Growth, deforestation and the efficiency of the REDD mechanism.

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Abstract

Since tropical deforestation in developing countries is responsible for large carbon emissions, the international community may want to preserve tropical forests by implementing an international transfer called the REDD mechanism (Reduced Emissions from Deforestation and Degradation). This paper analyzes the dilemma between economic growth and deforestation using a model that allows substitution between agricultural land and reproducible capital. We find that the REDD mechanism have negative returns on domestic activities for high rates of transfer. We also investigate the problem of implementing the optimal policy in a decentralized equilibrium, and the problem of tenure insecurity, which can be reduced by public investments in securing property rights.

Keywords: Avoided deforestation, growth, aid efficiency, insecure property rights

JEL Classification: F35; O13; Q56

1 Introduction

Deforestation in the tropics is currently responsible for about a quarter of total world carbon emissions and represents the main source of emissions in some developing countries. Hence, international efforts to reduce greenhouse gas emissions are hardly efficient in mitigating climate change if developing countries are excluded from the burden sharing agreement. Paying for the preservation of tropical forests might be an opportunity to include developing countries in the international negotiations on climate change (Copenhagen Accord, post-Kyoto framework). To participate, resource-rich countries need to be compensated for every effort in preserving their forest stock, which is called "avoided deforestation". Since avoiding deforestation provides a global externality that benefits to all consumers, resource-rich countries must receive a transfer that would cover the costs of preserving tropical forests. The main costs arise from losing the opportunity to use the land for other activities, in particular for agriculture. Therefore, the international community (especially, the countries who ratified the Kyoto Protocol) negotiates to fund a specific mechanism, which is called the REDD mechanism (where REDD stands for "Reduced Emissions from Deforestation and Degradation"). It corresponds to a conditional aid since the transfer depends on avoided deforestation. Hence, it has an impact both on the environment and on economic activities of the recipient economy. However, the economic impact is constrained by the fact that the most targeted countries are the ones with high deforestation rates, a high forest stock and slow growth patterns.[1] As illustrated by Myanmar, DR Congo, Bolivia or Lao PDR, high deforestation rates are more likely in countries characterized by low GDP, low investments and a large share of the agricultural sector in their GDP.

The focus of the paper is on the role of deforestation as a fuel for growth and on the efficiency of a transfer mechanism that limits agricultural land expansion in a one sector economy.[2] Our theoretical approach consists in introducing land conversion dynamics in a Ramsey growth model, allowing for factor substitution between man-made capital and land in the production of one aggregate good. The government of the developing country perfectly controls for land conversion and for its local externality, neglecting the greenhouse gas emissions that result from deforestation since its focus is on national

[1] The environmental services are highly concentrated since 75 percent of carbon stored in tropical forests belong to only five countries (Brazil, DRC, Indonesia, Peru and Colombia).

[2] Our specific mechanism reflects the current debate on the REDD mechanism (Copenhagen conference, 2009). It offers a constant rate of transfer multiplied by the difference between a negotiated baseline and the actual rate of deforestation, without mentioning the existing stock of forest and the risk of international leakage.

welfare. Our small open economy is initially endowed with a relatively large amount of forested lands, hence deforestation occurs due to the higher returns of land converted to agriculture [17]. The REDD mechanism leads to a trade-off between an extensive type of development where growth mainly depends on land conversion and an intensive type of development where capital investments tend to replace the "missing land".[3] The main finding of the paper is that the impact of the REDD mechanism on the economy is ambiguous. We obtain that the REDD mechanism influences agricultural intensification: The higher the rate of transfer, the less agricultural land, and the more man-made capital per unit of land. However, we show that the effect of the REDD mechanism on the stationary welfare levels is non-linear: For relatively low rates of transfer, the mechanism allows to reconcile growth with forest preservation, since domestic income is higher than without the REDD mechanism thanks to agricultural intensification. On the opposite, for high levels of transfer, the mechanism hits the limits of factor substitution since a shortage in agricultural land reduces the returns from capital investment, thus capital accumulation and domestic income. When the REDD mechanism offers a high price for not deforesting, forest preservation is obtained at the expense of economic development. In this context, aid is almost entirely diverted toward consumption of imported goods.

We also consider the implementation problem of the optimal policy in a decentralized equilibrium. Land conversion dynamics is driven by two opposite forces: a short-term productivity effect and a long-term environmental feedback effect [14]. Producers are aware of the short-term incentive to deforest, which arises from the fact that newly deforested lands are more fertile, whereas they ignore the environmental feedback effect, which reduces agricultural productivity due to erosion and ecosystem disturbance. We find that a tax on each input, capital and land accumulation, allows the government to lead the economy to the optimal path of deforestation and growth when producers do not internalize the impacts of deforestation. As one particularity of forest frontiers is the lack of secured property rights and the resulting tenure insecurity that diminishes the returns from production [18], we also investigate the problem of tenure insecurity in our setting. We stress on the role of the government in securing property rights through public investments. Comparing the environmental efficiency of the REDD mechanism with and without tenure insecurity reveals the importance of the benefit-sharing rule that allocates

[3] The trade-off between growth and the environment is traditionally represented through an inverted U-shaped relationship between per capita income and environmental quality, which is called the Environmental Kuznets Curve (EKC). López [23] demonstrated that internalizing an environmental feedback mechanism on production yields less degradation of natural resources while the economy grows, which endogenously generates the EKC. Naidoo [26] provides empirical evidence that deforesting and land clearing induce growth, using linear regression models over the period 1960 to 1999 and for over 70 countries.

the transfer between public spending and consumers: if the rule is biased toward public spending, tenure insecurity will be drastically reduced, but the environmental efficiency of the REDD mechanism will also decrease.

Many economists have emphasized that a transfer conditional on forest preservation must provide the right incentives to developing countries to be environmentally efficient: For instance, Stähler [28] analyzed the perverse incentives given by a variable rate of transfer, which leads to a higher level of deforestation that raises the amount of transfer (due to a scarcity effect); van Soest & Lensink [32] insisted on the need for a combined mechanism that offers a transfer which increases with the stock of forest and decreases with the rate of deforestation (using stick-and-carrot tactics); whereas Strassburg et al. [30] developed an empirically-derived mechanism of combined incentives where the size of the cake depends on all tropical countries' efforts in reducing deforestation (to avoid international leakage) and where the share that each country receives depends on the difference between its expected emissions and its actual ones. Focusing on forest stock dynamics, these studies neglect the analysis of economic impacts that emerge from input substitution and capital investments. Our findings can also be replaced in the broader literature on aid effectiveness. From the seminal work by Burnside & Dollar [4], a large body of empirical literature stresses the fact that foreign aid may have detrimental impacts on growth due to inefficient domestic policy, and that conditional aid has more positive impacts since it encourages policies that foster capital investments.[4] In our model, we depart from the literature that focuses on institutional failures, conflicts, and corruption [3, 19, 1] to explain deforestation and slow growth patterns, by assuming a social planner.

In the rest of the paper, we present the analytical framework and the program of the recipient country in Section 2. We compare the economy in laissez-faire, presented in Section 3, with the economy participating to the REDD mechanism, presented in Section 4. Section 5 presents a decentralized equilibrium where deforestation is controlled by the government. Section 6 discusses the role of the government in securing property rights in the context of tenure insecurity, and Section 7 concludes.

2 The analytical framework

Consider an economy with an infinitely lived representative agent. The economy is composed of one aggregate sector, labeled Y, whose product is either consumed or used for

[4] Recently, Rajan & Subramanian [27], Easterly [12], Djankov et al. [11] demonstrate that aid can have detrimental long-term effects on growth, through an institutional channel (weakening institutions and favoring corruption) and through a macroeconomic channel on competitiveness (Dutch disease).

investment. Two factors of production are required, land and capital, whose stocks accumulate either via deforestation or via investment and depreciate either via erosion and ecosystem disturbance or via constant capital depreciation. We do not consider the issue of technological change and of knowledge spillovers that generate endogenous growth, since the focus of the paper is on the trade-off between capital accumulation and deforestation. We assume that the country is a small open economy, so that the price of its aggregate product is given by the international market.

2.1 Agricultural expansion

The economy's endowment of land is normalized to one unit. Since the economy is initially endowed with a large amount of forested lands, the forest stock constitutes a land resource, which is subject to an irreversible conversion by an economic activity, agriculture. Hence, denoting by $F(t) \geq 0$ is the amount of lands left in native forests, $L(t) = 1 - F(t)$ represents agricultural land. Initially, the economy is characterized by a relatively low endowment L_0 of agricultural land.[5] Denoting by $d(t)$ the amount of resource conversion, land use changes over time are therefore determined by[6]

$$\dot{L}(t) = d(t). \tag{1}$$

We assume deforestation in the tropics is an irreversible process, that is, no reforestation occurs on cleared land. Otherwise, the carbon release due to deforestation would be partially compensated for by the regrowth process.[7]

Land conversion entirely benefits agricultural production, and no timber production is considered for simplicity reason. We describe two impacts of deforestation on production, one arises from a short-term incentive to deforest and the other is a stock feedback effect. First, the clearing and the burning of biomass that usually accompany land conversion release all nutrients at once. After one period of time, the newly converted lands lose their extra nutrients and productivity falls. Thus, a representative producer always prefers to use a newly deforested land rather than a land that has been deforested in the past, due

[5]The economy considered here does not necessarily correspond to a country with its actual national borders, but to a forest-covered region within a developing country.

[6]We use $\dot{x} \equiv dx/dt$.

[7]In the rest of the paper, we will study a mechanism aiming at reducing the rate of deforestation, which reduces carbon emissions from developing countries. We do not consider afforestation and we assume that deforestation is irreversible for two main reasons: first, afforestation and forest management projects are already considered in the Clean Development Mechanism of the Kyoto Protocol, whereas deforestation is not; second, accounting for carbon sequestration in the trees requires more information on species and on rotational management (age of the cohorts).

to a fertility gap. However, all land cannot be replaced at each period due to an implicit cost of conversion. Second, the cumulative decrease in forest stock yields a feedback effect on agricultural production, due to ecosystem disturbance. In fact, the tropical acid soils suffer from a decreasing protection from the near forest cover, which leads to erosion, and the disturbed local conditions can lead to irregular rainfalls and to a decrease in water supply.[8]

The output function, $Y : \Re^3_+ \rightarrow \Re_+$, $Y \in C^2$ is defined by

$$Y(d, L, K) = f(K, L + \nu d)(1 - \beta L), \tag{2}$$

where $f(.)$ corresponds to the production function, $1 - \beta L$ to the environmental feedback effect of deforestation, with $0 < \beta < 1$, and $\nu > 1$ to the productivity boost of newly deforested land. $f(.)$ is twice differentiable and strictly concave with respect to land and to capital. Both inputs are necessary; i.e. $f(K, 0) = f(0, L) = 0$. The partial derivatives of the output function with respect to newly deforested land, to agricultural land and to capital are denoted by Y_d, Y_L and Y_K, respectively. The output function is time invariant, since we assume no technological progress. It allows for imperfect substitution between man-made capital and land.[9] We also assume that newly deforested lands d and cumulated agricultural lands L are perfect substitutes. The newly deforested lands are more productive by a constant factor $\nu > 1$. After one period of time, the newly converted lands lose their extra nutrients and fall into the stock of agricultural lands L.[10] In the following, we further specified $f(.)$ as a Cobb-Douglas function:

$$f(K, L + \nu d) = K^\alpha (L + \nu d)^{1-\alpha}. \tag{3}$$

The partial derivatives of the production function with respect to capital and land are denoted by f_K and f_L. Output is net of costs and ν accounts for land clearing costs.

The environmental feedback effect, $1 - \beta L$, reflects the negative long term impact of cumulative deforestation on agricultural production.[11] Once a large amount of forest has

[8] Initiated in the literature by Ehui & Hertel [14], Ehui et al. [15], this combination of short-term and long-term effects of deforestation on agricultural yields is also considered by van Soest & Lensink [32], Barbier et al. [3].

[9] Labor input is not represented in this resource-capital model. This simplification is possible since there is no arbitrage with an alternative sector.

[10] The representation of land into two classes, one being more productive than the other since it is newly converted, can be compared to the vintage model for capital, where new capital endowing new technology is therefore more productive.

[11] Introducing a feedback effect in the production function is an alternative to representing an amenity effect in the utility function. It gives a value to the standing forest and can avoid the entire forest depletion.

been cleared, the local externality erodes the incentives to deforest. However, even the highest feedback effect does not lead to soil infertility or desertification, since production remains positive: $f(K,1)(1-\beta) > 0$.

2.2 The REDD mechanism: a transfer conditional on avoided deforestation

The developing country's government only considers the impacts of deforestation on its national production, neglecting the greenhouse gas (GHG) emissions. Introducing a REDD mechanism imposes a constraint on agricultural expansion, and eventually on growth. We assume that the international community is willing to preserve tropical forests for mitigating climate change, that is for reducing GHG emissions, and finds an agreement to fund the REDD mechanism. An international institution is in charge of providing and monitoring a transfer to the forest-rich country's government who agrees in reducing deforestation at the national scale. The welfare of the developing country must be improved while participating to the mechanism.[12]

The REDD mechanism could impose a cap either on productive land or on the deforestation rate. Here, we adopt a specific type of transfer that reflects the current debate on "avoided deforestation": the transfer, S, is assumed to be proportional to the decrease in the rate of deforestation, d, compared to an exogenous baseline d_{bas}:[13]

$$S(d) = A[d_{bas} - d], \tag{4}$$

where $A > 0$ denotes the price of carbon sequestrated in one hectare of tropical forest (using mean value for biomass yields). A is assumed to be constant through time. (4) reflects the opportunity costs (foregone profits from agricultural production) of a decrease in deforesting. Our transfer scheme thus corresponds to the estimates of the REDD opportunity costs obtained in the literature [16], except that monitoring costs (for forest preservation policy implementation) are not included. The controversial issue on how to evaluate d_{bas} is not addressed here: we assume that d_{bas} results from international negotiations.[14] Another interpretation consists in defining the baseline as proportional to

[12]We abstract from political reluctance to join the REDD mechanism for sovereignty reason. Even though there exists a risk of international leakage that would relocate land clearing in the neighboring countries, the scope of the paper is to assess the impacts of the REDD mechanism on one targeted developing economy.

[13]The debate has emerged at the conference of the Parties in Bali (2007) and continued at the Copenhagen conference (December, 2009). However, the REDD mechanism is not yet specified in practice.

[14] Following the literature [25, 13], the baseline can be evaluated through past trends in a business-as-usual scenario, through political negotiations or through econometric modeling [5].

the initial rate of deforestation, $d(0)$, in the economy without REDD mechanism.

If the international institution offers the transfer, $S(d) \geq 0$, the resulting mechanism is a foreign aid conditional on the environment. It increases the developing country's national revenue, I, which is given by

$$I = Y(d, L, K) + S(d), \tag{5}$$

using the agricultural output as the numeraire. Aid flows are not tied to capital investment, which allows us to capture the overall effect of the REDD mechanism.

2.3 Social planner's problem

In a centrally planned economy, the tropical country government's problem is to maximize the intertemporal utility of the representative agent. The population is constant and normalized at unity, all variables are thus defined per capita. We consider a small economy that opens to trade and where, relative to world prices, the relatively low initial endowment L_0 of agricultural land implies a process of land use change, which will bring the amount of land to its steady state value (denoted by L_∞).

The representative agent consumes the aggregate good, c, yielding the utility level $u(c)$. The utility function $u : \Re_+ \to \Re_+$ is at least twice continuously differentiable and has the standard properties: $u'(c) > 0$ and $u''(c) \leq 0$ for all c, and $\lim_{c\to 0} u'(c) = +\infty$. Total revenue of the economy is allocated between consumption and investment. Capital investments cover the depreciation needs, δK, and allow for capital accumulation, such that

$$\dot{K}(t) = Y(d(t), L(t), K(t)) + S(d(t)) - c(t) - \delta K(t). \tag{6}$$

The social planner chooses consumption and the deforestation rate at each period, to maximize intertemporal utility over an infinite horizon

$$W = \int_0^\infty u(c(t))e^{-\rho t} dt, \tag{7}$$

where ρ denotes the social rate of time preference, subject to the budget constraint (6) and to the land conversion dynamics (1), given $L(0) = L_0$ and $K(0) = K_0$, with $c(t) \geq 0$.

The (present-value) Hamiltonian of this two-state-variable problem is

$$H = u(c(t))e^{-\rho t} + \lambda(t) \left[Y(d(t), L(t), K(t)) + S(d(t)) - c(t) - \delta K(t)\right] - \psi(t)d(t), \tag{8}$$

where $\psi(t)$ and $\lambda(t)$ denote the co-state variables associated with forested land conversion (1) and with capital accumulation (6), respectively. Applying Pontryagin's maximum principle and assuming an interior solution result in necessary conditions for the optimal allocation of assets in the economy.[15]

$$u'(c(t))e^{-\rho t} = \lambda(t) \tag{9}$$

$$\lambda(t)\,[Y_d - A] = \psi(t),\;\; d(t)[\lambda(t)(Y_d(t) - A) - \psi(t)] = 0,\;\; d(t) \geq 0 \tag{10}$$

$$\dot{\lambda}(t) = \lambda(t)[\delta - Y_K] \tag{11}$$

$$\dot{\psi}(t) = \lambda(t)Y_L, \tag{12}$$

and the transversality conditions are given by

$$\lim_{t\to\infty} \lambda(t) \geq 0,\;\; \lim_{t\to\infty} \lambda(t)K(t) = 0,\;\; \lim_{t\to\infty} \psi(t) \geq 0,\;\; \lim_{t\to\infty} \psi(t)[1 - L(t)] = 0.$$

Condition (9) equalizes the present-value marginal utility of consumption with the shadow value of foregone accumulated capital. Similarly, (10) indicates that the shadow value of additional land conversion, $\psi(t)$, must equal the marginal benefit from deforesting one hectare to the economy. It reflects the intertemporal nonarbitrage condition according to which postponing deforestation from one period to another creates no profit. Only the shadow value of the forest stock, $\psi(t)$, is explicitly affected by the introduction of a REDD mechanism: A reduces the marginal benefit from deforesting. If A is sufficiently high to have $Y_d < A$, the marginal benefit of deforesting is negative and no deforestation occurs due to the complementary slackness condition. Since the economy starts with a low endowment of agricultural land, the initial marginal productivity of land is high, hence $Y_d|_{d=0,L=L_0,K=K_0} > A$.

Condition (11) combined with (9) implies that

$$\frac{\dot{\lambda}(t)}{\lambda(t)} = \delta - Y_K = \frac{\dot{c}(t)u''(c(t))}{u'(c(t))} - \rho,$$

which is negative if the consumption level rises through time. Hence, the shadow price $\lambda(t)$ will be decreasing over time. It measures how much a social planner is willing to pay for a marginal increase in the endowment of capital, hence it decreases with capital accumulation.

Using (12) and (10) implies that, during the deforestation process,

$$\frac{\dot{\psi}(t)}{\psi(t)} = \frac{Y_L}{Y_d - A}.$$

[15] An interior solution can be assumed since we can easily verify that the Arrow sufficient conditions are satisfied. Indeed, the stationary income $Y(0, L_\infty, K_\infty)$ can be written as $K_\infty^\alpha L_\infty^{1-\alpha} - \beta K_\infty^\alpha L_\infty^{2-\alpha}$, which is the sum of two concave functions. Hence, the maximized Hamiltonian is concave in (L, K) for all t. The Hamiltonian is also concave in c. Consequently, the necessary conditions, together with the transversality conditions, are sufficient.

With $Y_d > A$, we have two stages in the variation of $\psi(t)$: first, the marginal productivity of agricultural land is positive and $\psi(t)$ is increasing over time; second, a high environmental feedback effect can imply that Y_L is negative, and thus $\psi(t)$ finally decreases over time. As in Hartwick et al. [17], our formulation implies a specific meaning for $\psi(t)$, since total land area is held constant at unity, hence a small decrease in forest is necessarily obtained through an increase in agricultural land. It follows that $\psi(0)$ measures the initial relative desirability of forested land, relative to agricultural land. During the deforestation path, the relative desirability of forested land first increases. Surprisingly, a high feedback effect decreases both the marginal benefit from deforesting as well as the desirability of forest: as the production level falls, more clearing is required to avoid a decrease in consumption.

Assumption $\lim_{c\to 0} u'(c) = +\infty$ implies that $c(t) > 0$ holds. Taking the time derivative of (9) and substituting it into (11) yields the Keynes-Ramsey rule, which can be expressed as:

$$\frac{\dot{c}(t)}{c(t)} = \frac{1}{\epsilon_u(c(t))}\left[Y_K - (\delta + \rho)\right], \tag{13}$$

where $\epsilon_u(c(t)) \equiv -u''(c(t))c(t)/u'(c(t))$ is the elasticity of the marginal utility of consumption. Hence, consumption will be growing if the net return in capital investment exceeds the rate of time preference, ρ. Taking the time derivative of (10) and substituting into (12) allows to derive the patterns of deforestation:

$$\dot{d}(t) = \frac{1}{Y_{dd}}\left\{Y_L + [Y_d - A]\left(\epsilon_u(c(t))\frac{\dot{c}(t)}{c(t)} + \rho\right) - Y_{dL}\dot{L}(t) - Y_{dK}\dot{K}(t)\right\}. \tag{14}$$

The main difference with the standard Ramsey-Cass-Koopmans model is the interlink between capital and land accumulation. In the absence of technological change or population growth, we have $\dot{c} = \dot{L} = d = \dot{K} = 0$ at steady state. Denote by c_∞, K_∞ and L_∞ the long run levels of consumption, capital and land, respectively. Using capital accumulation dynamics (6) and consumption dynamics (13) allows us to derive the conditions for local stability of the steady state. Since additional land clearing modifies the long run level of agricultural land, it implies a transition toward another steady state. Consequently, we must have $d = 0$ and L_∞ constant to ensure the stability of the steady state. As proved in appendix A, the steady state is a (local) saddle point. A negative exogenous shock in capital, far from increasing the pressure on forest, reduces the incentive of deforesting and the economy tends toward the same steady state.

3 The impacts of the REDD mechanism

The objective of the paper is to compare the level of forest preserved in the long run with and without REDD mechanism, and to assess whether the mechanism is efficient in preserving the environment. Additionally, comparing the steady levels of income and production allows us to appraise its impacts on the welfare of the developing economy.

Using (13) and (14), we derive the steady state by setting $\dot{L} = d = \dot{c} = \dot{K} = 0$, which leads to the following conditions:

$$Y_K = \rho + \delta \tag{15}$$

$$Y_L + \rho Y_d = \rho A. \tag{16}$$

Hence, the marginal productivity of capital is constant and equal to the discount rate plus the depreciation rate of capital, and the marginal productivities of cumulated land and of newly deforested land are equal to ρA. More precisely, (16) is equivalent to

$$(1 + \rho\nu)(1 - \beta L) f_L = \beta f + \rho A,$$

which states that the marginal benefit of deforesting (including a discounted fertility boost) is equal to the marginal damage from deforesting, including a discounted marginal transfer loss. Since the environmental feedback effect is large due to cumulative deforestation, the incentive to deforest disappears at steady state. Combining (15) and (16) gives the following implicit equation for the stationary level of agricultural lands,

$$\left(\frac{\alpha(1 - \beta L)}{\rho + \delta}\right)^{\frac{\alpha}{1-\alpha}} \left[\xi - \beta L\left(1 + \xi\right)\right] = \rho A, \tag{17}$$

where $\xi \equiv (1 - \alpha)(1 + \rho\nu)$. We have

Lemma 1 *The stationary level of agricultural land is uniquely determined by (17) if β, α and ξ satisfy*

$$\frac{\xi}{1 + \xi} < \beta < \frac{1 - \alpha + \xi}{1 + \xi}. \tag{H1}$$

Proof: cf. the appendix.

By definition, $\xi/(1 + \xi)$ is increasing in the discounted fertility boost, $\rho\nu$, and in the output elasticity of land, $(1-\alpha)$. Hence, the first inequality in H1 imposes a high feedback effect β when the productivity surplus ν and the discount rate ρ are high, and when the output elasticity of capital α is low. The developing country is drawn to preserve some part of its forest stock when the productivity loss from a disturbed ecosystem (risk of erosion, less rainfalls) is high. However, the feedback effect is bounded upward, otherwise there is no incentive to deforest.

3.1 The laissez-faire economy

First assume that $A = 0$, thus the developing country receives no external revenue. Conditions (15) and (16) allow us to determine the stationary levels of agricultural land and capital in the laissez-faire economy:

$$L_\infty = \frac{\xi}{\beta[1+\xi]} \geq 0 \tag{18}$$

$$K_\infty = \left[\frac{\alpha}{\rho+\delta}\right]^{\frac{1}{1-\alpha}} \frac{\xi}{\beta[1+\xi]^{\frac{2-\alpha}{1-\alpha}}}, \tag{19}$$

Using $\xi > 0$ and H1 that ensures that $L_\infty < 1$, it corresponds to an interior solution.

In our one-sector model, growth is fueled by deforestation and capital accumulation. The two parameters, ν and β, that characterize land productivity, play a crucial role on growth patterns. β is the only factor that represents a damage from deforesting to the developing country. It reduces the long run levels of agricultural land L_∞ and of capital K_∞. Since the environmental feedback effect reduces the returns from production, the incentives to invest in capital and to deforest also decrease, leading to lower stationary levels of land and capital. Consequently, a high feedback effect decreases national income in the long run. However, β does not influence the technological choice, since the capital over land ratio does not depend on this parameter:

$$K_\infty/L_\infty = \left[\frac{\alpha}{(\rho+\delta)(1+\xi)}\right]^{1/(1-\alpha)}. \tag{20}$$

This ratio, which illustrates agricultural intensification, is decreasing in the depreciation rate of capital δ, in ρ and in ν, and is increasing in the output elasticity of capital α.

Since ν represents the short-term incentive to deforest, we obtain that ν limits agricultural intensification through two channels: it increases L_∞ and reduces K_∞.[16] This dual impact reflects a trade-off between exploiting natural fertility or improving it through man-made capital. It may be surprising that a short term productivity effect has an impact on the steady state. However, since all newly deforested lands feature the same productivity surplus, ν affects the long run. Given the definition of ξ, the impact of ν depends on the discount rate ρ: when ρ is low, which gives a relatively high value to the well-being in the future, the effect of ν is reduced and L_∞ is lower.

[16] Since ξ is increasing in ν, $dK_\infty/d\nu$ is proportional to

$$\frac{dK_\infty}{d\xi} = -\beta\rho\nu\left[\frac{\alpha(1+\xi)}{\rho+\delta}\right]^{\frac{1}{1-\alpha}} < 0.$$

3.2 Impacts on the environment and on the economy

Next consider that $A > 0$. Denote by $\tilde{X}_\infty$ the stationary level of variable X in the economy where the REDD mechanism has been introduced.

The stationary levels of land and capital depend on the rate of transfer, that is, on the price offered for not deforesting one hectare. For high rates of transfer, the economy becomes a "forest heaven" and bans deforestation from its territory. Denote by $\bar{A}$ the minimum rate of transfer for which the recipient country decides to protect its entire stock of forest. For $A \geq \bar{A}$, the level of agricultural land remains at its initial value, hence $\tilde{L}_\infty = L_0$. We obtain from (17)

$$\bar{A} = \frac{[\xi - \beta L_0(1+\xi)]}{\rho} \left[\frac{\alpha(1-\beta L_0)}{\rho+\delta}\right]^{\frac{\alpha}{1-\alpha}}. \tag{21}$$

We can define the environmental rent as the revenue induced by the REDD transfer when the forest stock is stabilized and generates a fixed revenue of Ad_{bas}. The government decides not to convert land when the environmental rent is sufficiently large to ensure a high welfare level. From (15), if the initial stock of capital K_0 is low, investments occur until the stationary level of capital reaches level

$$\tilde{K}_\infty = \left[\frac{\alpha(1-\beta\tilde{L}_\infty)}{\rho+\delta}\right]^{1/(1-\alpha)} \tilde{L}_\infty, \tag{22}$$

where $\tilde{L}_\infty = L_0$. In our "forest heaven", growth is limited since only capital can be accumulated and the stationary level of capital is proportional to the small initial level of land. Thus, the economy depends mostly on external transfer and spends most of its revenue on consumption. In this context, the economic efficiency of the conditional transfer is reduced since aid is mostly diverted to consumption, and especially, to imported good consumption.[17] We can draw a parallel between our economy that depends on environmental rents for preserving tropical forest and oil-rich Middle-Eastern countries that depend exclusively on oil rents.

Consider that the rate of transfer results from negotiations and varies on the interval $[0, \bar{A}]$. Using (17) and as illustrated in figure 1, we have

Lemma 2 *The introduction of the REDD mechanism reduces the stationary level of agricultural lands, which is a decreasing and convex function of the rate of transfer, A.*

[17] The issue of trade openness is not addressed here, since there is only one sector Y, whose product can be either consumed or invested. Hence, there is no possible impacts of trade on sectoral composition of the economy or on consumption. With the REDD mechanism, the supplementary revenue is spent on imports or invested. In fact, the price of Y, the numeraire, is a world price.

Proof: cf. the appendix.

We obtain an environmental success since the REDD mechanism decreases cumulative deforestation: $\tilde{L}_\infty \leq L_\infty$, and the marginal impact of the rate of transfer is decreasing. The convexity of $\tilde{L}_\infty$ with respect to A validates the optimistic view according to which low rates of transfer suffice to reduce sharply deforestation due to low opportunity cost projects [29]. The marginal cost of preserving one hectare of tropical forest increases while the stock of preserved forest increases.

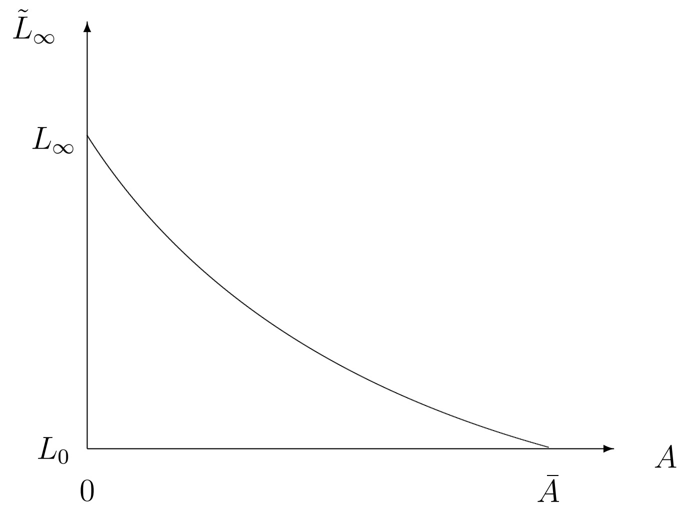

Figure 1: Environmental effect of REDD.

The REDD mechanism also modifies the production technique by affecting the capital over land ratio at steady state, which is determined by (22). The ratio is unambiguously decreasing in $\tilde{L}_\infty$. Since $\tilde{L}_\infty$ is decreasing in A, any increase in the rate of transfer substitutes more land to man-made capital. Consequently,

Proposition 3 *The REDD mechanism has a technical effect on production: a higher rate of transfer leads to further agricultural intensification.*

This technical effect relies upon factor substitution in production. While agricultural lands become scarcer when A increases, the representative producer compensates for the "missing lands" by intensifying its production. However, increasing the stationary level of capital $\tilde{K}_\infty$ is not sufficient to maintain production. In fact, denoting by A_i the rate of transfer that maximizes the stationary level of variable i, we obtain

Proposition 4 *The economic impacts of the REDD mechanism are*

i/ An increase in domestic revenue occurs only for relatively low rates of transfer;

ii/ Domestic revenue, capital investment, total income and consumption stationary levels are maximum for different rates of transfer that can be ranked as $0 < A_Y < A_K < A_I < A_c \leq \bar{A}$*;*

iii/ The REDD scheme that maximizes the stationary level of total income, A_I*, allows for some land conversion if*

$$d_{bas} < \frac{\rho[1-\alpha-(2-\alpha)\beta L_0]}{\beta(1+\xi)}.$$

Proof: cf. the appendix.

Point *i/* states that for a high rate of transfer, the economy faces the limits of factor substitution, and the low amount of agricultural land induces a low aggregate product. Hence the economy becomes dependent on external transfer. From figure 2, we find that the range of transfer rates offering both a decrease in deforestation and a higher domestic revenue is limited and is increasing in the discounted productivity boost $\nu\rho$.[18] Consequently, the impact of the conditional aid on the economy is ambiguous. Aid can have a detrimental effect on domestic revenue for relatively high rates of transfer. Points *ii/* and *iii/* specify the REDD impacts on total income and on the steady welfare levels. To ensure that A_I is inferior to $\bar{A}$, the deforestation baseline must be bounded upward, the upward bound being increasing in ρ and in $(1-\alpha)$, and decreasing in β and ν. Point *iii/* states that if the baseline is too high, the higher steady welfare level is obtained in our "forest heaven" economy (where no deforestation occurs).

More precisely, figure 2 illustrates the trade-off between consumption and investment by comparing the sources of revenue in the long run. While the environmental rents, $\tilde{S}_\infty = Ad_{bas}$, are linearly increasing in A, the stationary level of domestic revenue, $\tilde{Y}_\infty$, is a concave function of the rate of transfer and reaches a maximum for

$$A_Y = \frac{(1-\alpha)\nu}{2-\alpha}\left[\frac{\alpha}{(2-\alpha)(\rho+\delta)}\right]^{\frac{\alpha}{1-\alpha}}.$$

The threshold rate A_Y is independent of β, is increasing in ν and decreasing in ρ. The higher the fertility discrepancy ν, the higher A_Y is, since the transfer has to compensate for a higher opportunity cost of reducing deforestation. However, the maximum steady level of domestic income is unaffected by a change in ν.[19] The stationary level of domestic

[18] See the appendix for the demonstration that $A_Y/\bar{A}$ is inferior to one and is increasing in $\rho\nu$.

[19] Note that the stationary value of production reaches a maximum $\tilde{Y}_\infty^m$ for A_Y given by

$$\tilde{Y}_\infty^m = \frac{1-\alpha}{\beta(2-\alpha)^{\frac{2-\alpha}{1-\alpha}}}\left[\frac{\alpha}{\rho+\delta}\right]^{\frac{\alpha}{1-\alpha}}, \tag{23}$$

which is independent of ν but decreasing in β and ρ.

revenue is a hump-shaped function of the rate of transfer: for low rates of transfer, capital investment and production are fostered while the environmental rents are relatively small; conversely, for high rates of transfer, the environmental rents become the main source of revenue for the recipient economy while domestic production and investment are reduced. However, the recipient country's objective is to maximize its welfare, hence its consumption levels.[20] Comparing steady welfares, using $\tilde{c}_\infty = \tilde{I}_\infty - \delta\tilde{K}_\infty$ at steady state, we can infer that the recipient economy prefers an even higher rate of transfer than the one that maximizes its domestic revenue.[21] This result is consistent with developing countries' stand in favor of a high baseline and a high rate of transfer while negotiating in Bali (2007) and in Copenhagen (2009) at the conferences of the parties of the UNFCC. Hence, the forest-rich developing country may behave as even more "environmentally friendly" than the international community, assuming that the implicit objective of the international community is to maximize $\tilde{F}^a$ (or to minimize $\tilde{L}_\infty$) at the lowest possible cost.

4 Decentralized solution with open access

In this section, we study the conditions under which the socially optimal path of the previous section can be attained in a decentralized economy with open access to the forest [31]. When the representative producer does not internalize the local externality from deforesting, the government needs to implement a policy that affects both the marginal returns of land and capital.

The economy admits an infinitely-lived representative household whose preferences are given by (7) and a final good sector that produces one aggregate good. The representative household sells its working force through the selling of the use of its capital endowment, thus receiving the rate of returns r per unit of capital.[22] Assume the rep-

[20] Comparing steady welfares is not equivalent to comparing the discounted welfares. In fact, a constant level of welfare over time might be preferred to a welfare increasing patterns of development through time. The higher the discount rate, the higher the discounted welfare obtained for $\bar{A}$.

[21] To ensure that the participation constraint of the developing country is satisfied, we need to have $\tilde{c}_\infty > c_\infty$ at steady state. Since $\tilde{c}_\infty$ is a concave function of A, it suffices that $\tilde{c}_\infty(\bar{A}) = \bar{A}d_{bas} > Y_\infty(A) = c_\infty(A) + \delta K_\infty(A) > c_\infty(A)$ for $A < \bar{A}$. We easily find that a sufficient condition is

$$d_{bas} > \rho(1+\xi)^{-(2-\alpha)/(1-\alpha)}/\xi.$$

[22] Because the production function does not depend on labor, we consider instead that each household comes to work with its own tools and receives a payment that corresponds to the marginal productivity of those tools.

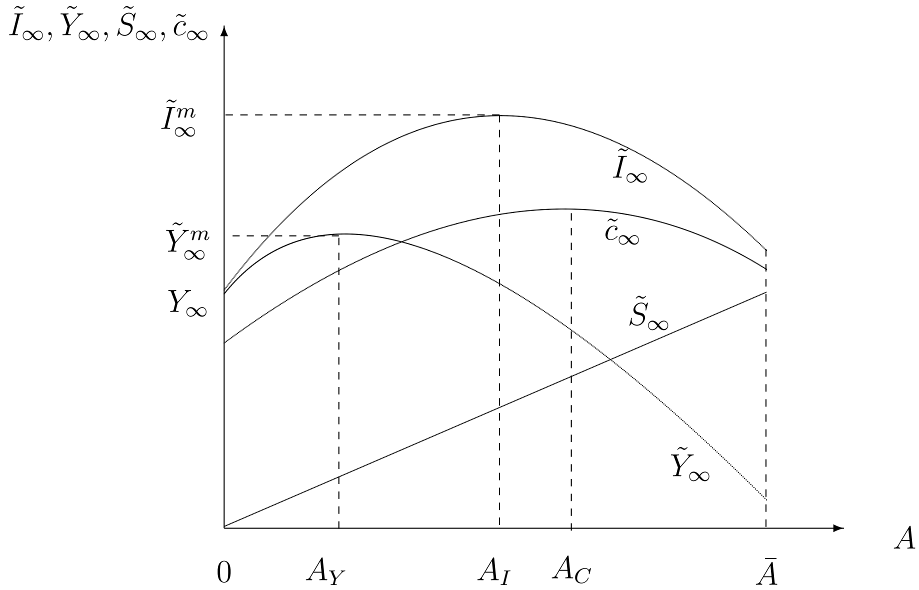

Figure 2: Development effect of REDD.

resentative firm maximizes the instantaneous profit π under perfect competition. Once a hectare has been deforested, we assume the property rights are clearly defined and the representative producer is the owner of the land. In the context of a forest frontier, land clearing often gives the settler property rights, which corresponds to the "ax right" or the rights of first occupancy [2]. However, due to open access, the (myopic) representative producer does not consider the impact of his individual decision to deforest on the stock of forest. The government thus introduces a linear tax $\tau(t)$ on newly deforested land, which varies through time according to the increasing scarcity of forest, and the proceeds are redistributed lump-sum back to households. The household also receives the international transfer $S(d)$.

First, assume similar functional forms as in the previous section. The problem of the representative consumer is therefore to

$$\max_{C\geq 0} \quad W = \int_0^\infty u(c(t))e^{-\rho t}dt \tag{24}$$

$$\text{s.t.} \quad \dot{K}(t) = \pi(t) + [r(t) - \delta]K(t) + S(d(t)) + \tau(t)d(t) - c(t), \tag{25}$$

and to $K(0) = K_0$ with $\lim_{t\to\infty} K(t) \geq 0$. The household determines the optimal levels of consumption and investment, given that capital depreciates at rate δ and that the household receives a unit payment $r(t)$ for lending its capital, as well as the redistributed externality transfers. The problem of the representative firm is to

$$\max_{K(t),d(t)\geq 0} \quad \pi(t) = Y(d(t), L(t), K(t)) - r(t)K(t) - \tau(t)d(t). \tag{26}$$

Since the producer owns the land once deforested, the productive use of land induces no cost. The government collects the externality tax $\tau(t)d(t)$. We obtain

Lemma 5 *If $\tau = Y_d$, where Y_d is the marginal productivity of deforesting in the social planner's optimal solution, the decentralized solution of (24)-(26) equals the socially optimal solution of (7).*

Proof. Due to the concavity of the profit equation (26) in (K, d), the first order conditions of the profit-maximizing firm are given by

$$Y_d = \tau \quad \text{and} \quad Y_K = r, \tag{27}$$

which are the implicit instantaneous demand functions for additional agricultural land and for capital. The (present value) Hamiltonian for the consumer's problem (24)-(25) is

$$\hat{H} = u(c(t))e^{-\rho t} + \mu(t)[\pi(t) + (r(t) - \delta)K(t) + A(d_{bas} - d(t)) + \tau(t)d(t) - c(t)],$$

where $\mu(t)$ corresponds to the co-state variable associated with capital accumulation (25). Applying Pontryagin's maximum principle gives the following necessary conditions[23]

$$u'(c(t))e^{-\rho t} = \mu(t) \tag{28}$$

$$\dot{\mu}(t) = -\mu(t)[r(t) - \delta], \tag{29}$$

and the transversality condition: $\lim_{t\to\infty} \mu(t)K(t) = 0$.[24] From (28) and (9), we obtain easily that $\mu(t) = \lambda(t)$, while (29) with (27) is similar to (11). Hence, consumption patterns are identical in the decentralized program and in the social planner's program. The government controls for the patterns of deforestation by taking into account the

[23] The present value Hamiltonian $\hat{H}$ is the sum of a concave function of c and a linear function of (K, c). Therefore, it is concave in (K, c).

[24] Substituting $\mu(t)$ for (28) and integrating the homogeneous differential equation (29) transforms the transversality condition in

$$\lim_{t\to\infty} u'(c(0))K(t)exp[-\int_0^t (r(s) - \rho - \delta)ds] = 0,$$

which corresponds to the no-Ponzi condition. Thus any solution to (28)-(29) is a unique solution to the household maximization problem.

equation of motion (1), and by maximizing the utility of the representative consumer who receives the international transfer. Given (27), and using (10), we have $\tau(t) = Y_d = A + \psi^*(t)/\lambda^*(t)$, where $\psi^*(t)$ is the shadow price of forested land, and $\lambda^*(t)$ is the shadow price of capital in the social planner's optimal solution in problem (7). Thus, the price of deforesting one more hectare is the social cost of deforestation, including the marginal loss of transfer and the relative value of forest. ∇

Lemma 5 states that the optimal policy for the government of the forest-abundant developing country consists exclusively in taxing land conversion. However, this result depends crucially on the assumption that the functional forms are preserved.

Next, assume that the representative producer does not internalize the environmental feedback effect of deforesting on agricultural productivity. Thus, the production function is $f(K, L+\nu d)$ instead of $Y(d, L, K)$, ignoring $(1-\beta L)$ at the individual level. As a result, the government needs to implement a policy that reflects both the local externality suffered by national producers and the externality in terms of GHG emissions that affects global welfare.

Modifying the production function in (26) gives the following first-order conditions for the profit-maximizing firm

$$\nu f_L = \tau \quad \text{and} \quad f_K = r, \tag{30}$$

where the marginal factor productivities are overestimated since the local externality is neglected: $\nu f_L = Y_d/(1-\beta L)$ and $f_K = Y_K/(1-\beta L)$. Consequently, the government needs to implement two policies that affect the accumulation of both factors: a tax on land conversion, $\hat{\tau}$, and a tax on capital denoted by s. The tax on capital affects the representative household by reducing his returns, and creates an incentive to better adjust capital investment. We replace (25) by

$$\dot{K}(t) = \pi(t) + [r(t) - s(t) - \delta]K(t) + \Gamma - c(t), \tag{31}$$

where $\Gamma \equiv S(d(t)) + \tau(t)d(t) + s(t)K(t)$ denotes all the proceeds redistributed to the household. We obtain

Proposition 6 *When the representative producer does not internalize the environmental feedback effect, if the government implements two policies:*

i/ a tax on land conversion, $\hat{\tau} = Y_d/(1-\beta L)$, *which reduces the returns from deforesting,*

ii/ and a tax on capital, $s = \beta L f_K$, *which reduces the returns from capital accumulation,* *the decentralized solution of (24)-(31) equals the socially optimal solution of (7).*

Proof. Given (31), the household's problem leads to the following intertemporal Euler condition

$$\frac{\dot{c}(t)}{c(t)} = \frac{1}{\epsilon_u(c(t))}[r(t) - s(t) - \delta - \rho].$$

Using (30), we obtain the socially optimal capital accumulation if the tax on capital is $s = \beta L f_K$. Note that the tax corrects the returns from capital by internalizing the feedback effect: $r - s = (1 - \beta L) f_K = Y_K$. Given (30), and using (10), we have $\hat{\tau}(t) = Y_d/(1 - \beta L(t))$, where Y_d and $L(t)$ follow the socially optimal path. Notice that $\hat{\tau}$ is higher than the tax obtained with similar functional forms: $\hat{\tau} = \tau/(1 - \beta L)$, and the difference precisely reflects the environmental feedback effect. ∇

Proposition 6 states that two instruments are necessary to internalize the local externality and the global pollution. In fact, each instrument modifies how marginal factor productivities are evaluated. Alternatively, the government could tax the use of capital in the final good sector, which increases the marginal cost of capital to $r(t) + s(t)$, with $s(t)$ defined as in proposition 6.

At steady state, we can compare the stationary level of the tax on land conversion with the rate of transfer since

$$\hat{\tau}_\infty = \frac{1}{1 - \beta \tilde{L}_\infty} \left[A - \frac{1 - \alpha - \beta \tilde{L}_\infty (2 - \alpha)}{\rho} \left(\frac{\alpha(1 - \beta \tilde{L}_\infty)}{\rho + \delta} \right)^{\frac{\alpha}{1-\alpha}} \right].$$

Note that when the rate of transfer is equal to A_Y, $\hat{\tau}_\infty$ simplifies to $(2 - \alpha)A_Y$, hence the tax is higher than the rate of transfer. When $A < A_Y$, we also have that the tax on land conversion is higher than A. However, for the highest rate of transfer $\bar{A}$ given by (21), the stationary level of the tax is $(1 - \alpha)\nu[(\alpha - \alpha\beta L_0)/(\rho + \delta)]^{\alpha/(1-\alpha)}$, which is lower than $\bar{A}$. Consequently, the land clearing tax is higher than the rate of transfer when the transfer allows for a relatively high stationary level of land. Similarly, we obtain the stationary level of tax on capital

$$s_\infty = \frac{(\delta + \rho)\beta \tilde{L}_\infty}{1 - \beta \tilde{L}_\infty},$$

which is increasing in $\tilde{L}_\infty$, hence decreasing in A. Since a higher transfer induces less domestic production and less agricultural land, the incentive to accumulate capital is also reduced, which explains the lower taxation level.

5 Insecure property rights and public spending

Since REDD rewards accrue nationally rather than locally, whether the mechanism will ultimately benefit individuals who bear an opportunity cost for not deforesting depends on benefit-sharing rules and on land tenure - that is, the system of rights, rules and institutions regulating resource access and use.[25] The efficiency of the transfer mechanism crucially depends on the allocation of benefits within the developing economy.

Most tropical forests are *de jure* state property, but the remoteness and the lack of institutional capacity to enforce government regulation often make forests *de facto* open access resources [2].[26] One particularity of frontier settlements is the presence of tenure insecurity [18]. Remotely located from the government's administrative centers, the settler will receive few support in the recognition of his land claims, regardless of their legitimacy. This opens up the possibility of land invasion, conflicts and social unrest. One obvious effect of tenure insecurity is to lower the returns from production since the settler may have to secure his rights through private defense expenditure [24], or he may have been evicted from the land before the gains have materialized, or those gains may have been destroyed during land invasion [10].[27]

In this section, we augment the resource-capital model by introducing a tenure insecurity index, which reduces the returns from production. The producer only receives a share p of its returns, with $0 < p < 1$ [9], the rest being lost during conflicts over land.[28] However, the central government can play a role in securing property rights through public defense expenditure (police services, land registry).[29] Culas [8] uses indicators of contract enforceability and bureaucracy efficiency [21] to demonstrate the positive impact of institutional arrangements for securing property rights on forest preservation. Hence the efficiency of the REDD mechanism in reducing deforestation may depend on the govern-

[25] As noted by Cotula & Mayers [7], "land tenure is key" to ensure that REDD schemes benefit local people. Furthermore, local people favors clearly defined benefit-sharing rules rather than central government schemes to distribute tax benefits, due to governance weaknesses.

[26] Actually, national laws assign approximately 77 percent of the world's forest to state ownership [33].

[27] As private defense expenditure reduces the net value of production, conflicts have a deteriorating impact on production possibilities and affect the returns from production [34].

[28] An alternative to our setting consists in introducing endogenous enforcement of property rights through private defense costs against poaching [20] or through imperfect control over cheating behaviors [6], which would require a decentralized setting.

[29] Recently, several countries, notably Brazil, Cameroon, Peru and Bolivia, have taken steps to increase local control over forestlands, by introducing private ownership (individually- or community-based) and strengthening customary land rights. However, land registration that establishes private ownership requires an efficient public sector. In Africa, less than 10 percent of the private lands are registered as such, due to long and cumbersome procedures, notably in Cameroon and DRC [7].

ment's effort in reducing tenure insecurity.

Denote by $g(t)$ the instantaneous public expenditure for securing property rights and assume that the higher the public expenditure, the higher the share p of returns received by the representative producer. We have $p(t) = p(g(t))$, with $p'(g) > 0$ and $p''(g) < 0$. Consider the social planner's program (7) with a modified budget flow constraint

$$\dot{K}(t) = p(g(t))Y(t) + A[d_{bas} - d(t)] - g(t) - c(t) - \delta K(t), \tag{32}$$

instead of (6). We will not implement the optimal policy where $g(t)$ is determined endogenously at each period so that the marginal benefit from more secure property rights equalizes the marginal cost of public spending, that is, $p'(g(t))Y(t) = 1$. The marginal benefit corresponds to the increase in the returns from production received by the representative producer, whereas the marginal cost is related to the opportunity cost of consumption.[30] Rather, we assume that the government adopts an explicit benefit-sharing rule, which defines $g(t)$ as a function of the REDD transfer, leading to

$$g(t) = g(S(t)) \quad \text{with} \quad g'(S) > 0 \text{ and } \quad g(0) = 0. \tag{33}$$

We also assume that $g'(S) < 1$ since the benefit-sharing rule allocates only a share of the transfer to public expenditure (for instance, if the allocation rule is constant, we can have $g(S(t)) = aS(t)$ with $0 < a < 1$). As a result, the government can use a certain share of the transfer mechanism to make public investments and redistribute the rest of the transfer to the representative consumer.[31] When the rate of deforestation is high, the level of transfer will be relatively low, leading to less public investments and to a smaller share p of returns for the producer. On the opposite, the smaller the rate of deforestation, the higher the level of transfer, the more public investments and the higher the share p will be. Denote by $\breve{L}_\infty$ the stationary level of agricultural lands in the context of tenure insecurity.

Using (8) with (32), we derive the intertemporal Euler condition, which replaces (13),

$$\frac{\dot{c}(t)}{c(t)} = \frac{1}{\epsilon_u(c(t))} \left[p(t)Y_K(t) - (\delta + \rho)\right], \tag{34}$$

where the marginal returns from capital are affected by tenure insecurity. The fact that p is influenced by public spending, hence by the level of transfer, modifies the decision to

[30] The optimal policy suggests that while production returns rise due to factor accumulation, public expenditure must decrease, leading to an increase in tenure insecurity through time.

[31] We avoid the issue of public debt by considering the international community that implements the REDD mechanism imposes a condition on the recipient government such that public investments must be entirely financed by national income.

deforest. At steady state (where $\dot{p} = 0$), we have

$$pY_K = \rho + \delta \tag{35}$$

$$p[Y_L + \rho Y_d] = \rho A \left[1 + g'(S)[p'(g)Y - 1]\right], \tag{36}$$

instead of (15) and (16). We obtain

Proposition 7 *When the REDD transfer is allocated to public investments in securing property rights and to consumers following a fixed benefit-sharing rule,*

i/ the environmental efficiency of the REDD mechanism is preserved if $\xi < 1$;

ii/ if the benefit-sharing rule is biased in favor of public expenditure, leading to a high share of returns for producers, the environmental efficiency of the REDD mechanism is reduced; whereas if the rule is biased toward consumers, leading to a low share of returns, the REDD efficiency is magnified.

Proof: cf. the appendix.

The proposition 7 states that the REDD mechanism has positive returns on deforestation reduction if the sufficient condition $\xi < 1$ holds, that is, if the discounted productivity boost $\rho\nu$ is relatively low. Point *ii/* states that a high tenure insecurity leads to a magnifying effect of aid on the environment. More forest is preserved in the long run because the returns from production are lower, hence the incentive to deforest is reduced, which requires a lower rate of transfer for the same environmental target. It corresponds to the tenure insecurity effect. This effect can be more easily observed if we assume that public spending has been determined optimally, leading to a simplified version of (36): $p[Y_L + \rho Y_d] = \rho A$. Hence, the implicit equation for the stationary level of agricultural lands becomes

$$p^{\frac{2-\alpha}{1-\alpha}} \left(\frac{\alpha(1 - \beta \breve{L}_\infty)}{\rho + \delta} \right)^{\frac{\alpha}{1-\alpha}} \left[\xi - \beta \breve{L}_\infty (1 + \xi) \right] = \rho A. \tag{37}$$

Note that when $A = 0$, we have $\breve{L}_\infty = L_\infty$. Observe that when p tends toward 1, (37) is similar to (17), whereas, given that $p < 1$, the LHS of (37) is reduced by $p^{(2-\alpha)/(1-\alpha)} < 1$. Since insecure property rights reduce the returns from production, a lower incentive to deforest requires a lower level of transfer for achieving the same environmental target. Consequently, tenure insecurity will magnify the environmental impacts of the REDD mechanism, leading to less deforestation. Similarly, using (35), note that when $A = 0$, we have $\breve{K}_\infty = p^{1/(1-\alpha)} K_\infty$. More generally, the presence of tenure insecurity reduces the scale of the economy, which reduces the incentive for investments.

However, other impacts of tenure insecurity on the efficiency of the REDD mechanism are channeled by the allocation of the transfer within the economy. Any increase in the rate of transfer A modifies the environment through two opposite forces: first, there is a direct effect since a higher rate of transfer gives more value to the standing forest; second, there is an indirect effect since a higher rate of transfer allows the government to raise public expenses g, thus the share p rises, which improves the returns from production and increases the incentive to deforest. As a result, if the indirect effect predominates (for high p), property rights are relatively secured but the environmental efficiency of the mechanism is reduced. This case corresponds to a benefit-sharing rule that allocates too much transfer to public expenditure. In fact, to have $p \geq 1 + g'(S)[p'(g)Y - 1]$, given $p < 1$, we need to have $p'(g)Y < 1$, where the marginal cost of public expenditure exceeds its marginal benefit. On the opposite, if the direct effect predominates (for low p), the environmental efficiency of the transfer improves. We have $p < 1+g'(S)[p'(g)Y-1]$, which necessarily holds if $p'(g)Y > 1$, that is, if the sharing rule is biased toward consumers and allocates less funding to the government than what the equalization of marginal cost and benefit of public spending requires.

Thus, the allocative rule has a great influence on the environmental efficiency of the REDD mechanism. The international institution must be sharp on how property rights are defined and how they are enforced in the recipient economy: in the context of open access where settlers can get property titles by clearing one hectare, a policy that secures those rights can be harmful and can reduce the efficiency of the REDD mechanism.

6 Concluding remarks

From a developing country's perspective, the REDD mechanism can play the role of a conditional aid. Using a growth model that allows for substitution between land and capital, we demonstrate that a transfer conditional on avoided deforestation has an ambiguous effect on the economy. In fact, it fosters capital investment and domestic activities for relatively low environmental targets. However, when the agricultural sector faces the limits of factor substitution, which corresponds to high forest preservation targets, it has an adverse effect on domestic production. The economy becomes a "forest heaven". The non-linear effect of the conditional aid on national income at steady state reflects a type of "Aid Laffer curve" [22]. Interestingly, for relatively low rates of transfer, aid allows the developing economy to accumulate more capital and to intensify its agriculture, leading to higher steady welfare levels than without the REDD mechanism. The adverse effect is due to the constraint on land accumulation and to the limits of factor substitution.

In the literature on aid effectiveness, this detrimental impact often passes through an institutional channel (by favoring corruption) or through a diminishing-competitiveness channel. Here, in the absence of corrupted behavior and using a one sector model, it is only generated by the trade-off between consumption and investment.

A surprising implication of the model is to discourage the international community to offer a high price for the preservation of one hectare of forest, since it would bear the risk of deterring investment and growth in the recipient country. However, the developing country will lobby for a high level of transfer, since it maximizes its welfare. If the environmental gains predominate the development target, the international institution and the recipient country will easily find a consensus over a high level of transfer. On the opposite, if the international institution aims at encouraging a less deforestation-dependent growth, the agreement will be less easy to find.

The introduction of tenure insecurity modifies the impacts of the REDD mechanism. When tenure insecurity is relatively high, the environmental efficiency of the REDD mechanism is magnified due to the lower opportunity cost of not deforesting. As a result, if the government decides to invest in securing property rights without modifying the open-access condition of forested land, that is, if clearing a plot of land is sufficient to obtain clearly defined property rights, the environmental efficiency of the REDD mechanism will be reduced.

The framework relies on simplistic assumptions, such as perfect foresight and a fixed and permanent transfer. The main restriction of the model consists in considering only one agricultural sector, where land is a necessary factor. Hence, for high environmental targets, the economy is forced to abandon its domestic activities, rather than developing an alternative sector. We could also have introduced technological change that would allow for improving land productivity. Yet, introducing an endogenous source of growth, such as knowledge accumulation, would lead to the analysis of another issue, that is, the emergence of sectoral diversification in the rural economy.

Appendix

A Local stability of the steady state

Assume $d = 0$. More cleared lands would lead to another steady state and we want to demonstrate that the steady state obtained when $d = 0$ is locally stable. Assume that the utility function has a constant intertemporal elasticity of substitution in consumption, with $\epsilon_u(c(t)) = \theta$, to simplify the expressions. To do so, we use the dynamic equations (6) and (13):

$$\dot{K} = K^\alpha L^{1-\alpha}(1-\beta L) + Ad_{bas} - C - \delta K$$
$$\dot{C} = \frac{C}{\theta}\left[\alpha(L/K)^{1-\alpha}(1-\beta L) - (\delta+\rho)\right].$$

At the steady state equilibrium, we have

$$K^\alpha L^{1-\alpha}(1-\beta L) + Ad_{bas} - C - \delta K = 0$$
$$\alpha(L/K)^{1-\alpha}(1-\beta L) = \delta + \rho.$$

Hence, using a first order Taylor development,

$$\begin{bmatrix}\dot{K}\\ \dot{C}\end{bmatrix} = \begin{bmatrix}\rho & -1\\ \eta & 0\end{bmatrix}\begin{bmatrix}K-K_\infty\\ C-C_\infty\end{bmatrix},$$

where $\eta \equiv -\frac{(1-\alpha)(\delta+\rho)}{\theta}\left[\frac{(1-\alpha)\delta+\rho}{\alpha} + \frac{Ad_{bas}}{K_\infty}\right] < 0$, which depends on the stationary level of capital. Hence, the Jacobian matrix is characterized by the determinant:

$$detJ_E = \eta.$$

To establish that the steady state is locally a saddle point, the two roots of the Jacobian matrix must have opposite signs, which always holds since $\eta < 0$.

Consider an exogenous shock in capital, which reduces K_∞ by ϵ. The classical trade-off between consumption and investment implies a temporary decrease in consumption, which should be sufficient to reinvest in capital and to compensate the impact of the shock. However, the shock in capital may increase the pressure to deforest, which would modify instantaneously the steady state. Since the decrease in capital implies a decrease in the marginal productivity of deforesting, using (10), we have at steady state

$$\lambda_\infty[Y_d(0, L_\infty, K_\infty - \epsilon) - A] < \psi_\infty,$$

which implies that $\partial H/\partial d < 0$ and $d = 0$. Hence, a shock in capital results in a land surplus compared to the capital level, which reduces the marginal productivity of deforesting. Thus, there is no rise in deforestation and the economy tends toward the same steady state.

B Proof of Lemma 1

(17) can be expressed as

$$g(x) - \rho A = 0 \tag{38}$$

with

$$g(x) = \left[\frac{\alpha(1-\beta x)}{\rho+\delta}\right]^{\frac{\alpha}{1-\alpha}} \left[\xi - \beta x \left(1+\xi\right)\right]. \tag{39}$$

We have

$$g'(x) \quad = -\tfrac{\beta}{1-\alpha}\left[\tfrac{\alpha(1-\beta x)}{\rho+\delta}\right]^{\frac{\alpha}{1-\alpha}}\left[1+\xi-\tfrac{\alpha}{1-\beta x}\right],$$

whose sign depends on the last bracketed term, which is positive if and only if $x < (1-\alpha+\xi)/[\beta(1+\xi)]$. Since $x \in [0,1]$, a sufficient condition that ensures $g'(x) < 0$ is that $\beta < 1 - \alpha/(1+\xi)$. Furthermore, (38) has a unique solution when $A = 0$ if $g(0)$ and $g(1)$ have opposite signs. We have $g(0) = \xi[\alpha/(\rho+\delta)]^{\alpha/(1-\alpha)} > 0$ and $g(1) < 0$ iff $\beta > \xi/(1+\xi)$. Consequently, $\xi/(1+\xi) < \beta < 1-\alpha/(1+\xi)$, where the two bounds are mutually compatible since $\xi < 1-\alpha+\xi$. For $A > 0$, we have an interior solution if $g(0) > \rho A$ and we have $x = 0$ if $g(0) < \rho A$.

C Proof of lemma 2

Denote $\tilde{x}(A) \equiv \tilde{L}_\infty$ where $\tilde{x}(A)$ is a function satisfying $\tilde{x}(0) = L_\infty$ and $\tilde{x}(\bar{A}) = L_0$. Since $\tilde{x}(A)$ is determined by $g(\tilde{x}(A)) = \rho A \geq 0$ using (38), we have $\tilde{x}(A) \leq \xi/[\beta(1+\xi)]$. More precisely, using the implicit function theorem gives

$$\tilde{x}'(A) = \rho/g'(x). \tag{40}$$

For $x \leq \xi/[\beta(1+\xi)] < (1-\alpha+\xi)/[\beta(1+\xi)]$, $g'(x) < 0$ without condition. Hence, $\tilde{x}(A)$ is a decreasing function of A. Using $\tilde{x}''(A) = -g''(x)[\tilde{x}'(A)]^2/g'(x)$ and

$$g''(x) \quad = -\tfrac{\beta\alpha g'(x)}{(1-\alpha)(1-\beta x)} + \tfrac{\beta^2}{(1-\alpha)(1-\beta x)^2}\left[\tfrac{\alpha(1-\beta x)}{\rho+\delta}\right]^{\frac{\alpha}{1-\alpha}} > 0$$

allows to conclude that $\tilde{x}(A)$ is a convex function of A.

D Proof of Proposition 4

(22) is a function of $\tilde{x}(A)$, whose derivative is

$$\tilde{K}'_\infty(x) = \left[\frac{\alpha(1-\beta x)}{\rho+\delta}\right]^{\frac{1}{1-\alpha}}\left[1 - \frac{\beta}{(1-\alpha)(1-\beta x)}\right], \tag{41}$$

which is equal to zero for $x_K = \frac{1-\alpha-\beta}{\beta(1-\alpha)} < 1$, since we have $\frac{1-\alpha}{2-\alpha} < \frac{\xi}{1+\xi} < \beta$ using H1. Since $d\tilde{K}_\infty/dA = \tilde{K}'_\infty(x)\tilde{x}'(A)$, the stationary level of capital reaches a maximum for the transfer

$$A_K = \frac{1}{\rho}\left[\frac{\beta(\xi+1)}{1-\alpha} - 1\right]\left[\frac{\alpha\beta}{(\rho+\delta)(1-\alpha)}\right]^{\alpha/(1-\alpha)},$$

which is positive if $\beta > (1-\alpha)/(1+\xi)$, which always holds since $\beta > \xi/(1+\xi) > (1-\alpha)/(1+\xi)$ using H1.

The stationary level of income from production $\tilde{Y}_\infty$ is a function of $\tilde{L}_\infty = \tilde{x}(A)$, hence it implicitly depends on A:

$$\tilde{Y}_\infty(x) = \left[\frac{\alpha}{\rho+\delta}\right]^{\frac{\alpha}{1-\alpha}} [1-\beta x]^{1/(1-\alpha)}\, x. \tag{42}$$

The impact of A on the stationary production level is derived from $d\tilde{Y}_\infty/dA = \tilde{Y}'_\infty(x)\tilde{x}'(A)$, where

$$\tilde{Y}'_\infty(x) = \left[\frac{\alpha(1-\beta x)}{\rho+\delta}\right]^{\frac{\alpha}{1-\alpha}}\left[1 - \frac{2-\alpha}{1-\alpha}\beta x\right].$$

If $\tilde{x}(A) \leq \frac{1-\alpha}{\beta(2-\alpha)}$, then $\tilde{Y}'_\infty(x) \geq 0$ whereas if $\frac{1-\alpha}{\beta(2-\alpha)} \leq \tilde{x}(A) \leq \frac{\xi}{\beta(1+\xi)}$ then $\tilde{Y}'_\infty(x) \leq 0$. Given that $\tilde{x}'(A) < 0$, we reach a maximum of production when $x_Y = \frac{1-\alpha}{\beta(2-\alpha)}$, which corresponds to a transfer threshold A_Y, where

$$A_Y = \frac{(1-\alpha)\nu}{2-\alpha}\left[\frac{\alpha}{(2-\alpha)(\rho+\delta)}\right]^{\frac{\alpha}{1-\alpha}}.$$

For $A \in [0, A_Y[$, $\tilde{Y}_\infty$ is increasing in A, whereas for $A \in]A_Y, \bar{A}]$, it is decreasing in A.

We have $x_Y > x_K$ since $\frac{1-\alpha}{2-\alpha} < \frac{\xi}{1+\xi} < \beta$ using H1. Hence, $A_Y < A_K$. We can also compare A_Y with $\bar{A}$ (determined by $\tilde{x}(\bar{A}) = L_0$):

$$\frac{A_Y}{\bar{A}} = \frac{(1-\alpha)\rho\nu}{\xi - \beta L_0(1+\xi)}\left[(2-\alpha)(1-\beta L_0)^\alpha\right]^{-1/(1-\alpha)} < 1,$$

which is increasing in $\rho\nu$ iff $L_0 < x_Y$.

The total revenue function finds a maximum for A_I, which is determined by $d\tilde{Y}_\infty/dA = -d_{bas}$. Hence $\tilde{Y}'_\infty(x) > 0$, which implies $x_I < x_Y$ and $A_I > A_Y$. To ensure that $A_I < \bar{A}$, which is equivalent to $x_I > \tilde{x}(\bar{A}) = L_0$, we obtain an implicit equation for x_I:

$$(1-\beta x)\left[\rho(2-\alpha)\left(x - \frac{1-\alpha}{\beta(2-\alpha)}\right) + d_{bas}(1+\xi)\right] = \alpha d_{bas} > 0, \tag{43}$$

hence the bracketed term in the LHS must be positive, which implies

$$x_I > x_Y - \frac{d_{bas}(1+\xi)}{\rho(2-\alpha)}.$$

A sufficient condition is that the RHS is higher than L_0, hence

$$d_{bas} < \frac{\rho[1-\alpha-(2-\alpha)\beta L_0]}{\beta(1+\xi)}, \tag{44}$$

where the upper bound is positive iff $L_0 < x_Y$.

For A_c, we adopt a proof by contradiction. We have $A_K < A_I$. Assume $A_c < A_K < A_I$. Since A_c is determined by $d\tilde{c}_\infty/dA = 0$, it implies that $d\tilde{I}_\infty/dA = \delta d\tilde{K}_\infty/dA > 0$, hence $d\tilde{I}_\infty/dA > 0$ and $d\tilde{K}_\infty/dA > 0$. When we reach A_K, we have $d\tilde{c}_\infty/dA = d\tilde{I}_\infty/dA > 0$, which is contradictory with the fact consumption finds a maximum before.

Assume $A_K < A_c < A_I$. We must have for A_c the following equality $d\tilde{I}_\infty/dA = \delta d\tilde{K}_\infty/dA$. However, it is impossible since $d\tilde{I}_\infty/dA > 0$ and $d\tilde{K}_\infty/dA < 0$.

Finally assume $A_K < A_I < A_c$. For A_c, we have $d\tilde{I}_\infty/dA = \delta d\tilde{K}_\infty/dA < 0$, with $d\tilde{I}_\infty/dA < 0$ and $d\tilde{K}_\infty/dA < 0$, which leads no contradiction.

E Proof of Proposition 7

Using (35) and (35) gives the following implicit function for the stationary level of agricultural land, instead of (37),

$$p^{1/(1-\alpha)}h(x)m(x,A) - \rho A[1-g'(S)] = 0, \tag{45}$$

where

$$h(x) = \left[\frac{\alpha(1-\beta x)}{\rho+\delta}\right]^{\frac{\alpha}{1-\alpha}}$$
$$m(x,A) = p\xi - p\beta x\,(1+\xi) - \rho A g'(S)p'(g)x(1-\beta x).$$

When $A = 0$, we obtain $\breve{x} = L_\infty$, where $\breve{x}$ is the solution of (45). Using the implicit function theorem gives

$$\breve{x}'(A) = \frac{\rho[1-g'(S)] - p^{1/(1-\alpha)}h(x)\partial m(x,A)/\partial A}{p^{1/(1-\alpha)}[h'(x)m(x,A) + h(x)\partial m(x,A)/\partial x]}.$$

First, observe that $h(x) > 0$ and $m(L_\infty, 0) = 0$. Assume $p'(g)$ is sufficiently small to have $m(x,A) > 0$ for $x < L_\infty$ (to ensure that (45) has a solution). We also have

$$\frac{\partial m(x,A)}{\partial A} = -\rho g'(S)p'(g)x(1-\beta x) < 0,$$

and

$$h'(x) = -\frac{\beta\alpha^2}{(1-\alpha)(\rho+\delta)}\left[\frac{\alpha(1-\beta x)}{\rho+\delta}\right]^{\frac{2\alpha-1}{1-\alpha}} < 0.$$

Finally,

$$\frac{\partial m(x,A)}{\partial x} = -\beta p(1+\xi) + \rho A g'(S) p'(g)[2\beta x - 1].$$

It suffices that $x < 1/(2\beta)$ to ensure that $\partial m(x,A)/\partial x < 0$ without ambiguity. Hence, since we have $\breve{x} \leq \xi/[\beta(1+\xi)]$, it implies the following sufficient condition: $\xi < 1$, where $\xi = (1-\alpha)(1+\rho\nu)$. For a low rate of time preference, the condition is satisfied. Thus, we obtain $\breve{x}'(A) < 0$.

Denote by $\breve{A}$ the rate of transfer ensuring that $\breve{x}(\breve{A}) = L_0$. We obtain $\breve{A} > \bar{A}$ if and only if

$$p^{\frac{2-\alpha}{1-\alpha}} > 1 + g'(S)\left[p'(g)p^{\frac{1}{1-\alpha}}\left(\frac{\alpha(1-\beta L_0)}{\rho+\delta}\right)^{\frac{\alpha}{1-\alpha}} L_0(1-\beta L_0) - 1\right] \equiv T(L_0),$$

where $T(x)$ denotes a threshold that depends on the stationary level of land. Comparing the slope of the function when $A = 0$, that is, $\breve{x}'(A)|_{A=0}$, with (40) gives that the function $\breve{x}(A)$ is steeper than $\tilde{x}(A)$ iff

$$p^{\frac{2-\alpha}{1-\alpha}} < 1 + g'(S)\left[p'(g)p^{\frac{1}{1-\alpha}}\left(\frac{\alpha}{(\rho+\delta)(1+\xi)}\right)^{\frac{\alpha}{1-\alpha}} \frac{\xi}{\beta(1+\xi)^2} - 1\right] \equiv T(L_\infty).$$

Consequently, if $p^{\frac{2-\alpha}{1-\alpha}} > T(L_\infty)$ and $p^{\frac{2-\alpha}{1-\alpha}} > T(L_0)$, we have $\breve{x} \geq \tilde{x}$. If $p^{\frac{2-\alpha}{1-\alpha}} < T(L_0)$ and $p^{\frac{2-\alpha}{1-\alpha}} < T(L_\infty)$, we have $\breve{x} \leq \tilde{x}$. Finally, if $p^{\frac{2-\alpha}{1-\alpha}}$ is higher than one threshold and lower than the other, comparing the environmental efficiency of the REDD mechanism with and without tenure insecurity is ambiguous.

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