September 2003

Deforestation and the Real Exchange Rate

Abstract

Deforestation is a phenomenon that has largely been concentrated in the developing world. We construct a theoretical model of deforestation that focuses on the factors affecting the incentives to transform forested land into agricultural land. We show that: (i) lower discount rates (associated with higher income levels), stronger institutions, and increases in the relative price of timber decrease deforestation; (ii) depreciations in the real exchange rate increase deforestation in developing countries whereas the opposite obtains in developed countries; (iii) paradoxically, better institutions exacerbate the deleterious impact of depreciations in developing countries. These hypotheses are tested on an annual sample of 122 countries over the 1963-1994 period, and are not rejected by the data. Our results suggest that short-term macroeconomic policy, institutional factors, and the interaction between the two, are potentially important determinants of environmental outcomes.

Keywords: deforestation, real effective exchange rate, institutions.
JEL: O13, Q23, F31, F41

"La forêt ici manque et là s'est agrandie," Victor Hugo, *Les Rayons et les Ombres*

"Fear not till Birnam wood do come to Dunsinane," William Shakespeare, *Macbeth*

1 Introduction

In recent years, deforestation, particularly in developing countries, has been of increasing concern, mainly because of widespread fears of global warming and declining biodiversity. The 2003 *World Development Report* states that "one-fifth of all tropical forests have been cleared since 1960. According to the Food and Agriculture Organization of the United Nations (FAO), deforestation has been concentrated in the developing world. At the same time, forest cover in industrial countries is stable or even increasing slightly."[1] [2]

Since land has several alternative uses, economic analysis can contribute to our understanding of the process of deforestation. On the one hand, forests allow for wood production for domestic and export markets: wood may be used domestically for industrial and firewood purposes, and timber products may be exported. On the other, forest land is subject to encroachment by agricultural activities and grazing. The choice between forest and agriculture use of the land depends, *ceteris paribus*, on the time preference of individuals since wood production implies a long term investment in the forest. Since it is often believed that discount rates are higher in poor countries than in rich countries, a

[1] We thank Elisabeth Sadoulet for her careful reading of an early draft, as well as participants in the "Cinquièmes journées scientifiques du Réseau analyse économique et développement de l'Agence universitaire de la Francophonie (Economie de l'environnement et développement)," Montréal, Québec, Canada, September 2001. We are particularly grateful to Henning Bohn and Robert T. Deacon for providing us with their data on institutions. The usual disclaimer applies.

[2] *World Development Report 2003*, p. 3.

bias in favor of deforestation may exist in the former. Moreover, important institutional issues arise because of the common property resource aspect of forests, as well as because of poorly defined property rights. These forms of market failure are usually held to be more likely in developing countries. To whit, forest resources are often over-utilized in developing countries because individual property rights are neither established nor enforced. The example of collective land resulting from forest clearing, and used for grazing, is a case in point.

The alternative uses of forest land also lie behind the importance accorded to population growth and agricultural development in the analysis of deforestation. These factors have been the subject of a good deal of empirical microeconomic analysis (for a survey see Angelsen and Kaimowitz, 1999). However, simple economic models, such as the three good, two factor general equilibrium model sketched by Foster, Rosenzweig and Berhman (1999), suggest that the impact of economic development on forest cover will depend upon the relative rates of return to the forest and to alternative uses of the land in question. The normal focus on factors which are associated with readily available data and amenable to direct quantitative treatment explains why there has been relatively little work dealing explicitly with the impact of relative prices on forestation. In most microeconomic datasets, there is little, if any, variation across households in the price of wood or in the price of factor inputs, especially at the local level.[3] Even if data on several regions dispersed geographically do allow one to address the lack of variation in prices using microeconometric analysis, such data are rare.[4] Even in this case, however, though the prices of factor inputs (notably wages) are likely to vary, the price of wood is likely to be deter-

[3] Angelsen and Kaimowitz (1999), p. 78.

[4] See, e.g., Foster, Rosenzweig and Berhman (1999).

mined internationally, and is therefore unlikely to display much variability on a regional basis. The forest, though immobile (Macbeth and Birnam wood notwithstanding...), is in fact an internationally tradable good whose price is determined largely on international markets. This is obvious for exported timber, but it is also true for timber consumed by local industry producing internationally traded goods such as paper or furniture, as it is for firewood, which has ready substitutes in the form of imported petroleum products.

It is therefore clear that there is room for useful macroeconomic analyses of deforestation. Indeed, the numerous microeconomic studies of the factors that determine forest area have dealt with a relatively limited number of countries and run the usual risks inherent in using microeconomic studies to generalize concerning global processes. Most importantly, a macroeconomic approach has less difficulty in accounting for the relative return to the forest. This observation yields what we hold to be the most important contribution of our paper: using macro panel data on deforestation allows us to take the relative rate of return to the forest into account through macro-price indices such as the relative price of wood to agricultural goods and the real exchange rate of each country.

Intuitively, it is clear that an increase in the relative price of wood should have a positive effect on land under forest cover. The consequence of a change in the real exchange rate is less obvious. The real exchange rate represents the price of tradables relative to non-tradables and is a proxy for the price of wood (an internationally tradable good) relative to the price of labor (wages), which is domestically determined. But it is also a proxy for the price of agricultural goods relative to wages, provided that the agricultural sector is not overly protected vis-à-vis the outside world. It is striking how sharp currency devaluations in developing countries, leading to real exchange rate depreciation, have resulted in deforestation. For instance, following the 50 percent devaluation of the

CFA franc in 1994, heavy timber traffic on roads in Gabon increased, domestic furniture production boomed in Abidjan and Dakar, carts carrying firewood proliferated in rural Burkina Faso, and clearing obtained almost everywhere in the CFA franc area. Similarly, after the collapse of the Indonesian rupiah in 1997, timber exports increased and wood was substituted for petroleum products for domestic use.

One manifest inconvenience of the macroeconomic approach to deforestation is that the FAO forest data, which are unique in being internationally comparable, have been the subject of a good deal of criticism, which is clearly justified in many cases (Rudel and Roper, 1997). In particular, the FAO uses extrapolations based on a hypothesized relationship between forest cover and population to "fill in" missing observations. On the other hand, to the extent that such measurement error is country-specific and relatively persistent over time, the use of appropriate econometric technique, such as country-specific fixed effects, should allow one to temper the initial pessimism concerning the possibility of obtaining valid results using these data.[5]

The aim of this paper is to understand why forest cover is decreasing in developing countries while it is increasing in developed areas.[6] Our line of reasoning is based on a simple theoretical model which revolves around the choice facing an individual endowed with a unit of forested land, and who has to decide whether to keep it as forest or clear it and turn it into agricultural land. Higher discount rates and less developed institutions provide a simple explanation for why more individuals in developing countries are induced to deforest their land than is the case in developed countries. Moreover we

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[5] Moreover, their credibility is clearly high enough for the World Bank to use these data as part of its overall assessment of sustainable development (*World Development Indicators*, 2002).

[6] In the sample used in the regression results presented in the first three columns of Table 2, the annual rate of deforestation in the poorest quartile of observations is equal to 0.1 percent, whereas the corresponding figure for the richest quartile of observations is equal to −0.2 percent.

show, under plausible assumptions, that a depreciation of the real exchange rate increases deforestation in developing countries and reduces deforestation in developed ones. Since the real exchange rate has been appreciating in developed countries and depreciating in the developing world, it may have contributed significantly to deforestation at the global level. Our model also allows us to simultaneously address the role of more traditional factors that should affect deforestation, such as population density or its growth rate.

Several authors have considered an environmental Kuznets curve for forest cover (Panayotou,1993, Cropper and Griffiths, 1994, Rock, 1996, Bhattarai and Hammig, 2001). According to this hypothesis, the marginal impact of GDP per capita on deforestation is positive for low levels of income, and becomes negative once a certain threshold level of income has been reached. One of the most commonly-held justifications for its existence is that: "logging and fuelwood uses of the forest are likely at first to increase with income. Agricultural and fuelwood motives for deforestation, however, are eventually likely to decline with per capita GDP."[7] Another explanation is based on a threshold level of income per capita above which the psychological value ascribed to "pristine forests" becomes sufficiently high for it to be in the interests of the population to reduce deforestation.[8] This last argument suggests that it is difficult to envisage testing for the presence of a deforestation Kuznets curve without controlling for the relative price of the forest : if psychological relative values are important, *monetary* relative values should be so as well. The inclusion of the real exchange rate in such a specification is therefore essential.

This paper is organized as follows. In part 2, we present our theoretical model and derive a series of PROPOSITIONS that describe the comparative statics of deforestation

[7] Cropper and Griffiths (1994), p. 252.

[8] The expression "pristine forests" is from Angelsen and Kaimowitz (1999), p. 89.

with respect to a number of key variables of interest, including the rate of time preference, institutional quality relative prices, and income. In part 3, we set out the empirical counterpart to our theoretical model, and highlight a series of easily testable (and refutable) hypotheses. We then present our empirical results, based on estimation using country-specific fixed effects on a panel of 122 countries over a thirty year time span. These results largely corroborate the theoretical hypotheses set out in part 2.

2 A theoretical model of deforestation

2.1 Preliminaries

Consider a population of individuals each of whom is endowed with one unit of forested land.[9] Individuals are infinitely lived and decide in the first period of their lives what to do with their endowment of land. All agents are blessed with perfect foresight. Two choices are possible.

First, they may keep the land as forest, which yields a per period profit at time t of $\pi^F(t) = p^B(t)q^F(l^F(t)) - w(t)l^F(t) - \phi^F(t)$, where labor, denoted by $l(t)$, is the sole *variable* factor input, $w(t)$ is the wage rate, $q^F(.)$ is the production technology that turns labor (and other fixed factors) into wood output, and $\phi^F(t)$ are other fixed costs incured in the production process. The latter are essentially associated with the quality of institutions (denoted by I), where we expect $\partial\phi^F(t)/\partial I = \phi^F_I(t) < 0$.

The second choice involves turning the endowment of forest land into agricultural land and, in the process, selling the wood that is obtained through clearing. In what follows, we assume that the process of deforestation is irreversible. The sale of the wood from clearing

[9] Note that one could begin with the alternative hypothesis that each individual is endowed with one unit of agricultural land. This would lead to a model of *reforestation* (rather than deforestation), where most of the arguments that follow would be reversed.

yields a profit equal to $\pi^C(t) = p^B(t)q^C(l^C(t)) - w(t)l^C(t) - \phi^C(t)$, where $q^C(.)$ represents the clearing technology, while agricultural use of the land yields $\pi^A(t) = p^A(t)q^A(l^A(t)) - w(t)l^A(t) - \phi^A(t)$, where $q^A(.)$ is the agricultural production technology. In each of these activities, individuals are assumed to minimize costs and to maximize profits. Assuming that each production technology is increasing and concave in $l(t)$ yields conventional profit functions $\pi^F(p^B(t), w(t); .)$, $\pi^C(p^B(t), w(t); .)$, $\pi^A(p^A(t), w(t); .)$ as well as conventional costs functions $C^i(q^i(t), w(t); .)$, $i = F, C, A$ that satisfy the usual properties, such as Shephard's or Hotelling's Lemma. The theoretical model presented below will show that the choice of whether to deforest or not will depend on (i) the rate of time preference, (ii) the quality of institutions, (iii) relative prices, and (iv) other factors traditionally associated with deforestation.

2.2 Choosing whether to deforest or not: the role of the rate of time preference

From the outset, we pose the following hypotheses that will guarantee that the choice between deforesting and keeping land under forest cover will not become degenerate.

Assumption 1: $\pi^C(p^B(t), w(t); .) - \pi^F(p^B(t), w(t); .) > 0$.

Assumption 2: $\pi^F(p^B(t), w(t); .) - \pi^A(p^A(t), w(t); .) > 0$.

Assumption 3: $C^F(q^F(t), w(t); .) = C^C(q^C(t), w(t); .)$.

Assumption 1 states that the single period profit from clearing a plot of land is greater than the single period profit from a "sustainable" harvesting of forest resources. Assumption 2, on the other hand, states that the single-period profit from sustainable harvesting of forest resources is greater than the corresponding profit from switching the land into agriculture. Assumption 2 is crucial in that, were it not to be satisfied, it would be individually rational to deforest *all* land. ASSUMPTION 1 combined with ASSUMPTION 2 implies that there is an interesting tradeoff involved in deforestation. On the one hand, clearing yields a one-shot single period profit that is larger than what one would obtain from sustainable harvesting of forest resources. On the other hand, this short-term increase in profits is tempered by the fact that one then loses the difference between π^F and π^A (which is positive by ASSUMPTION 2) for all successive periods. The tradeoff between short-term gains to clearing and long-term losses to having cleared constitutes the crux of our model, and invariably leads to a key role for an individual's discount rate.

ASSUMPTION 3 is not crucial (and can be weakened somewhat), but simply translates the intuitively appealing notion that ASSUMPTION 1 stems not from differences in costs of clearing versus costs of sustainably harvesting the forest, but rather from the greater revenue one obtains by clearing all trees off the land (and thus rendering it amenable to agricultural activity) *versus* harvesting forest resources sustainably.

The present-discounted value (PDV) of keeping the land as forest is given by:

$$W^F = \sum_{t=0}^{t=+\infty} \frac{\pi^F(p^B(t), w(t); .)}{(1 + r(t))^t}$$

If one assumes that the profit from sustainable forest use is the same in each period and that the interest rate is constant, one obtains:

$$W^F = \pi^F(p^B, w; .) \sum_{t=0}^{t=+\infty} \left(\frac{1}{1+r}\right)^t = \pi^F(p^B, w; .)\frac{1+r}{r}$$

When the choice is to deforest, the PDV of the cleared land is given by:

$$W^A = \pi^C(p^B, w; .) + \pi^A(p^A, w; .) \sum_{t=1}^{t=+\infty} \left(\frac{1}{1+r}\right)^t$$

where we assume that agricultural profit obtains only in the period following clearing (i.e., starting in period 1). This expression can be rewritten as:

$$\begin{aligned} W^A &= \pi^C(p^B, w; .) + \pi^A(p^A, w; .)\left[\sum_{t=0}^{t=+\infty}\left(\frac{1}{1+r}\right)^t - 1\right] \\ &= \pi^C(p^B, w; .) + \pi^A(p^A, w; .)\frac{1}{r} \end{aligned}$$

Individuals will then deforest when:

$$W^F = \pi^F(p^B, w; .)\frac{1+r}{r} < \pi^C(p^B, w; .) + \pi^A(p^A, w; .)\frac{1}{r} = W^A$$

Assume that individuals differ according to their discount rate r. More formally, suppose that the discount rate r is distributed in the population according to the probability density function $f(r)$ over the interval $[0, \overline{r}]$, where we assume that:

$$\pi^F(p^B, w; .) - \pi^A(p^A, w; .) < \overline{r}\left(\pi^C(p^B, w; .) - \pi^F(p^B, w; .)\right).$$

This assumption states that the gain to clearing (with respect to sustainable harvesting of the forest) must be "sufficiently" large relative to the loss in profits stemming from conversion to agriculture. Essentially, this is a technical condition which, as will be shown below, ensures that some individuals do in fact choose to deforest their land. Let r^* be the "limit" discount rate such that an individual is just indifferent between leaving his land as forest or clearing it. This value of the discount rate is defined implicitly by:

$$\pi^F(p^B, w; .)\frac{1+r^*}{r^*} - \pi^C(p^B, w; .) - \pi^A(p^A, w; .)\frac{1}{r^*} = 0$$

which implies that

$$r^* = \frac{\pi^F(p^B, w; .) - \pi^A(p^A, w; .)}{\pi^C(p^B, w; .) - \pi^F(p^B, w; .)} \tag{1}$$

The definition of r^* given in equation 1 constitutes the basis of all of the theoretical results that follow. ASSUMPTIONS 1 and 2 imply that $r^* > 0$, since both the denominator and the numerator of this expression will then be positive, while the assumption made above guarantees that $r^* < \overline{r}$. It follows that $r^* \in [0, \overline{r}]$ and that some portion of the population will choose to deforest their land, while the remainder will chose to keep their land under forest cover. ASSUMPTION 2, on the other hand, implies that $\Delta W = W^F - W^A$ is *decreasing* in r. To see why, consider the derivative of ΔW, with respect to r. This yields:

$$\frac{d\Delta W}{dr} = \frac{\pi^A(p^A, w) - \pi^F(p^B, w)}{r^2} < 0$$

where the sign follows directly from ASSUMPTION 2. Consider now the limits of ΔW as $r \to 0$ and as $r \to \overline{r}$. We obtain:

$$\lim_{r \to 0} \Delta W = \lim_{r \to 0} \frac{1}{r} \left(\begin{array}{c} \pi^F(p^B, w) - \pi^A(p^A, w) \\ -r\left(\pi^C(p^B, w) - \pi^F(p^B, w)\right) \end{array} \right) = +\infty$$

and

$$\lim_{r \to \overline{r}} \Delta W = \frac{1}{\overline{r}} \left(\pi^C(p^B, w) - \pi^F(p^B, w)\right)(r^* - \overline{r}) < 0$$

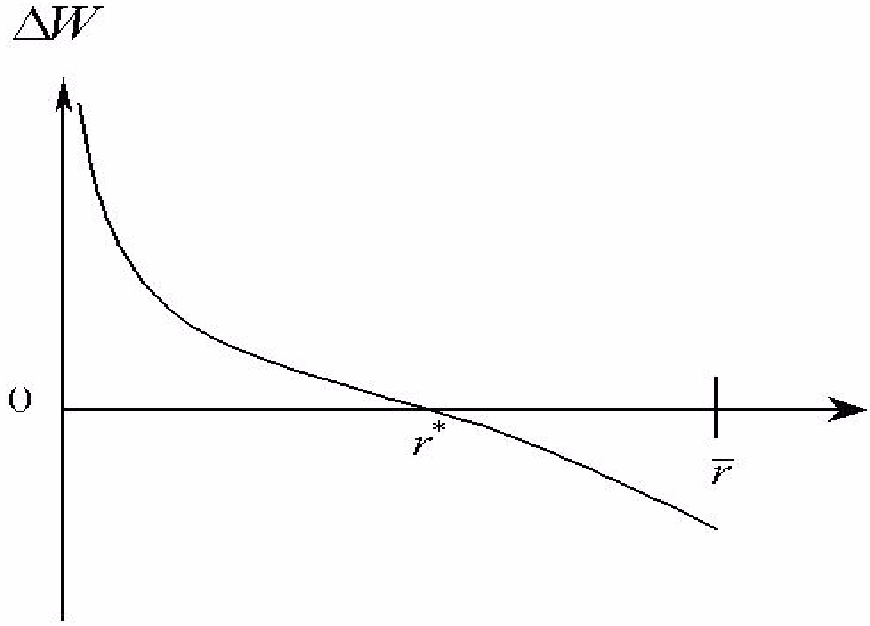
The relationship is illustrated in Figure 1.

Intuitively, individuals such that $r \in [0, r^*]$ choose to keep their land under forest cover since their discount rate is "low": they therefore put more weight on the loss in profits stemming from conversion to agricultural activity than on the short-term gains to clearing. Individuals with $r \in [r^*, \overline{r}]$ choose to clear: they put relatively more weight on the short-term gains to clearing than on the intertemporal losses stemming from conversion to agricultural activities. The preceding results immediately yield the following important PROPOSITION:[10]

Proposition 1 *Under* ASSUMPTIONS *1 and 2, deforestation is an increasing function of the average discount rate of the population.*

[10] All proofs are relegated to the APPENDIX.

Figure 1: Individuals to the left of r^* keep their land under forest cover, individuals to the right of r^* deforest.



PROPOSITION 1 implies that if the average discount rate in the population decreases as per capita income increases, deforestation should decrease. Conversely, the poorer a country, and thus the greater the average discount rate of the population, the greater should be deforestation.

In the following sections, we consider the comparative statics of deforestation with respect to five different changes in the underlying environment. Formally, all proofs are based on the comparative statics of r^*. We begin with the impact of institutions, followed by the main topic of this paper, relative prices, with a focus on the effect on deforestation of increases in the relative price of timber and depreciations of the real exchange rate. We also show that, under reasonable assumptions, the impact of depreciations will be different in developing and developed countries. We then consider the impact on deforestation of demographic factors, and conclude the subsection with a discussion of the environmental Kuznets curve.

2.3 The quality of institutions

Among the determinants of deforestation, institutions are often held to play a leading role. In what follows, we show how institutional concerns can easily be incorporated into the basic model. We then derive the comparative statics of deforestation with respect to institutions.

While it is clear that institutions affect the profits associated with all three forms of activity (sustainable forest harvesting, clearing, and agricultural production), it is probably not unreasonable to assume that it is sustainable harvesting of forest products that is most sensitive to the existence of clear property rights and their enforcement (see Bohn and Deacon, 2000). By its very nature, agricultural production entails "living on the land," while clearing is often associated with "hit and run" operations, and may indeed be a means of establishing squatters' rights to agricultural land. As such, our basic working hypothesis shall be that $\pi^A(p^A, w)$ and $\pi^C(p^B, w)$ are unaffected by institutional concerns, whereas $\pi^F = \pi^F(p^B, w; I), \pi_I^F > 0$, where I denotes institutions (with a higher value of I denoting better institutions). Strictly-speaking, it is of course not true that $\pi^A(p^A, w)$ is unaffected by institutional concerns: for example, decisions surrounding the maintenance of land quality and investment are intimately related to institutional arrangements. On the other hand, our assumption is not meant to translate strict independence, only that π^F is *more sensitive* to institutions than are π^A and π^C. The comparative statics in this case are particularly easy to establish, and immediately yield the following PROPOSITION:

Proposition 2 *Under* ASSUMPTIONS *1 and 2, an improvement in institutions reduces deforestation.*

In terms of the graphical illustration given by Figure 1, an improvement in institutions shifts r^* towards the right ($\frac{dr^*}{dI} > 0$), thereby reducing the proportion of the population that wishes to clear its endowment of forest land. If institutional underdevelopment is a characteristic of developing countries, as is a high rate of time preference, then our model clearly predicts greater rates of deforestation in developing countries than in developed countries.

2.4 Changes in relative prices

Define the relative price of timber as $p^R = \frac{p^B}{p^A}$ and the real exchange rate as $e = \frac{p^T}{p^{NT}}$, where p^T is the price of tradables and p^{NT} the price of non-tradables. Given the simple structure of our model, $p^T = (p^B)^{1-\alpha}(p^A)^\alpha$, where α is the share of agricultural production in total output of tradables, and p^{NT} is entirely determined by the domestic wage, which we chose as the numeraire: $p^{NT} = w = 1$. Simple algebra then implies that one can write:

$$p^A = e\left(p^R\right)^{\alpha-1}, \; p^B = e\left(p^R\right)^{\alpha}$$

This implies that we can rewrite r^* as:

$$r^* = \frac{\pi^F\left(e\left(p^R\right)^\alpha, w; .\right) - \pi^A\left(e\left(p^R\right)^{\alpha-1}, w; .\right)}{\pi^C\left(e\left(p^R\right)^\alpha, w; .\right) - \pi^F\left(e\left(p^R\right)^\alpha, w; .\right)} \tag{2}$$

2.4.1 The relative price of timber

Consider a permanent change in the relative price of timber. The following Proposition is immediate:

Proposition 3 *Under* Assumptions *1, 2, and 3, a permanent increase in the relative price of timber reduces deforestation.*

Proposition 3 stems from the limit value r^* being an increasing function of the relative price of timber. Graphically, an increase in p^R shifts r^* to the right in Figure 1 ($\frac{dr^*}{dp^R} > 0$).

2.4.2 The real exchange rate

A key aspect of our model is that it generates opposite comparative statics results for developing and developed countries concerning the impact of changes in the real exchange rate on the incentives to engage in deforestation. Recall that a depreciation in the real exchange rate (an increase in the price of tradables versus non-tradables) may affect the real price of timber and of agricultural goods (with respect to the numeraire). First, a depreciation increases the relative price of exported timber. Second, a depreciation increases the return to timber-consuming activities that produce internationally traded goods (such as paper or furniture). This is true whether the goods in question are destined for the export market or compete with imports. Third, a depreciation increases the relative price of energy (oil, gas and electricity) and thus the price of wood for heating and cooking. Finally, a depreciation increases the return to agricultural activities, irrespective of whether these are constituted by export or food crops (some of which may compete with imported products).

Our basic result is that real depreciations result in an increase in deforestation in developing countries, whereas the opposite obtains in developed countries. Three different hypotheses can generate this result. The first approach contrasts developing and developed countries in terms of the relative costs of sustainable forest harvesting versus agricultural production, and focuses on changes in the real exchange rate that are seen as being permanent. The second explanation is based on the assumption that, in general, variations in the real exchange rate are perceived as being temporary phenomena in developing countries: we show that, when a depreciation is seen as being temporary, it will always *increase* deforestation. Finally, when protectionism results in agricultural goods becoming non-tradables (as is arguably the case for the agricultural sectors of most developed countries), a depreciation always results in a decrease in deforestation.

We begin with the comparative statics of a permanent increase in the real exchange rate. The crucial hypotheses that we need are summarized in the following ASSUMPTIONS.

ASSUMPTION 4: For developing countries, $C^F(q^F(t), w(t); .) < C^A(q^A(t), w(t); .)$.

ASSUMPTION 5: For developed countries, $C^F(q^F(t), w(t); .) > C^A(q^A(t), w(t); .)$.

ASSUMPTIONS 4 and 5 can be justified by assuming that agriculture is extremely labor-intensive in developing countries. Since labor costs will constitute the most important element of C^A in developing countries, it does not seem unreasonable to assume that $C^F < C^A$. In developed countries, on the other hand, agriculture is much less labor-intensive, whereas forest-harvesting technologies are not always of an industrial nature: assuming that $C^F > C^A$ therefore would appear to be reasonable for developed countries.

With these ASSUMPTIONS in hand, we then have the following PROPOSITION:

Proposition 4 *Under* ASSUMPTIONS *1, 2, and 3:*
(i) when ASSUMPTION *4 holds (i.e., for less developed countries) a depreciation of the real exchange rate increases deforestation;*
(ii) when ASSUMPTION *5 holds (i.e., for developed countries), a depreciation of the real exchange rate reduces deforestation.*

PROPOSITION 4(i) is based on the fact that, for less developed countries, $\frac{dr^*}{de} < 0$. In Figure 1, this means that a depreciation shifts r^* to the left. It follows that a depreciation (an increase in e) will increase deforestation in developing countries, whereas (by PROPOSITION 4(ii)) the opposite ($\frac{dr^*}{de} > 0$) will occur in developed countries. PROPOSITION 4 is readily amenable to empirical testing, as we shall show below.

We now consider our second explanation for the deleterious impact on deforestation, in developing countries, of depreciations in the real exchange rate. Why would depreciations be more likely to be considered temporary in developing countries than in developed countries? Casual empiricism suggests that, since the floating of exchange rates at the begining of the 1970s, all countries have suffered from a great deal of volatility in their real exchange rates, with that affecting developing countries being significantly greater. Most producers in these countries have therefore grown used to wide fluctuations in the real exchange rate. It follows that there is a widespread belief in these countries that most variations in the real exchange rate are transitory.[11]

Consider then a *temporary* increase in the real exchange rate, which lasts one period (more precisely, it last only for the first period). This is equivalent to an initial value of $e(0) = \overline{e}$, followed thereafter by a real exchange rate $e(t) = e, t > 0$, with $e < \overline{e}$. In this case, one can write

$$\begin{aligned} W^F &= \pi^F\left(\overline{e}\left(p^R\right)^\alpha, w\right) + \pi^F\left(e\left(p^R\right)^\alpha, w\right)\sum_{t=1}^{t=+\infty}\left(\frac{1}{1+r}\right)^t \\ &= \pi^F\left(\overline{e}\left(p^R\right)^\alpha, w\right) + \pi^F\left(e\left(p^R\right)^\alpha, w\right)\frac{1}{r} \end{aligned}$$

whereas W^A is now given by

$$W^A = \pi^C\left(\overline{e}\left(p^R\right)^\alpha, w\right) + \pi^A\left(e\left(p^R\right)^{\alpha-1}, w\right)\frac{1}{r}$$

Individuals will then deforest when:

$$\begin{aligned} W^F &= \pi^F\left(\overline{e}\left(p^R\right)^\alpha, w\right) + \pi^F\left(\left(p^R\right)^\alpha, w\right)\frac{1}{r} \\ &< \pi^C\left(\overline{e}\left(p^R\right)^\alpha, w\right) + \pi^A\left(\left(p^R\right)^{\alpha-1}, w\right)\frac{1}{r} = W^A \end{aligned}$$

This expression defines a different "limit" value of r^*, denoted by $\widetilde{r}^*$, given by

$$\widetilde{r}^* = \frac{\pi^F\left(e\left(p^R\right)^\alpha, w\right) - \pi^A\left(e\left(p^R\right)^{\alpha-1}, w\right)}{\pi^C\left(\overline{e}\left(p^R\right)^\alpha, w\right) - \pi^F\left(\overline{e}\left(p^R\right)^\alpha, w\right)} \tag{3}$$

[11] This intuition is confirmed in our data. In the poorest quartile of the sample used in the estimations presented in the first three columns of Table 2, the standard deviation of the real effective exchange rate is equal to 52.2, whereas in the richest quartile, the corresponding figure is 30.8.

It is then easy to establish the following result:

Proposition 5 *Under* Assumptions *1 and 3, a temporary depreciation increases deforestation.*

In terms of Figure 1, a temporary increase in the real exchange rate results in a leftward shift in the limit value $\widetilde{r}^*$ ($\frac{d\widetilde{r}^*}{de} < 0$), and thus yields an increase in deforestation, *contrary* to the impact of a permanent increase in the same variable.

Note that a third explanation for the difference in the impact of a depreciation of the real exchange rate between developing and developed countries can be furnished by assuming that, because of protectionist agricultural policies in developed countries, agricultural goods should *not* be considered as tradables. We summarize this idea in the following Proposition:

Proposition 6 *Suppose that agricultural output is non-tradable; then a permanent depreciation reduces deforestation.*

Essentially, Proposition 6 stems from the fact that an increase in e, when agricultural output is non-tradable, yields the same result as an increase in the relative price of timber (considered in Proposition 3): a depreciation therefore results in a decrease in deforestation in this case (since $\frac{dr^*}{de} > 0$).

To summarize, our main arguments concerning the impact of real depreciations on deforestation are that in developing countries, an increase in e increases deforestation. This effect obtains either because (i) the depreciation is perceived as being permanent concomitantly with Assumption 4 holding (Proposition 4(i)); or (ii) the increase in e is perceived as being temporary (Proposition 5). In contrast, in developed countries an increase in e decreases deforestation, and this obtains either (i) because the increase in e is permanent and Assumption 5 holds (Proposition 4(ii)); or (ii) agricultural output is non-tradable because of protectionism; an increase in e is then equivalent to a permanent increase in the relative price of timber (Propositions 3 and 6).

2.4.3 The interaction of institutions and the real exchange rate

Of equal interest, given our focus on the impact of relative prices, is how institutions affect the marginal impact of the real exchange rate on deforestation. In this case, the relevant derivative is given by

$$\frac{d^2r^*}{dIde} = \left(p^R\right)^\alpha \frac{d}{dI} \frac{\left[\frac{1}{p^B}\left(p^Bq^F - p^Aq^A\right)\left(\pi^C - \pi^F\right) - \left(q^C - q^F\right)\left(\pi^F - \pi^A\right)\right]}{\left(\pi^C - \pi^F\right)^2}$$

We show in the Appendix (proof of Proposition 7) that this expression can be rewritten as

$$\frac{d^2r^*}{dIde} = \left(p^R\right)^\alpha \frac{\left[C_I^F\left(q^C - q^F\right) - q_I^F\left(C^F - C^A\right)\right]}{\left(\pi^C - \pi^F\right)^2} + 2\left(\frac{\pi_I^F}{\pi^C - \pi^F}\right)\frac{dr^*}{de} \tag{4}$$

In order to determine the sign of equation 4, some additional structure is needed in terms of how exactly institutions affect profits stemming from sustainable harvesting. Recall from our preliminaries that we see weak institutions as imposing a fixed cost on sustainable harvesting: $\pi^F = p^Bq^F(l^F) - wl^F - \phi_I^F(I)$, where $\phi_I^F(I) < 0$. This specification implies that $\pi_I^F = -\phi_I^F(I) > 0$, $C_I^F = \phi_I^F(I) < 0$ and $q_I^F = 0$. We then have the following Proposition, which is essentially a corollary to Proposition 4:

Proposition 7 *Under* Assumptions *1, 2, and 3:*
(i) when Assumption *4 holds (i.e., for developing countries), an improvement in institutions exacerbates the marginal impact of a depreciation on deforestation;*
(ii) when Assumption *5 holds (i.e., for developed countries), the impact of an improvement in institutions on the marginal effect of the exchange rate on deforestation is ambiguous.*

Recall that Proposition 4(i) has established that a depreciation of the real exchange rate increases the rate of deforestation in developing countries. Proposition 7 (i), for its part, shows that there are two effects, of opposite signs, of institutions in terms of their impact on deforestation in developing countries. On the one hand, the result established earlier (Proposition 2) shows that institutional strengthening has an unambiguously beneficial impact in that it reduces deforestation. On the other hand, a strengthening of institutions exacerbates the deleterious effects of depreciations of the real exchange rate (because $\frac{d^2 r^*}{dIde} < 0$).

2.5 Traditional factors affecting deforestation

2.5.1 Demographic factors

There exists a vast literature that considers the impact of demographic factors on deforestation. The findings of this literature are ambiguous and sometimes contradictory. Population growth or increases in population density are often held to increase deforestation, although it is sometimes posited that, beyond a certain threshold, they induce technological change in agriculture that slows the process (Boserup, 1965; see Angelsen and Kaimowitz, 1999, for a survey of this literature). It is worth emphasizing, however, that most work on this topic bases its analysis of the impact of population factors on deforestation on the effect of the former on relative prices (for example, through changes in the wage rate or in food prices). As such, the price variables considered above should already be accounting for many of the effects of population pressures. For example, if population growth leads to lower wages, this would be translated in our model by a depreciation of the real exchange rate. The results presented in Propositions 4, 5 and 6 therefore apply. In particular, our results imply that population pressures should, through their impact on relative prices, increase deforestation in developing countries.

2.5.2 The Kuznets curve

Several authors have considered that the marginal impact of GDP per capita may be positive for low levels of income and negative for high levels. As we recalled in the introduction, the environmental Kuznets curve hypothesis, applied to the forest, is based on various arguments. The first explanation assumes that during the early stages of development, logging or fire wood demand are on the rise while forest clearing for agricultural activities or grazing also increase. After a threshold level of development is reached, these factors are dampened by the diversification of activities into the industrial and service sectors, as well as by urbanisation. As in the case of population pressures, the impact of these factors on deforestation operates through changes in relative prices, which are already accounted for in our model. An alternative explanation of a potential Kuznets curve for deforestation is based on the psychological value ascribed to pristine forests, which is assumed to be decreasing during the early phases of development and increasing thereafter. In the framework of our model, this hypothesis corresponds to a very particular relationship between the average rate of time preference of the population and GDP per capita. Instead of being a monotonically decreasing function, the average discount rate of the population may at first be an increasing function of GDP per capita (because of a highly pressing need to improve living standards) and, after a threshold level of income is reached, this relationship may turn negative. To test for the presence of an environmental Kuznets curve, we shall introduce GDP per capita, as well as GDP per capita squared, into the specification.[12]

[12] The Balassa-Samuelson effect states that the equilibrium real exchange rate appreciates as GDP per capita increases. Assume for argument's sake that this relationship is linear. If, as we have shown, the marginal effect of the real exchange rate on deforestation is a function of the level of GDP per capita (Propositions 4, 5 and 6) and takes a multiplicative form then, by substitution of the Balassa-Samuelson effect, one obtains *by construction,* an *inverse* environmental Kuznets curve, in which deforestation will

3 Econometric specification and results

3.1 The estimating equation

Our basic econometric specification is given by an equation in which the dependent variable is the rate of deforestation, and where the explanatory variables are those suggested by our theoretical model. Formally-speaking, assume that there exists a steady-state level of the logarithm of forest cover in country i at time t, $\ln T_{i,t}^{F*}$, as determined by our theoretical model, and that the dynamics of forest cover can be described by a non-linear first-order difference equation that is given by $\ln T_{i,t}^{F} = \theta(\ln T_{i,t-1}^{F})$. By a first-order Taylor approximation around the steady-state (defined by the value of $T_{i,t}^{F}$ such that $\ln T_{i,t}^{F*} = \theta(\ln T_{i,t}^{F*})$), one can write:

$$\ln T_{i,t}^{F} = \ln T^{F*} + \left(\ln T_{i,t-1}^{F} - \ln T_{i,t}^{F*}\right)\theta',$$

where $\theta' = \frac{\partial\theta(\ln T_{i,t-1}^{F})}{\partial \ln T_{i,t-1}^{F}}$, evaluated at $\ln T_{i,t}^{F*}$. Subtracting $\ln T_{i,t-1}^{F}$ from both sides and rearranging yields

$$-\left(\ln T_{i,t}^{F} - \ln T_{i,t-1}^{F}\right) = (1-\theta')\ln T_{i,t-1}^{F} + (\theta'-1)\ln T_{i,t}^{F*}.$$

The basic econometric specification then follows by posing $(1-\theta')\ln T_{i,t-1}^{F} = \phi\left(\ln T_{i,t-1}^{F}\right)$ and $(\theta'-1)\ln T_{i,t}^{F*} = X_{it}\gamma$, which yields

$$-\left(\ln T_{i,t}^{F} - \ln T_{i,t-1}^{F}\right) \equiv z_{it} = \phi\left(\ln T_{i,t-1}^{F}\right) + X_{it}\gamma + \lambda_t + \mu_i + \varepsilon_{it} \qquad (5)$$

where $\phi(.)$ is a polynomial in the initial level of forest cover (in order to allow for more complex non-linear dynamics than would be possible with the simple linear specification suggested by $(1-\theta')\ln T_{i,t-1}^{F}$), X_{it} is a matrix of explanatory variables corresponding to

be first decreasing and then increasing in GDP per capita. It follows that if, aside from exchange rate effects, there are reasons to expect an environmental Kuznets curve, it may be obscured by the inverted Kuznets curve generated by the real exchange rate, if the real exchange rate is not explicitly included as an explanatory variable in the empirical specification.

those determinants of the steady-state level of forest cover identified in our theoretical work, λ_t is a time-specific effect, μ_i is a country-specific effect, and ε_{it} is a disturbance term that satisfies the usual properties. More explicitly,

$$X_{it} = \left[y_{it}, y_{it}^2, I_{it}, p_{it}^R, e_{it}, I_{it}e_{it}, y_{it}e_{it}, D_{it}\right]$$

where D_{it} represents demographic variables. Restricting our attention to a third-degree polynomial for $\phi(.)$ yields the following empirical specification:[13]

$$\begin{aligned} z_{it} &= \ln T_{i,t-1}^F \phi_1 + \left(\ln T_{i,t-1}^F\right)^2 \phi_2 + \left(\ln T_{i,t-1}^F\right)^3 \phi_3 \\ &\quad + y_{it}\gamma_1 + y_{it}^2\gamma_2 + I_{it}\gamma_3 + p_{it}^R\gamma_4 \\ &\quad + e_{it}\gamma_5 + y_{it}e_{it}\gamma_6 + I_{it}e_{it}\gamma_7 + D_{it}\gamma_8 \\ &\quad + \lambda_t + \mu_i + \varepsilon_{it} \end{aligned} \tag{6}$$

Our theoretical results suggest the following predictions on the partial derivatives of z_{it} with respect to the various dependent variables:

Table 1. Theoretical predictions

[13] The reader familiar with the existing econometric literature on the determinants of deforestation will have noted that we explicitly consider the *dynamics* of deforestation, which we model as a first-order difference equation. Just as it is appropriate to write a conventional growth of GDP per capita equation while allowing for convergence effects through the inclusion of the initial level of GDP per capita, one should include the initial level of forest cover as an explanatory variable. Most existing empirical treatments of the question have not taken this key fact into account.

PROPOSITION 1	a higher discount rate (proxied by lower GDP per capita) increases deforestation: $\frac{\partial z_{it}}{\partial y_{it}} = \gamma_1 < 0$
PROPOSITION 2	better institutions reduce deforestation: $\frac{\partial z_{it}}{\partial I_{it}} = \gamma_3 < 0$
PROPOSITION 3	an increase in the relative price of timber reduces deforestation: $\frac{\partial z_{it}}{\partial p_{it}^R} = \gamma_4 < 0$
PROPOSITIONS 4, 5 AND 6	a depreciation in the real exchange rate increases deforestation in developing countries and reduces deforestation in developed countries; econometrically, this is tested through the hypotheses that $\frac{\partial z_{it}}{\partial e_{it}} = \gamma_5 > 0, \frac{\partial z_{it}}{\partial (y_{it} e_{it})} = \gamma_6 < 0$, with $\widetilde{y}$ being defined as the value of y such that: $\frac{\partial z_{it}}{\partial e_{it}} + \widetilde{y} \frac{\partial z_{it}}{\partial (y_{it} e_{it})} = 0$
PROPOSITION 7	for developing countries, better institutions exacerbate the the deleterious effect of depreciations of the real exchange rate $\frac{\partial z_{it}}{\partial (I_{it} e_{it})} = \gamma_7 > 0$

3.2 The data

Our dependent variable is the annual rate of deforestation (*minus* the difference in logarithms of forest area, expressed in thousands of hectares), when forest area is strictly positive (source: FAO, *The State of the World's Forests,* various years). GDP per capita and demographic variables are from the World Bank's *World Tables.* Note that, according to our theoretical model, the average rate of time preference of the population is a key determinant of deforestation. It would have been appropriate to proxy this variable by the long-term interest rate. Unfortunately, such an interest rate is unavailable for most developing countries, and the corresponding short-term rates, that are available, are subject to so much short-run variation that it is difficult to see them proxying for the rate of time preference. Since the average discount rate of the population is likely to be a decreasing function of GDP per capita, the latter will constitute our proxy for r, although it is difficult to identify the time preference effect alone with this variable.

Our measures of institutions are given by two types of variables. First, we consider the indicator developed by Bohn and Deacon (2000), who construct an index of ownership risk (given by the probability of expropriation π), by postulating that ownership risk is related to observable political attributes of countries (political instability and types of government regimes).[14] They then use cross-country data on the investment rate and political characteristics to estimate the form of the relationship. They then construct "an index of ownership security, a monotone decreasing function of π ... by multiplying together the political variables and coefficients (of the previous regression) and summing."[15] The second measure of institutions we use comes from Freedom House's *Freedom in the World Survey*.[16] "The *Survey* rates countries based on real world situations caused by state and nongovernmental factors." It encompasses two general sets of characteristics grouped under political rights (index 1) and civil liberties (index 2). The countries are rated from 1 to 7 for each index with the quality of institutions decreasing with the value of the indices. In order to facilitate the reading of our econometric results, we have inverted the scale, with the poorest institutions corresponding to 0 and the best to 6.[17]

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[14] They use the indicators of political institutions developed by Banks, 1990.

[15] We are very grateful to Henning Bohn and Robert T. Deacon for providing us with their index. This comprises 3146 observations and has been used with success by the authors in their explanations of oil discovery and production, as well as deforestation.

[16] Available online at www.freedomhouse.org.

[17] We also carried out estimations using measures of institutions drawn from the POLITY project. This is a source of cross-national, longitudinal data on the degree of democracy and autocracy, available in its most recent version from the Centre for International Development and Conflict Management at

The relative price of timber p_{it}^R is approximated by the ratio of the price of wood from all sources quoted in London (source: IMF, *International Financial Statistics*, various issues) to the country-specific unit export values of agricultural goods (source: FAO). The real exchange rate of country i at time t is approximated by the real effective exchange rate computed as

$$e_{it} = \prod_{j=1}^{j=10} \left(e_{ijt}^n \frac{p_{jt}}{p_{it}} \right)^{\alpha_j} \tag{7}$$

where e_{ijt}^n is the nominal exchange rate index of country i *versus* country j (expressed in terms of the national currency), p_{it} is the consumer price index in country i (and similarly for j), α_j represents the share in country i's imports furnished by country j, and where the js are constituted by the ten most important (non-oil) trading partners of country i (these shares are given by the average values for the period 1980-6; the source for all these data is the IMF).[18] Note that an increase in this index corresponds to a real depreciation. Descriptive statistics for all of the variables used in the econometric work are presented in Table 2.

3.3 Results

Our econometric results, obtained after the within transformation (in order to account for μ_i in equation 6), and the inclusion of time dummies (to account for λ_t) are presented in Table 3.[19] In columns (1) to (3) we present results corresponding to the Bohn and Deacon index of expropriation risk. In columns (4) and (5), in contrast, our institutional variable is given by the Freedom House indices of political freedom.

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the University of Maryland. None of the available indicators from this source was found to be statistically significant in our empirical work.

[18] Note that, when p_{it} or p_{jt} were missing, they were replaced by the domestic GDP deflator.

[19] For the sake of brevity we do not present the coefficients associated with the time dummies in Table 3.

In column (1), which corresponds to the specification suggested by our theoretical work, we include two demographic variables (the population growth rate and rural population density). Both are statistically insignificant, suggesting that our intuition that the impact of these variables operates through relative prices is indeed confirmed in the data. In all subsequent results, the demographic variables are therefore dropped, since their inclusion did not affect the results and the coefficients associated with these variables were never statistically different from zero.

Regardless of the institutional variable used (the Bohn and Deacon index or either of the Freedom House indices), the basic empirical results remain largely the same, and are the following. First, the coefficient associated with the relative price of timber is negative in all specifications, and statistically significant when the Bohn and Deacon index of expropriation risk is our institutional variable. As predicted by PROPOSITION 3, an increase in the relative price of timber decreases deforestation.

Second, the coefficient associated with the real exchange rate is positive and statistically significant, while that associated with the real exchange rate times the log of GDP per capita is negative and statistically significant. This confirms the theoretical predictions of PROPOSITIONS 4, 5 and 6: a real depreciation increases deforestation in poor countries, with the effect becoming negative once a threshold level of GDP per capita is reached. This threshold level varies from $US 790 (corresponding to 32.4 percent of the sample) in column 4, to $US 1340 (corresponding to 47.2 percent of the sample) in column 3. Clearly the threshold is operative, whatever its precise level may be, and there is indeed a crisp separation between the behavior of deforestation with respect to depreciations in the real exchange rate in poor and rich countries.[20]

[20] Table 3 presents the threshold level of GDP for each specification. Note that, because of the

Third, the coefficient associated with institutions is negative and statistically significant, while the coefficient associated with institutions times the real exchange is positive and statistically significant. The first result is consistent with PROPOSITION 2, in that better institutions do indeed reduce deforestation, while the second result confirms the prediction of PROPOSITION 7, that better institutions exacerbate the deleterious effects of depreciations in developing countries (recall that PROPOSITION 7 also showed that this relationship was ambiguous for developed countries). The marginal impact of institutions on the rate of deforestation, evaluated at the mean value of the real exchange rate, is positive, though never statistically distinguishable from zero at the usual levels of confidence.[21] This brings into sharp focus the importance of clearly separating the effect of institutions into their direct effect *versus* the effect that operates through the real exchange rate.

Fourth, in column 3 we test for the presence of an environmental Kuznets curve, which would correspond to a positive coefficient associated with GDP per capita and a negative coefficient associated with GDP per capita squared: it should be clear that no evidence exists for an environmental Kuznets curve. Finally, according to our results, the total marginal impact of log GDP per capita on the rate of deforestation varies between 0.005 and 0.0007, with none of these marginal impacts being significant at the usual levels of confidence.[22] While this does not confirm PROPOSITION 1, the empirical result is not

multiplicative terms, the total marginal impact of the real exchange rate on deforestation is given by: $\frac{dz_{it}}{de_{it}} = \gamma_5 + y_{it}\gamma_6 + I_{it}\gamma_7$, which implies that the threshold level of GDP per capita below which the impact of a depreciation on deforestation is negative is given by $\widetilde{y} = -\left(\gamma_5 + \overline{I_{it}}\gamma_7\right)/\gamma_6$, where $\overline{I_{it}}$ is the mean level of the indicator of institutional quality.

[21] The total marginal effect of institutions on the rate of deforestation is given by $\frac{dz_{it}}{dI_{it}} = \gamma_3 + \overline{e_{it}}\gamma_7$, where $\overline{e_{it}}$ is the average value of the real effective exchange rate in the sample.

[22] The total marginal effect of log GDP per capita on the rate of deforestation is given by $\frac{dz_{it}}{dy_{it}} = \gamma_1 + 2\overline{y_{it}}\gamma_2 + \overline{e_{it}}\gamma_6$.

surprizing *per se* in that GDP per capita proxies for other effects, above and beyond those associated with the rate of time preference.

How important has real exchange rate depreciation been in terms of its impact on deforestation in the developing world, and what are the relative orders of magnitude involved? Consider the empirical results presented in column 4 of Table 3. The average annual depreciation of the real exchange rate in those countries with GDP per capita below the threshold level of 790 dollars was equal to 1.3 percent. If we use the coefficient estimates to compute the predicted annual rate of deforestation and compare it with the predicted annual rate of deforestation had the real exchange rate been 1.3 percent higher each year, the mean difference is equal to 0.025 percent. Given that the average annual rate of deforestation in these countries was equal to 0.11 percent, the absence of real exchange rate depreciation in poor countries would have reduced their mean rate of deforestation by 23 percent ($0.025 \div 0.11 = 0.227$). In contrast, institutional quality has improved in the same sample of countries by 0.02552 points (on the Freedom House scale) per year. Had this institutional strengthening not obtained, similar simulations yield a mean increase in the annual rate of deforestation of 9.57×10^{-4}, which corresponds to an increase of 0.8 percent ($(9.57 \times 10^{-4}) \div 0.11 = 0.008$). The small reduction in deforestation that has been achieved by the strengthening of institutions has therefore been overwhelmingly wiped out by real exchange rate depreciation. Our results highlight how avoiding real exchange rate depreciation would have significantly reduced deforestation in the developing world.

4 Concluding remarks

The main finding of this paper involves the impact of the real effective exchange rate on deforestation: our econometric results do not reject the null hypothesis that real depreciations increase deforestation in poor countries and decrease deforestation in rich countries. Given that economic policy over the past two decades has tended to favor real depreciation in the developing world (in contrast to what has obtained in the developed world), it has tended to exacerbate the process of deforestation. Simulations based on our empirical results show that real exchange rate depreciation is responsible for one quarter of the deforestation experienced by poor countries over the past 15 years.

In the long run, our results suggest that it is likely that the major determinant of deforestation at the global level will be constituted by the relative rates of growth of the developing and developed worlds, and the impact that this process will have on real exchange rates. If convergence obtains, real effective exchange rates will appreciate in poor countries and depreciate in rich countries, leading to a reduction in deforestation. On the other hand, an increase in inequality at the international level (divergence) will lead to a depreciation of the real effective exchange rates of the developing world, leading to an increase in deforestation.

Our results also highlight the importance of international markets for agricultural exports and timber, as well as the key role played by institutions, in terms of their impact on deforestation. Improvements in institutional quality will have a beneficial (negative) effect on deforestation in developing countries, as long as they are not accompagnied by real exchange rate depreciation.

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5 Appendix. Proofs

Proof of Proposition 1. The proportion of land devoted to agriculture is given by $\frac{T^A}{T} = 1 - \frac{T^F}{T} = \int_{r^*}^{\overline{r}} f(r;\mu_r)dr = 1 - F(r^*;\mu_r)$, where $\mu_r = \int_0^{\overline{r}} rf(r;\mu_r)dr$ is the average discount rate in the population and $F(r;\mu_r)$ is the cumulative density function associated with $f(r;\mu_r)$. The definition of First-Order Stochastic Dominance is that $F_{\mu_r}(r^*;\mu_r) < 0$. It follows that $\frac{dT^A}{d\mu_r} = -F_{\mu_r}(r^*;\mu_r) > 0$. $[QED]$

Proof of Proposition 2. Straigthforward differentiation of the expression for r^* (equation 1 in the text) yields

$\frac{dr^*}{dI} = \frac{\left[\left(\pi^C - \pi^F\right) + \left(\pi^F - \pi^A\right)\right]}{\left(\pi^C - \pi^F\right)^2}\pi_I^F > 0$. It follows that $T_I^F = \frac{d}{dI}F(r^*;.) = f(r^*;.)\frac{dr^*}{dI} > 0$. $[QED]$

Proof of Proposition 3. Differentiation of the expression for r^* (equation 2 in the text) yields:

$$\frac{dr^*}{dp^R} = \frac{\left[\begin{array}{c}\left(e\alpha\left(p^R\right)^{\alpha-1}\pi_{p^B}^F - e\left(\alpha-1\right)\left(p^R\right)^{\alpha-2}\pi_{p^A}^A\right)\left(\pi^C - \pi^F\right)\\ -\left(e\alpha\left(p^R\right)^{\alpha-1}\pi_{p^B}^C - e\alpha\left(p^R\right)^{\alpha-1}\pi_{p^B}^F\right)\left(\pi^F - \pi^A\right)\end{array}\right]}{\left(\pi^C - \pi^F\right)^2}$$

By Hotelling's Lemma, we know that $\frac{d}{dp}\pi(p,w) = q(p,w)$ (i.e., the derivative of the profit function with respect to the output price is equal to the supply function). Therefore, $\pi_{p^B}^F = q^F$, $\pi_{p^A}^A = q^A$, and $\pi_{p^B}^C = q^C$. It follows that one can rewrite the preceding expression as:

$$\frac{dr^*}{dp^R} = \frac{\left[\begin{array}{c}\left(\alpha q^F - \left(\alpha-1\right)\left(p^R\right)^{-1}q^A\right)\left(\pi^C - \pi^F\right)\\ -\alpha\left(q^C - q^F\right)\left(\pi^F - \pi^A\right)\end{array}\right]}{\left(\pi^C - \pi^F\right)^2}e\left(p^R\right)^{\alpha-1}$$

from which it follows that

$$sign\left(\frac{dr^*}{dp^R}\right) = sign\left(\left(\frac{q^F(p^B)\alpha - q^A(p^A)\left(\alpha - 1\right)\left(p^R\right)^{-1}}{\alpha\left(q^C(p^B) - q^F(p^B)\right)}\right) - \left(\frac{\pi^F - \pi^A}{\pi^C - \pi^F}\right)\right)$$

This can be written (using the cost functions) as

$$sign\left(\frac{dr^*}{dp^R}\right) = sign\left(\frac{\pi^F - \pi^A + C^F - C^A}{\pi^C - \pi^F} + \frac{\pi^A + C^A}{\alpha\left(\pi^C - \pi^F\right)} - \left(\frac{\pi^F - \pi^A}{\pi^C - \pi^F}\right)\right)$$

which boils down to

$$sign\left(\frac{dr^*}{dp^R}\right) = sign\left(\frac{\alpha C^F + (1-\alpha)\,C^A + \pi^A}{\alpha\left(\pi^C - \pi^F\right)}\right)$$

It will therefore *always* be the case (since $\pi^C > \pi^F$ by ASSUMPTION 1) that $\frac{dr^*}{dp^R} > 0$.

Since $T^F = F(r^*;.)$ it follows that

$$T^F_{p^R} = \frac{d}{dp^R}F(r^*;.) = f(r^*;.)\frac{dr^*}{dp^R} > 0.[QED]$$

Proof of Proposition 4. As with the proof of the previous PROPOSITION, Hotelling's Lemma allows one to rewrite the derivative of r^* (defined by equation 2) with respect to e as:

$$\frac{dr^*}{de} = \left(p^R\right)^{\alpha}\frac{\left[\begin{array}{c}\frac{1}{p^B}\left(p^Bq^F - p^Aq^A\right)\left(\pi^C - \pi^F\right)\\ -\left(q^C - q^F\right)\left(\pi^F - \pi^A\right)\end{array}\right]}{\left(\pi^C - \pi^F\right)^2}$$

which implies that

$$sign\left(\frac{dr^*}{de}\right) = sign\left(\left(\frac{p^Bq^F - p^Aq^A}{p^Bq^C - p^Bq^F}\right) - \frac{\pi^F - \pi^A}{\pi^C - \pi^F}\right)$$

In terms of the corresponding cost functions, this is equivalent to

$$sign\left(\frac{dr^*}{de}\right) = sign\left(\frac{\pi^F - \pi^A + C^F - C^A}{\pi^C - \pi^F + C^C - C^F} - \frac{\pi^F - \pi^A}{\pi^C - \pi^F}\right)$$

By ASSUMPTION 3 ($C^C = C^F$), this simplifies to

$$sign\left(\frac{dr^*}{de}\right) = sign\left(\frac{\pi^F - \pi^A + C^F - C^A}{\pi^C - \pi^F} - \frac{\pi^F - \pi^A}{\pi^C - \pi^F}\right) = sign\left(\frac{C^F - C^A}{\pi^C - \pi^F}\right)$$

Under ASSUMPTIONS 1 and 2, and ASSUMPTION 4 ($C^F < C^A$), it will therefore be the case that $\frac{dr^*}{de} < 0$, whereas the opposite will obtain under ASSUMPTION 5. Since

$$T_e^F = \frac{d}{de}F(r^*;.) = f(r^*;.)\frac{dr^*}{de} < 0,$$

it follows that a depreciation (an increase in e) will increase deforestation in developing countries, whereas the opposite will occur in developed countries. [QED]

Proof of Proposition 5. By a first-order Taylor expansion of $\pi^C\left(\overline{e}\left(p^R\right)^\alpha, w\right)$, we obtain (posing $\overline{e} = e + \Delta e$)

$$\pi^C\left(\overline{e}\left(p^R\right)^\alpha, w\right) = \pi^C\left(e\left(p^R\right)^\alpha, w\right) + \frac{\partial \pi^C\left(e\left(p^R\right)^\alpha, w\right)}{\partial p^B}\Delta e\left(p^R\right)^\alpha$$

By Hotelling's Lemma, this can be rewritten as:

$$\pi^C\left(\overline{e}\left(p^R\right)^\alpha, w\right) = \pi^C\left(p^B, w\right) + q^C\left(p^B, w\right)\frac{\Delta e}{e}p^B$$

Similarly

$$\pi^F\left(\overline{e}\left(p^R\right)^\alpha, w\right) = \pi^F\left(p^B, w\right) + q^F\left(p^B, w\right)\frac{\Delta e}{e}p^B$$

It follows that the denominator of the expression for $\widetilde{r}^*$ (equation 3 in the text) can be written as:

$$\begin{aligned} & \pi^C\left(\overline{e}\left(p^R\right)^\alpha, w\right) - \pi^F\left(\overline{e}\left(p^R\right)^\alpha, w\right) \\ = \; & \pi^C\left(p^B, w\right) - \pi^F\left(p^B, w\right) + \frac{\Delta e}{e}\left[p^B q^C\left(p^B, w\right) - p^B q^F\left(p^B, w\right)\right] \end{aligned}$$

which can be rewritten as

$$\begin{aligned} & \pi^C\left(\overline{e}\left(p^R\right)^\alpha, w\right) - \pi^F\left(\overline{e}\left(p^R\right)^\alpha, w\right) \\ = \; & \pi^C\left(p^B, w\right) - \pi^F\left(p^B, w\right) + \frac{\Delta e}{e}\left[\pi^C - \pi^F + C^C - C^F\right] \end{aligned}$$

One can therefore write:

$$\widetilde{r}^* = \frac{\pi^F\left(p^B, w\right) - \pi^A\left(p^A, w\right)}{\pi^C\left(p^B, w\right) - \pi^F\left(p^B, w\right) + \frac{\Delta e}{e}\left[\pi^C - \pi^F + C^C - C^F\right]}$$

which, by ASSUMPTION 3 ($C^F = C^C$), becomes:

$$\widetilde{r}^* = \frac{\pi^F\left(p^B, w\right) - \pi^A\left(p^A, w\right)}{\pi^C\left(p^B, w\right) - \pi^F\left(p^B, w\right) + \frac{\Delta e}{e}\left[\pi^C - \pi^F\right]}$$

By ASSUMPTION 1 ($\pi^C - \pi^F > 0$), it then follows that

$$\begin{aligned}\widetilde{r}^* &= \frac{\pi^F\left(p^B, w\right) - \pi^A\left(p^A, w\right)}{\pi^C\left(p^B, w\right) - \pi^F\left(p^B, w\right) + \frac{\Delta e}{e}\left[\pi^C - \pi^F\right]} \\ &< \frac{\pi^F\left(p^B, w\right) - \pi^A\left(p^A, w\right)}{\pi^C\left(p^B, w\right) - \pi^F\left(p^B, w\right)} = r^*.[QED]\end{aligned}$$

Proof of Proposition 6. This is equivalent to redefining prices as $p^A = \overline{p}^A =, \; p^B = e$, from which it follows that

$$r^* = \frac{\pi^F\left(e, w; .\right) - \pi^A\left(\overline{p}^A, w; .\right)}{\pi^C\left(e, w; .\right) - \pi^F\left(e, w; .\right)}$$

It is then immediate that an increase in e in this case will yield the same result as an increase in the relative price of timber (considered in PROPOSITION 3): a depreciation therefore results in a decrease in deforestation.$[QED]$

Proof of Proposition 7. Using the same arguments as in the proof of PROPOSITION 2, the second cross-partial derivative given in the text (equation 4) can be rewritten as

$$\frac{d^2 r^*}{dIde} = \left(p^R\right)^\alpha \frac{d}{dI}\left[\frac{\left(q^C - q^F\right)\left(C^F - C^A\right)}{\left(\pi^C - \pi^F\right)^2}\right]$$

Taking the derivative yields

$$\frac{d^2 r^*}{dIde} = \left(p^R\right)^\alpha \frac{\left\{\begin{array}{c}\left[C_I^F\left(q^C - q^F\right) - q_I^F\left(C^F - C^A\right)\right]\left(\pi^C - \pi^F\right)^2 \\ +2\pi_I^F\left(\pi^C - \pi^F\right)\left(q^C - q^F\right)\left(C^F - C^A\right)\end{array}\right\}}{\left(\pi^C - \pi^F\right)^4}$$

or

$$\frac{d^2r^*}{dIde} = \left(p^R\right)^\alpha \frac{\left[C_I^F\left(q^C - q^F\right) - q_I^F\left(C^F - C^A\right)\right]}{\left(\pi^C - \pi^F\right)^2} + 2\left(\frac{\pi_I^F}{\pi^C - \pi^F}\right)\frac{dr^*}{de}$$

Recall from our preliminaries that we see weak institutions as imposing a fixed cost on sustainable harvesting: $\pi^F = p^B q^F(l^F) - wl^F - \phi_I^F(I)$, where $\phi_I^F(I) < 0$. This specification implies that $\pi_I^F = -\phi_I^F(I) > 0$, $C_I^F = \phi_I^F(I) < 0$ and $q_I^F = 0$. The derivative of interest is then given by

$$\frac{d^2r^*}{dIde} = \left[\left(p^R\right)^\alpha \frac{\left(q^C - q^F\right)}{\left(\pi^C - \pi^F\right)^2} - \left(\frac{2}{\pi^C - \pi^F}\right)\frac{dr^*}{de}\right]\phi_I^F(I)$$

From PROPOSITION 4 (i), which holds when ASSUMPTION 4 is valid, we know that $\frac{dr^*}{de} < 0$ for less developed countries, from which it follows that the term in square brackets is positive. Therefore $sign\left(\frac{d^2r^*}{dIde}\right) = sign\left(\phi_I^F(I)\right)$, implying that $\frac{d^2r^*}{dIde} < 0$. For developed countries, on the other hand, PROPOSITION 4 (ii) tells us that $\frac{dr^*}{de} > 0$; the term in square brackets is therefore of ambiguous sign and so is $\frac{d^2r^*}{dIde}$. $[QED]$

Table 2. Descriptive statistics (2063 observations)

	Mean	Median	Standard deviation
Annual rate of deforestation	0.00097	0.0000	0.0164
Log forest cover (in thousands of hectares)	8.4929	8.9186	2.2968
Log Real effective exchange rate	4.2993	4.2747	0.4292
Log GDP per capita	7.5538	7.3510	1.5199
Population growth rate	2.09	2.31	1.08
Rural population density	116.83	35.29	404.67
Relative price of timber to agricultural exports	127.06	99.99	139.83
Bohn and Deacon index of expropriation risk	12.72	13.20	4.11
Freedom House index 1 of political freedom	3.33	3.00	2.15
Freedom House index 2 of political freedom	3.34	3.00	1.84

Note: descriptive statistics for the Freedom House indices correspond to the sample with 2196 observations used in the estimation results presented in columns 4 and 5 of Table 3.

Table 3. "Within" estimation of the determinants of the annual rate of deforestation

Institutional variable	Bohn and Deacon index of expropriation risk			Freedom House index Index 1	Freedom House index Index 2
	(1)	(2)	(3)	(4)	(5)
Log initial forest cover	1.156	1.157	1.163	0.535	0.537
	(19.78)	(20.41)	(20.56)	(28.58)	(28.69)
Log initial forest cover, squared	−0.134	−0.134	−0.134	−0.061	−0.062
	(−17.60)	(−18.01)	(−18.09)	(−13.54)	(−13.79)
Log initial forest cover, cube	0.005	0.005	0.005	0.002	0.002
	(15.47)	(15.72)	(15.68)	(8.66)	(8.93)
Log GDP per capita	0.020	0.020	−0.006	0.050	0.050
	(2.92)	(2.92)	(−0.53)	(7.24)	(7.14)
Log GDP per capita, squared			0.002		
			(3.07)		
Institutions	−0.004	−0.004	−0.004	−0.012	−0.013
	(−1.97)	(−2.01)	(−2.16)	(−2.71)	(−2.44)
Relative price of timber	−0.0008	−0.0010	−0.0010	−0.0006	−0.0006
	(−2.54)	(−3.23)	(−3.53)	(−1.59)	(−1.58)
Log real effective exchange rate	0.016	0.017	0.022	0.064	0.062
	(1.80)	(1.84)	(2.35)	(6.29)	(6.13)
Log real effective exchange rate	−0.004	−0.004	−0.005	−0.011	−0.011
× log GDP per capita	(−2.60)	(−2.66)	(−3.09)	(−7.04)	(−6.91)
Log real effective exchange rate	0.001	0.001	0.001	0.003	0.003
× Institutions	(2.19)	(2.24)	(2.40)	(2.71)	(2.40)
Population growth rate	0.0002				
	(0.33)				
Rural population density	-3×10^{-6}				
	(−0.43)				
$\overline{R}^2$	0.346	0.345	0.348	0.387	0.386
Number of observations	2063	2064	2064	2197	2197
Threshold level of log GDP per	7.0155	7.0109	7.2005	6.6728	6.6755
capita below which $\frac{dT^F}{de} < 0$ (s.e.)	(0.3811)	(0.3751)	(0.3091)	(0.2162)	(0.2225)
Corresponding level in $US 1990	1113	1108	1340	790	792
% of observations below threshold	43.3	43.3	47.2	32.4	32.4
Marg. effect of institutions at mean	0.0003	0.0004	0.0004	0.008	0.009
value of real exchange rate (t-stat)	(1.07)	(1.12)	(1.18)	(1.83)	(1.68)
Marg. effect of log GDP per capita	0.003	0.003	0.003	0.005	0.005
at first quartile of real exchange rate	(1.64)	(1.55)	(1.45)	(1.73)	(1.92)
Marg. effect of log GDP per capita	0.002	0.002	0.002	0.002	0.002
at median of real exchange rate	(1.22)	(1.11)	(0.94)	(0.77)	(0.97)
Marg. effect of log GDP per capita	0.001	0.001	0.0008	0.0001	0.0007
at third quartile of real exchang rate	(0.73)	(0.60)	(0.36)	(0.03)	(0.23)

Note: t-stastistics in parentheses unless otherwise noted.