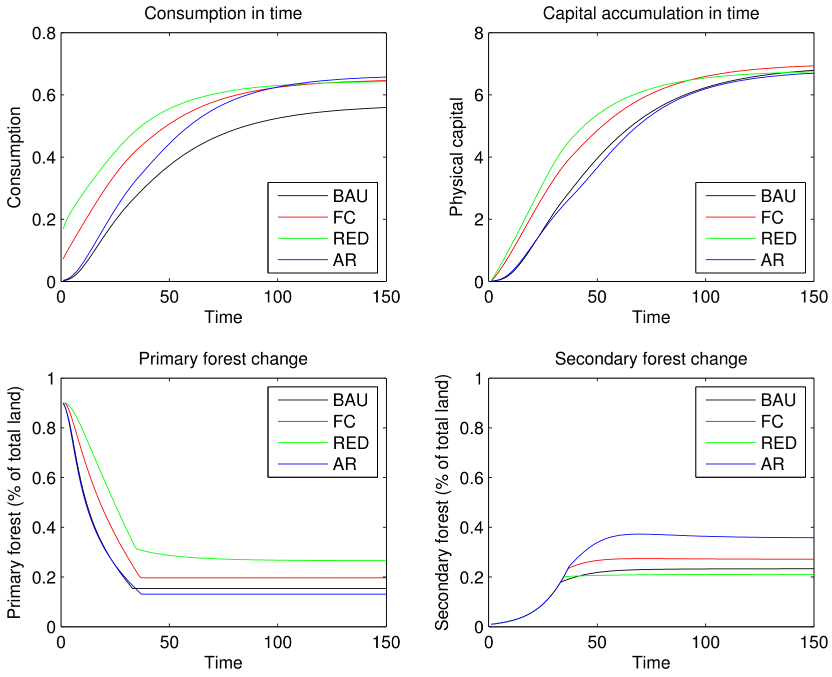
[7] Please, find the proofs for FC and AR in Appendix B.

A higher T'_S thus implies a higher level of consumption.[8] Figure 6 illustrates those results.

Figure 6: The impact of REDD+ in the economy



The level of consumption is always higher with REDD+ than without. The more the payment is based on primary forest, the highest the initial consumption C_0 is. REDD+ is thus a way to value the initial green capital in the economy, i.e. the natural endowments in primary forest. As we can see on Figure 6 and Table 2, the gain in consumption is not based on a larger level of deforestation, as more forest cover is preserved than in BAU.

Table 2: Forest cover change under the different REDD+ programs

Program	$\sum_t (S_t - S_{BAU})$	$\sum_t (R_t - R_{BAU})$
FC	12.9	7.9
RED	30.5	-3.5
AR	-3.3	21.5

The loss of secondary forest with RED, and the loss of primary forest with AR, is a result in accordance with Wolfersberger et al. (2014). When public policies target one specific type of forest, there is a direct effect that boosts the share of this forest in total land. However, there is

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[8] Note that we have also tested other forms for the REDD+ programs, with, for instance, explicit levels of reference. It does not modify the results and the general conclusions of this work.

also an indirect effect by which the other type of forest decreases. As a consequence, programs of reforestation can lead to a larger depletion of primary forests.

In Figure 6, examining consumption over time, two periods can be distinguished. Early in the transition, from 0 to 60, the conservation of the primary forests yields the highest level of consumption, thanks to the initial stock. From time-period 60 to 150, this is the payment for establishment of secondary forest (AR) that provides the highest level of consumption. Over the long-run, while growth under FC and RED remains important, the absence of REDD+ (BAU) gives the lowest level. It is always beneficial to participate in REDD+ for the developing economy. Another interesting piece of information comes from the fact that FC never provides the highest output in terms of growth. Finally, our numerical results indicate that, in terms of costs, $T(S_t) > T(R_t) > T(R_t, S_t)$. In other words, RED is the most costly program for the international community, while FC is the least.[9]

Then, over the total transition, in spite of the fact that it is the most costly, the RED program should be implemented. Indeed, this program allows to preserve the highest amounts of both primary forest and total forest cover, as shown in Table 2. The FC program presents the advantage of being the least costly for the international community, but it never yields the highest amount of consumption for the recipient economy. Implementing AR may lead to the highest consumption over the long-run, but it also leads to the lowest level of primary forest preservation.

3.2 Aligning public policies with transition stages

In this section, we study the implementation of REDD+ at different stages of the forest transition. Countries involved in REDD+ are not all at the same level of development, and thus, not at the same level of cumulative deforestation.[10] For instance, Congo and Guyana have a high forest cover remaining and a low level of development. In those countries, the average of the GDP per capita was $812 US dollars in 2013 (World Bank Data). On the contrary, countries such as Mexico or Vietnam are assumed to be at the turning point, i.e. these have largely harvested their forests in the past. Their averaged GDP per capita was $4774 US dollars in 2013. This heterogeneity within participants may involve differences regarding programs' efficiency.

To investigate this, we introduce the AR, FC and RED programs at two different time-periods: t=10 (early transition stage) and t=50 (late transition stage). The early transition stage corresponds to countries such as Congo and Guyana, while the late transition stage conforms to Mexico and Vietnam.

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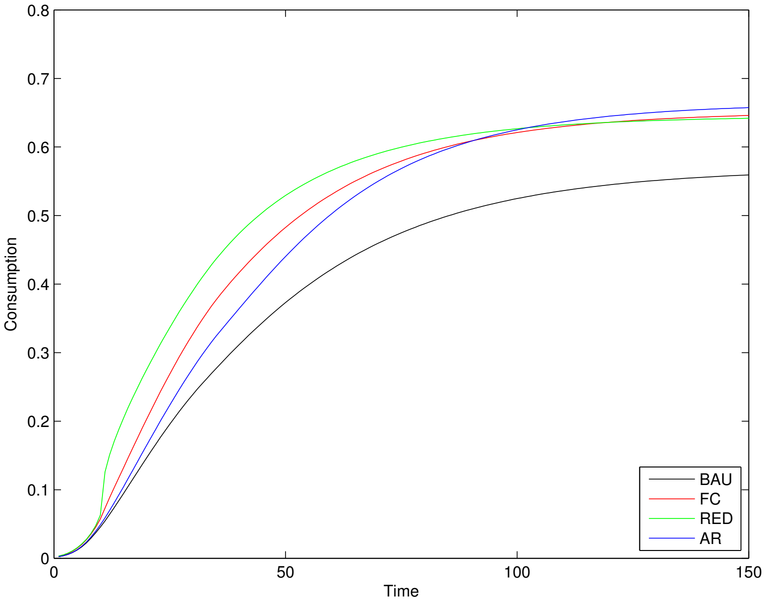
[9] Please find, in the Appendix C, a representation of the costs, in time, of all the public policies studied in this paper.

[10] By cumulative deforestation we mean the total amount of forest depletion before the implementation of REDD+. On this, see for instance Wolfersberger et al. (2013).

Early transition stage

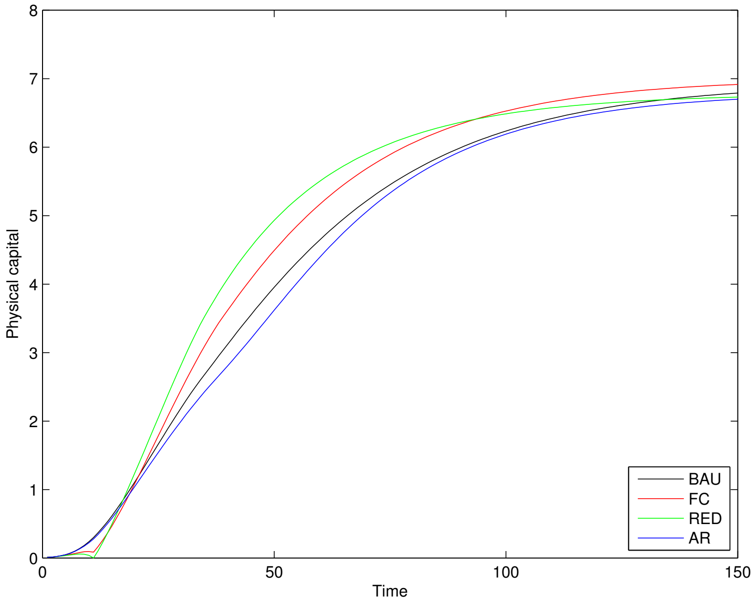
Figure 7 represents the consumption in BAU and when REDD+ is implemented at the 10th time-period.

Figure 7: Consumption and REDD+ in early transition stage



The patterns of consumption are similar to our findings when REDD+ was applied over the whole transition (Figure 6). This was expected since the delay before the implementation, ten years, is quite short. Examining the areas, the highest level of consumption is reached with RED. To obtain the best output in terms of economic growth, REDD+ should be utilized in the protection of primary forest in countries with a large stock of forest remaining. Let us now look at the physical capital in Figure 8.

Figure 8: Physical capital and REDD+ in early transition stages



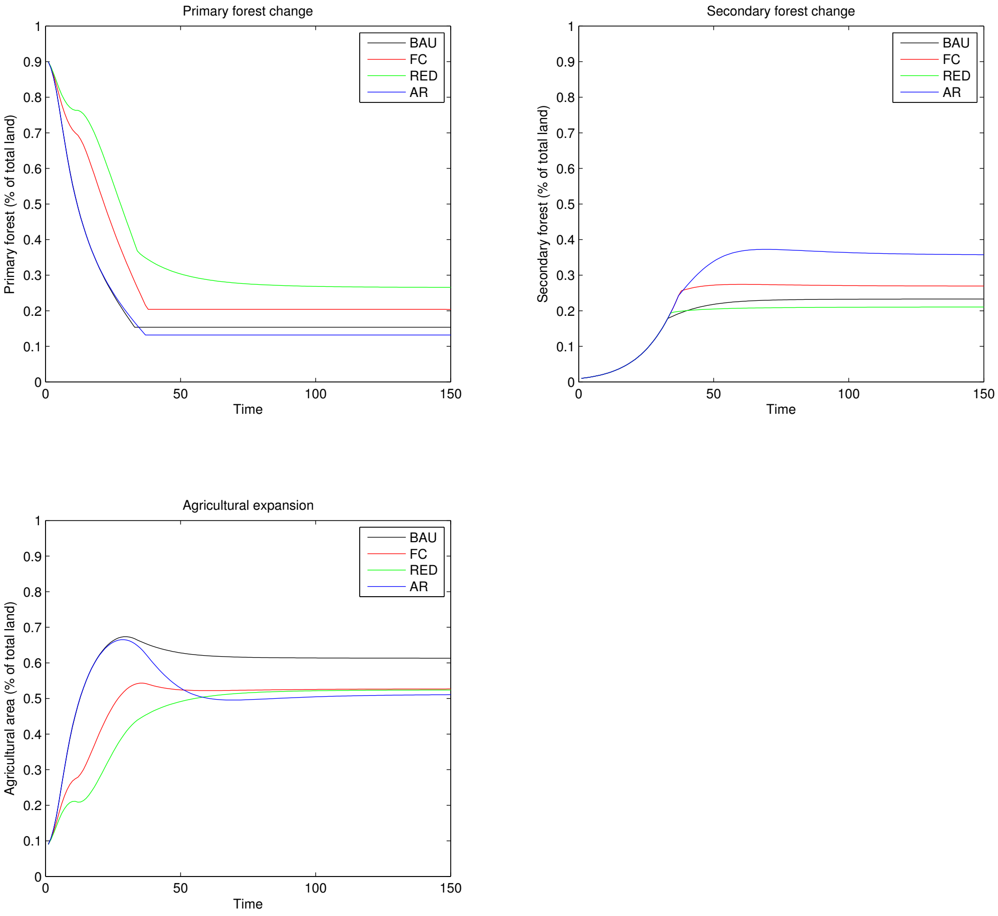
Over the long-run, the stock of physical capital in the economy is higher with REDD+. However, it is interesting to notice that this is not verified to be true over the short-run. Since AR is the only program in which primary forests are not considered, its trend differs from that of FC and RED programs. The three programs exhibit a certain time with a level of physical capital lower than in absence of REDD+ (BAU). This result is very important, and needs to be linked with the land uses given in Figure 9.

With REDD+, agricultural land expansion is lower than in BAU. More forest area is preserved as REDD+ adds a financial value to it (compare to BAU). This preservation occurs at the expense of the stock of physical capital, as less agricultural area is available for production.

The social planner thus invests in green capital, at the expense of physical capital. Green capital is represented by the stock of forest, valued by REDD+. It is now optimal to save more forest (in comparison with BAU), in order to obtain a rent later. This rent is paid at an interest rate given by the level of REDD+ compensation.

The highest share of primary forests is preserved with RED, and then with FC. Since with AR the only incentive to preserve these forests is the environmental feedback on production, the social planner deforests a larger amount and makes space for secondary forests. A few periods before the switch to renewable forests, the country also invests in green capital (secondary forests) to receive a rent until the end of the transition. To summarize on this point, under AR, agricultural expansion is similar to BAU during the first development stage (Figure 9) since there is no incentive to conserve primary forest. Once the turning point is reached, croplands are then re-converted into secondary forest. This conversion is important since the level of agricultural land in steady state

Figure 9: Land uses with REDD+ in early transition stages



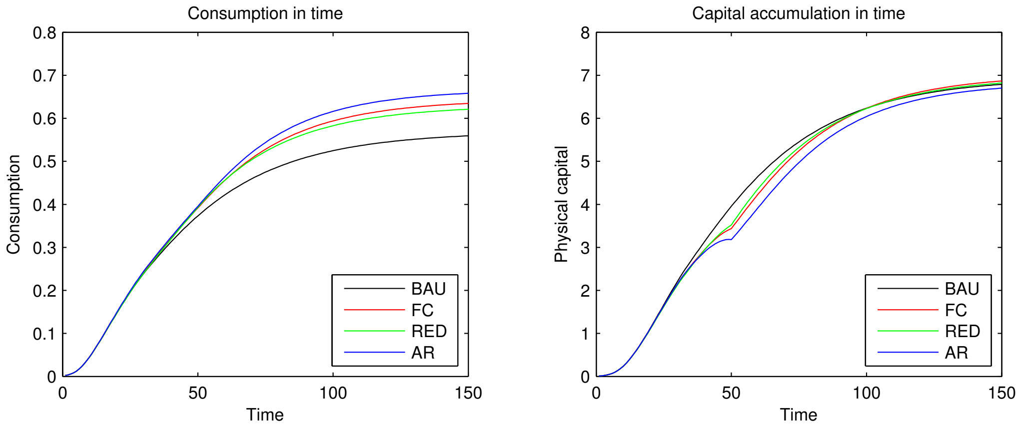
ends up to be lower than under FC and RED. Looking at the costs of the different programs, we find that $T(R_t) > T(S_t) > T(R_t, S_t)$. Hence, in addition to providing the highest environmental output (since the most valuable species are preserved), protecting primary forest is even less costly for the international community than promoting reforestation.

Two important conclusions emerge from this section. In countries at an early stage of transition, the REDD+ incentive scheme must provide a monetary payment to ensure the preservation of primary forests, given the environmental and financial benefits of this type of program. On the other hand, a tradeoff occurs between physical and green capital. In order to obtain a rent over the long-run, the social planner invests in green capital at the expense of physical one. The value of the rent is equal to the interest rate on green capital, which is the REDD+ compensation.

Late transition stage

Figure 10 represents the consumption in BAU and when REDD+ is implemented at the 50th time-period. It corresponds to countries which have already depleted a substantial share of forests and have thus accumulated a certain amount of capital.

Figure 10: Consumption and capital under REDD+ in late transition stages



Again, consumption is always higher with REDD+. The more the program targets secondary forests, the higher the level of consumption is. The same applies for costs since we find that $T(R_t) > T(R_t, S_t) > T(S_t)$. This result provides useful insights. As illustrated in the previous section, we found that when REDD+ was implemented in early transition stage, it was optimal to fund the preservation of primary forests (RED). Here, in late transition stage, when examining consumption patterns, we find that it is better to pay for reforestation of secondary forests (AR), with the inconvenience of a higher cost for the international community.

The representation of the land-use change (Figure 13 in Appendix C) corroborates our previous findings: the social planner invests in green capital in order to obtain a rent over the long-run. That leads him to have a lower level of physical capital than in BAU, but a higher level of consumption. REDD+ is finally a way to add value to the green capital.

4 Calibration: an application to Indonesia

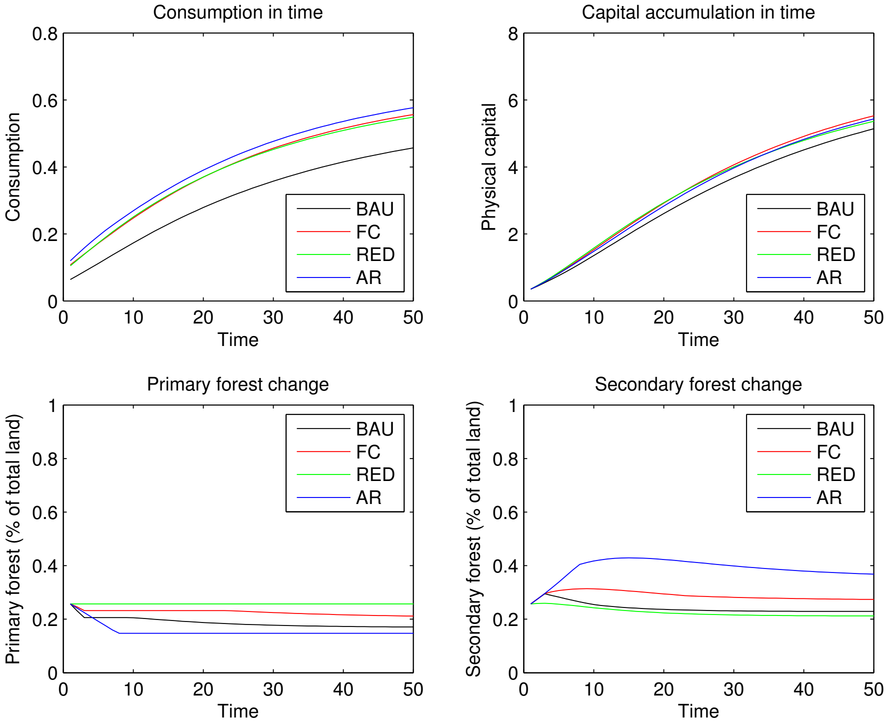
To provide further analysis, we calibrate the model to the Indonesian economy. Indonesia is a relevant case-study since it contains one of the three largest world stands for forests, with the Amazon and Congo basins, and it is involved in REDD+, unlike Brazil or China for instance. Because of deforestation, Indonesia is also the third largest emitter of greenhouse gases in the world. Using high-resolution data, Burgess et al. (2012) estimated the rate of deforestation, for production per district, at about 1500 ha per year between 2000 and 2008.

It is scheduled that governance systems allowing and facilitating the implementation of REDD+ programs in the country must be effective by 2020, and, as a long-term goal, Indonesia's forests must become a net carbon sink by 2030. To do this, the scope of the Indonesian REDD+ strategy includes RED and AR programs. Among the RED programs, Indonesia plans decreasing emissions from deforestation and degradation, and improving biodiversity preservation. Other REDD+ Indonesian programs, such as the rehabilitation and restoration of damaged areas, and the sustainable forest management, are in line with AR programs. What we have called FC program in our numerical simulations, would then correspond to a situation where the REDD+ national-agency in Indonesia would implement a mix of these activities (shared between AR and RED programs).

To calibrate our model, we use the World Bank data. Given the most recent data available for the maximum of our variables, we use the values of the year 2012. In 2012, Indonesia's share of forest area in total land was 51.4%. According to the Global Forest Watch project, half of this land area is primary native forests ($S_0 = R_0 = 0.257$). The same year, the gross capital formation was 35% of the total GDP ($K_0 = 0.35$). We lean on Brown and Lugo (1990) to determine the intrinsic growth rate of secondary forests ($\tau = 0.18$).

It is important to note that numerical results are hardly interpretable per se (for example the gain/loss in percentage of total land), but they are useful to provide a qualitative analysis of growth and forest change for the future of Indonesia, according to our model. As we simulate the application of the three types of REDD+ programs (RED, AR, FC), we hope that our work will provide insights for the design of the Indonesian REDD+ strategy. Figure 11 shows the prediction of our model regarding growth, capital and land uses in the country over the next 50 years.

Figure 11: REDD+ in Indonesia



According to our model, in absence of public policies in Indonesia (BAU), the share of primary forest will continue to significantly decrease in the next 50 years. In the meantime, the share of secondary forest will slightly grow within the five coming years, and then will decrease too. This result confirms the need for public incentive schemes in order to preserve forests in the country.

The highest level of consumption will be reached with the AR program. FC and RED yield the same intermediate level of growth, between AR and BAU. Capital accumulation is constantly growing and has the same level in all programs. Because of the brevity of the period, the social planner can barely adjust its physical capital which is already at a certain initial level ($K_0 = 0.35$). Looking at the sum of the costs and their representation in Appendix C, we find that $T(R_t) > T(S_t) > T(R_t, S_t)$. On the basis of these results, we can draw recommendations for the application of REDD+ in Indonesia.

If the international community wants to fund the most valuable output for environment, the RED program should be chosen. Indeed, it is the one that allows to preserve the highest share of primary forest, since its harvesting is null over the 50 periods. With this program, only secondary forests are used for production.

The AR program offers a different option. Its implementation will lead to the highest level of economic growth, and, on the other hand, the total forest cover will increase thanks to large reforestation. However, the loss in primary forest will be more important than in absence of REDD+. Hence, there is a tradeoff for policy-makers between the environmental and the financial quality of the coming forest transition in Indonesia. The solution that may lead to the highest economic performances (AR), is also the one that implies the largest depletion of the most valuable forest. Also, $T(R_t)$ is the most expensive program for the international community. Given its economic and land uses outputs, an intermediate solution can be found with the FC program, that is also the least expensive program.

5 Conclusion

In this paper we have analyzed economic growth in a developing economy that experiences a forest transition. We distinguished the different phases of production: the exhaustible primary forests are first solely depleted, then these are converted simultaneously with secondary forests, and finally, secondary forests are solely harvested in a sustainable way until the end of the forest transition. In this context, we have discussed the importance of the switching time from primary to secondary forests harvesting, since the former have the highest ecological value and can be considered as a nonrenewable resource.

We studied an economy in which the green capital, represented by forests, has a positive externality on production. This externality notably translates the role of forests in curbing global warming. Indeed, climate change can harm an economy's productivity through a decrease in agricultural yields, pollution or natural disasters. In this context, we found that the more a country depends on its green capital, the lower the consumption. It is explained by the fact that, in absence of public policies, the forest cover *in situ* has no financial value; and as the social planner cannot convert it into agriculture, the growth in the economy is lower. This result allowed us to depict the tradeoff existing between physical and green capital.

Then, we studied the implementation of public policies, namely REDD+, in the developing economy. Our approach corresponds to what currently takes place in more than 40 tropical countries. However, today, these public policies to halt deforestation in developing countries remain unclear, and countries' national strategies are not defined. We contribute to this debate by testing three different types of programs (limiting deforestation, promoting reforestation, or both) and examining their impact on growth and land uses. Our analysis thus provides insights for decision-makers.

When introducing REDD+ in the developing economy, agricultural area in steady state decreases, consumption increases, and a tradeoff occurs between physical and green capital. The social planner invests in the green capital, at the expense of the physical one, in order to receive a rent from the international community. This investment translates into the fact that less forests are converted into agriculture, and this decreases the level of physical capital. The level of the potential rent provided by REDD+ is the interest rate on green capital.

Additionally, we showed that the application of REDD+ must take into account each country's level of development, in order to implement the most efficient programs. In a country that has largely depleted its forest stock, like Chile, Mexico or Vietnam, REDD+ should consist in financing reforestation. On the contrary, in a country with large forest endowments remaining, like Gabon or Guyana, the priority should be given to the implementation of protected areas on primary forests.

Our results may thus allow progress on the definition of REDD+ national strategies, taking into account the effects mentioned above. In Indonesia, our work suggests that protecting forests, through the implementation of REDD+, will not slow economic growth, and may even boost it. To reach the highest level of consumption, the Indonesian REDD+ strategy should promote A/R projects (reforestation). However, to obtain the best environmental output, projects to preserve primary forests should be favored. As a result of applying REDD+, we can see that the course of action that is best for the environment and the course of action that is best for growth may differ.

In conclusion, with the correct public policies, catered to the stage of economic growth and the phase of forest transition for each unique country, it is possible to reduce deforestation without financial losses in the recipient economy. Assigning a tangible value to the green capital through REDD+, and explaining the necessary tradeoff with physical capital, will allow stakeholders to accurately assess a comprehensive economic and environmental benefit to fight against climate change.

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Appendix

A Details on simulations

In this section we provide all the details regarding our numerical simulations that illustrate our theoretical model. First, we list the explicit functions. The utility function is specified as $U(C_t) = ln(C_t)$. The depletion of the exhaustible primary forests, $\dot{S} = -X_t$, does not require further specification. For the renewal of the secondary forests, $\dot{R} = g(R_t) - Q_t$, we chose:

$$g(R_t) \quad = \quad \tau R_t(1 - R_t/R_{max}). \tag{26}$$

This is the standard logistic model for the renewal of a natural resource. R_{max} is the biomass maximum carrying capacity, that is, in our model, the total land area. τ is the intrinsic growth rate of the secondary forest.

For the production function $Y(1 - R_t - S_t, K_t, Q_t + X_t)$, we specify a two-level nested CES function:

$$Y \quad = \quad (\alpha K_t^{\varphi} + (1-\alpha)L^{\varphi})^{\frac{1}{\varphi}}, \text{ with} \tag{27}$$

$$L \quad = \quad (\beta(1 - R_t - S_t)^{\lambda} + (1-\beta)(Q_t + X_t)^{\lambda})^{\frac{1}{\lambda}}. \tag{28}$$

By imposing $\varphi < 0$ and $\lambda > 0$, we focus on the empirically more relevant case, i.e. complementarity between physical capital and land uses, and substitutability between agriculture and deforested lands. This is also the major asset of using a CES form rather than a Cobb-Douglas for our production function.

The feedback from green capital on production, given by $F(R_t, S_t, K_t, Q_t, X_t) = Y(1 - R_t - S_t, K_t, Q_t + X_t)\delta H(R_t, S_t)$ with $0 < \delta < 1$, is specified as:

$$H(R_t, S_t) \quad = \quad R_t^{\psi} S_t^{1-\psi}. \tag{29}$$

Using this form, the parameter ψ allows us to weigh the importance of each type of forest. With $\psi \in [0, 1]$, the lowest the ψ is, the more primary forests are essential to maintain a sustainable level of production. $H(.)$ also allows to account for the complementarity between primary and secondary forests. Through benefits such as biodiversity conservation, soil and water quality or regular precipitations, the presence of primary forests may impact that of secondary ones.[11]

In the benchmark model we impose the values given in Table 3 to the parameters.

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[11] :Else, $H(R_t, S_t) = R_t$ if $R_t > 0$ and $S_t = 0$; $H(R_t, S_t) = S_t$ if $R_t = 0$ and $S_t > 0$.

Table 3: Parameters for simulations

$S(0)$	0.9	ρ	0.03
$R(0)$	0.1	α	0.6
$K(0)$	0.01	β	0.5
R_{max}	1	τ	0.1
δ	0.8		
γ	0.5		
θ	0.5		

B Proofs

B.1 FC program

When applying the FC program, the social planner maximizes:

$$\max_{\{C_t, Q_t, X_t\}} \int_0^\infty e^{-\rho t} u(C_t) dt$$

Subject to:

$$\begin{aligned}
\dot{S}_t &= -X_t \\
\dot{R}_t &= g(R_t) - Q_t \\
\dot{K}_t &= F(R_t, S_t, K_t, Q_t, X_t) - C_t - \gamma Q_t - \theta X_t + T(R_t, S_t) \\
A_t &= 1 - S_t - R_t \\
F(R_t, S_t, K_t, Q_t, X_t) &= Y(1 - R_t - S_t, K_t, Q_t + X_t)\delta H(R_t, S_t)
\end{aligned}$$

With $C_t \geq 0, K_t \geq 0, Q_t \geq 0, R_t \geq 0, S_t \geq 0, X_t \geq 0$ and $S(0) = S_0, K(0) = K_0, R(0) = R_0$.

The constant value Hamiltonian and given by:

$$\mathcal{H} = U(C_t) + \lambda_t(\dot{K}_t) + \phi_t(\dot{S}_t) + \mu_t(\dot{R}_t)$$

When solving, one obtains the following first-order conditions:

$$\begin{aligned}
\lambda &= U'(C_t) \\
\phi &= \lambda(F'_X - \theta) \\
\mu &= \lambda(F'_Q - \gamma) \\
\dot{\lambda} &= \rho\lambda - \lambda F'_K \\
\dot{\phi} &= \rho\phi - \lambda(F'_S + T'_S) \\
\dot{\mu} &= \rho\mu - \lambda(F'_R + T'_R) - \mu g'_R
\end{aligned}$$

With the following transversality conditions:

$$\begin{aligned}
\lim_{t\to\infty} \phi(t)S(t)e^{-\rho t} &= 0 \\
\lim_{t\to\infty} \mu(t)R(t)e^{-\rho t} &= 0 \\
\lim_{t\to\infty} \lambda(t)K(t)e^{-\rho t} &= 0
\end{aligned}$$

B.2 AR program

When applying the AR program, the social planner maximizes:

$$\max_{\{C_t,Q_t,X_t\}} \int_0^\infty e^{-\rho t}u(C_t)dt$$

Subject to:

$$\begin{aligned}
\dot{S}_t &= -X_t \\
\dot{R}_t &= g(R_t) - Q_t \\
\dot{K}_t &= F(R_t,S_t,K_t,Q_t,X_t) - C_t - \gamma Q_t - \theta X_t + T(R_t) \\
A_t &= 1 - S_t - R_t \\
F(R_t,S_t,K_t,Q_t,X_t) &= Y(1-R_t-S_t,K_t,Q_t+X_t)\delta H(R_t,S_t)
\end{aligned}$$

With $C_t \geq 0, K_t \geq 0, Q_t \geq 0, R_t \geq 0, S_t \geq 0, X_t \geq 0$ and $S(0) = S_0, K(0) = K_0, R(0) = R_0$.

The constant value Hamiltonian and given by:

$$\mathcal{H} = U(C_t) + \lambda_t(\dot{K}_t) + \phi_t(\dot{S}_t) + \mu_t(\dot{R}_t)$$

When solving, one obtains the following first-order conditions:

$$\begin{aligned}
\lambda &= U'(C_t) \\
\phi &= \lambda(F'_X - \theta) \\
\mu &= \lambda(F'_Q - \gamma) \\
\dot{\lambda} &= \rho\lambda - \lambda F'_K \\
\dot{\phi} &= \rho\phi - \lambda F'_S \\
\dot{\mu} &= \rho\mu - \lambda(F'_R + T'_R) - \mu g'_R
\end{aligned}$$

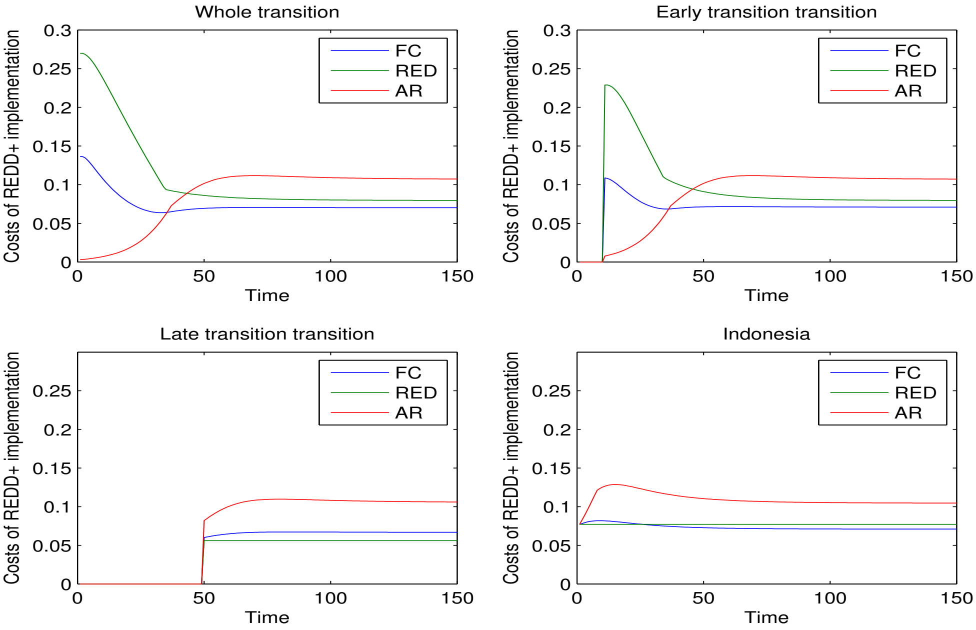
With the following transversality conditions:

$$\begin{aligned}
\lim_{t\to\infty} \phi(t)S(t)e^{-\rho t} &= 0 \\
\lim_{t\to\infty} \mu(t)R(t)e^{-\rho t} &= 0 \\
\lim_{t\to\infty} \lambda(t)K(t)e^{-\rho t} &= 0
\end{aligned}$$

C More numerical results

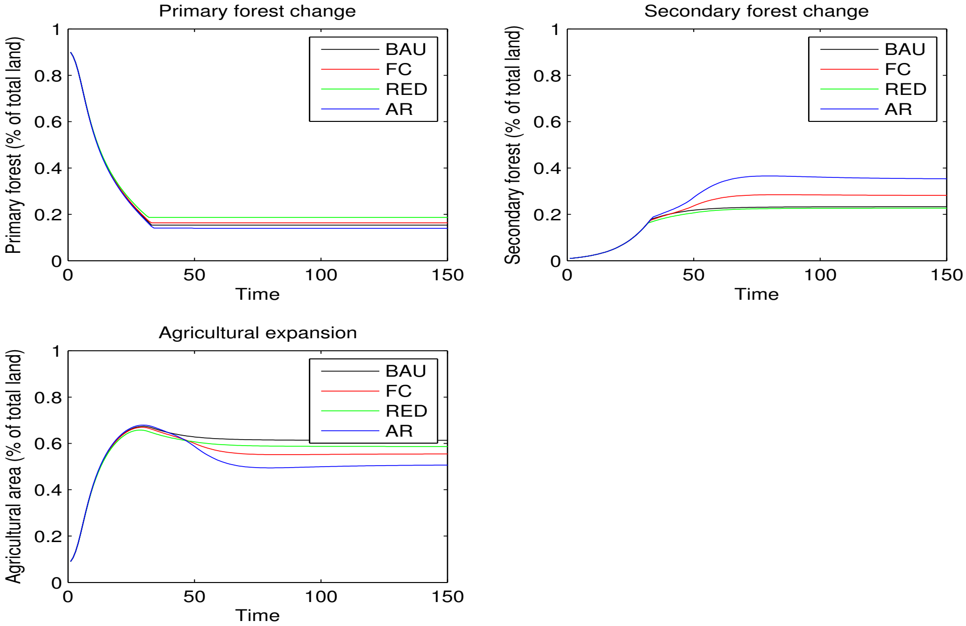
C.1 Public policies costs

Figure 12: Costs of public policies



C.2 Land uses and REDD+

Figure 13: Land uses with REDD+ in late transition stage



D Forest Transition in Vietnam

Figure 14: Forest Transition in Vietnam

According to FAO data, Vietnam experienced its turning point at the end of the 1980s. The country is now experiencing reforestation and participates in REDD+.

WORKING PAPER

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