# Reducing Deforestation and Forest Degradation: Leakage or Synergy?

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ABSTRACT. *Policies to reduce deforestation and forest degradation focus on limiting agricultural expansion and nonsustainable (and often illegal) harvesting of forest products. The feedbacks between these two policy instruments are rarely discussed. A simple agricultural household model assesses the impact of a payment for environmental services on both deforestation and harvesting, and the impact of increasing the control on illegal harvesting on deforestation. When land and labor are substitutes, both policies have positive feedbacks and win-win potential. Conversely, when production factors are complements, they have negative feedbacks. A novel result is that the production factors can become substitutes if distance costs are high, making a win-win situation more likely.* (Q15, Q58)

## I. INTRODUCTION

Agricultural expansion is responsible for the highest share of deforestation in the developing world (IPCC 2007; Rudel 2007; Angelsen 2009; Hosonuma et al. 2012). Effective policies aiming to reduce deforestation must therefore target agricultural expansion. However, when the agents of deforestation are poor agricultural households, they frequently mix their activities between agriculture and (sometimes illegal) forest products harvesting and poaching, which can lead to forest degradation (Godoy et al. 1997; Pattanayak and Sills 2001; Delacote 2007, 2009). In situations of imperfect markets, as frequently found in remote, forested areas, different activities are interlinked in household decision-making. In this context, what happens if the policy to reduce deforestation focuses on agricultural expansion only, while the deforestation agents are also illegal loggers and poachers?[1] Similarly, how does better control of illegal harvesting influence deforestation? In other words, do policies aimed at reducing deforestation and illegal harvesting present policy makers with a menu of synergies or trade-offs (leakage) between the two interventions?

Leakage, or "emission displacement" (in official climate language), refers to a situation where reduction in emissions of greenhouse gases (GHGs) in one area or activity leads to higher emissions of GHGs in another. There are several channels of leakage (Wunder 2008), including activity-shifting among agricultural households. Addressing leakage is a major challenge in designing and implementing effective climate mitigation policies.

In this paper we address one particular channel of leakage between policy interventions, namely, those resulting from agricultural households shifting between various emissions-generating activities. We develop a simple agricultural household model. Households allocate labor both to agriculture and forest harvesting (both timber and nontimber forest products) and choose the area to deforest for agricultural purposes. Policies to reduce agricultural expansion may take the form of payment for environmental services (PES) (cf. Wunder 2005). We consider a PES scheme in which agricultural households are

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[1] From now on, we will employ the term "illegal harvesting" when talking of illegal logging and poaching of (both timber and nontimber) forest products. Note, however, that agricultural expansion may also be illegal when forest clearing is made without the clearer having property rights or when legal restrictions apply on forest conversion.

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paid to reduce their agricultural expansion compared to a BAU scenario. While such a scheme should—at least in theory—reduce deforestation, its impact on illegal harvesting is not straightforward. Similarly, controlling illegal harvesting can be a policy instrument to contain forest degradation, and we ask how this will impact deforestation.

Our results show that the relation between production factors is the main factor influencing those feedback effects. When labor and agricultural land are substitutes, the PES scheme yields a win-win outcome: it directly decreases deforestation and indirectly decreases labor allocated to illegal harvesting and, thereby, forest degradation. Similarly, better control over illegal harvesting leads to less labor being allocated to this activity, and deforestation also decreases. In this case, both policy instruments have positive feedbacks. In contrast, when both factors are complements, the PES scheme generates a shift in labor allocation from agriculture to illegal harvesting. In this case, both policy instruments imply a trade-off between avoided deforestation and forest degradation. Our simulations based on Brazilian data show that a situation with factor complementarity is more likely than a situation with factor substitutability.

A novel feature of the model is the introduction of distance costs. Whether the factors are substitutes or complements in the net benefit function does not depend only on the technical properties of the agricultural production function but also on the level of the distance costs. A surprising result is that high distance costs may create a substitution effect between land and labor, even if the factors are technically complementary, making a win-win outcome more likely.

## II. A HOUSEHOLD MODEL OF AGRICULTURAL EXPANSION AND FOREST HARVESTING

In many regions of the developing world, poor rural communities expanding their agricultural land to improve their livelihood are major agents of deforestation. The households pursue a mix of economic activities (Banerjee and Duflo 2007) including agriculture (both crops and cattle) and harvesting of wood (e.g., fuelwood and timber) and nonwood (e.g., fruits, edible plants, and game meat) forest products. Those products may be directly consumed by the household or sold on local markets. One reason for high diversification is market incompleteness, where constrained access to (high transaction costs) output and labor markets makes rural households pursue a broad range of self-employing activities. Moreover, harvesting forest products is frequently considered an activity that is particularly attractive to households with few options in agriculture (small landholdings) and off-farm employment (Agarwal 1991; Baland and Francois 2005; Reddy and Chakravaty 1999).

The labor market assumptions are critical for the logic and results of an agricultural household model (Amacher, Koskela, and Ollikainen 2009; Angelsen 1999). If we assume that labor can be sold (and hired) freely at a given wage rate in a labor market (and more generally when markets are complete), the decisions of consumption and production are separable (Singh, Squire, and Strauss 1986). The interaction between the two activities included in our model would disappear. A more realistic assumption is to incorporate labor market constraints into the model, for example, that farmers sell a fixed amount of labor in the market and allocate the remaining labor to productive activities and leisure in order to maximize utility. This is referred to as the Chayanovian approach. The consumptions and production decisions are made simultaneously, and the model gives a subjective equilibrium wage rate (shadow wage) as the marginal rate of substitution between leisure and consumption (cf. Nakajima 1986).

Our model makes one more simplifying assumption, namely, that leisure is also fixed. The problem is therefore to allocate a given amount of family labor $\bar{l}$ to agriculture ($l$) and to illegal harvesting ($\bar{l} - l$).[2] This keeps the model simple and tractable and is sufficient to analyze our key problem, namely, the inter-

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[2] The assumption is made here that harvesting is illegal. However, our analysis holds whenever harvest is considered nonsustainable, whether it is legal or not. The case of legal forest harvesting is considered briefly in the subsection "Addressing Illegal Harvesting: Improved Control Quality" in Section III.

dependency between agricultural production and harvesting of forest products in a context where access to an off-farm labor market is constrained. The assumption is commonly used in in other studies (e.g., Amacher, Koskela, and Ollikainen 2009; Baland and Francois 2005; Delacote 2009). A more complete Chayanovian model would enrich the analysis, but at a high costs in terms of model tractability and without changing the basic leakage mechanism analyzed in this paper. Further, the fixed off-farm labor assumption could be relaxed; for example, off-farm employment might be available but at higher transaction costs (a lower effective wage).

The household also must make the decision of how much land to use for agriculture $L$. The cost of land conversion and maintenance is $cL$ (net of any timber sale). The cost $c$ depends mainly on land tenure costs, property rights, and land clearing costs. Households then make two decisions: (1) how much land will be cultivated, $L$, and (2) how to allocate family labor between agriculture and illegal harvesting.

Forest clearing can be part of a long-term investment in agricultural land, which may require a dynamic model. In a general dynamic model (Kerr, Talikoff, and Sanchez 2002), forest clearing takes place when (1) the net present value of forest clearing is positive, and (2) the arbitrage condition holds, that is, it must not be even more profitable to delay forest clearing (e.g., due to much lower clearing costs in the future). If we make the reasonable assumption that the arbitrage condition holds, that the (annual) agricultural rent increases relative to the forest rent over time, and that there is no strategic forest clearing (i.e., clearing forest to claim or strengthen property rights to the land), then Angelsen (1999) and Kerr, Talikoff, and Sanchez (2002) show that the dynamic problem boils down to a static problem of maximizing the current profit, and land is brought under cultivation once net agricultural rent outweighs the loss in forest rent. These assumptions will of course make the model more tractable, and we thus develop a timeless static model. Dynamic issues (such as price and technological change) can be addressed through comparative statics.

### Business-as-Usual Situation

In the BAU case, no policy is implemented to control forest harvesting or to reduce agricultural expansion. Assuming risk neutrality,[3] households choose their land and labor allocation to maximize net return from their activities:

$$\max_{L,l} Y(l,L) = A(l,L) + H(l,L) - cL. \qquad [1]$$

$A(l,L)$ is the net return from agriculture, and $L$ is the size of agricultural land (deforestation). We assume standard features of the agricultural production function: labor allocated to agriculture has positive and decreasing marginal productivity, representing congestion effects and tiredness; the most productive forest land is converted first to agriculture, resulting in positive and decreasing marginal productivity:

$$A_l = \frac{\partial A}{\partial l} > 0 \text{ and } A_{ll} = \frac{\partial^2 A}{\partial l^2} < 0;$$

$$A_L = \frac{\partial A}{\partial L} > 0 \text{ and } A_{LL} = \frac{\partial^2 A}{\partial L^2} < 0.$$

Forest harvesting provides net return of $H(l,L)$. Marginal labor productivity is positive and decreasing, that is, negative in labor allocated to agriculture ($l$):

$$H_l = \frac{\partial H}{\partial l} < 0 \text{ and } H_{ll} = \frac{\partial^2 H}{\partial l^2} < 0.$$

Agricultural expansion affects illegal harvesting negatively, as it reduces the remaining forest stock:

$$H_L = \frac{\partial H}{\partial L} < 0 \text{ and } H_{LL} = \frac{\partial^2 H}{\partial L^2} < 0.$$

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[3] Assuming risk-aversion would bring potentially important modifications here. First, forest products harvesting is frequently mentioned as a risk-management tool against agricultural risk (Delacote 2007, 2009). Second, if we assume, like we do in this paper, that forest product harvesting is illegal, risk-averse agents would consider here the risk of being caught and fined in their decisions. We can therefore assume here that risk neutrality tends to overestimate illegal harvesting in the following model.

Note that the cross-derivatives $A_{lL}$ of the agricultural production function and $H_{lL}$ of the illegal harvesting function are not explicitly signed (thus $Y_{lL}$ is not signed either). As we will show, the sign will influence the win-win potential of the REDD policies.

The first-order conditions give

$$A_l = H_l, \qquad [2]$$

$$A_L + H_L = c, \qquad [3]$$

which implicitly defines the optimal BAU labor allocation $l^{\mathrm{BAU}}$, and agricultural expansion $L^{\mathrm{BAU}}$. Note that [3] defines two types of costs of agricultural expansion: the clearing costs $c$ and the costs in terms of reduced forest stock and availability of forest products ($H_L$).[4]

### How Distance Costs May Influence Factor Complementarity

As noticed earlier, we do not make any assumptions on factor complementarity or substitutability in the net income function ($Y_{lL}$ may be positive or negative). In this section, we analyze how this relation between production factors may be related to distance costs. The literature on distance costs and forest products extraction (essentially nontimber forest products) is quite well developed. Our approach follows that of Robinson, Williams, and Albers (2002) and Robinson, Albers, and Williams (2011): we distinguish between time spent on forest product harvesting (extraction intensity) and time spent on traveling (as determined by distance). Our contribution is that we consider that the time spent on traveling depends on the level of agricultural expansion or deforestation. Consider the case where agricultural expansion follows a circular von Thunen pattern, where agricultural land forms a circle around the village, with forests beyond that agricultural frontier (Angelsen 1999). Household members will then have to walk farther to reach new agricultural fields and to harvest products in the forest. In addition, the cost of transportation of agricultural and forest products increases as fields and forests are farther away from the village.

In the model and consistent with the work of Robinson, Williams, and Albers (2002), we capture those costs related to distance and transportation by considering travel time as unproductive labor, that is, it does not contribute to higher production of either agricultural or forest products.

We model labor allocated to illegal harvesting as follows: $f = \bar{l} - l - kL$. $kL$ represents the time spent on traveling (both walking to the field and carrying agricultural and forest products). $k$ is a parameter determined by terrain and local infrastructure. As $L$ increases, the share of unproductive labor dedicated to traveling increases as new agricultural land and available forests are located farther away from the homestead and the village.[5] We can rewrite this as $H(l,L) = I(\bar{l} - l - kL)$. This specification implies a slight modification of model presented in equation [1], in the sense that $L$ enters the illegal harvest return function trough labor allocation. We note that for sufficiently high distance costs, namely, $k > (\bar{l} - l)/L$, illegal harvesting becomes totally unproductive and the household allocates all its effort to agriculture. For the remaining part of the paper, we will thus use function $H(l,L)$ for the general case, and function $I(\bar{l} - l - kL)$ for the distance costs case. Analogies between functions $H(l,L)$ and $I(\bar{l} - l - kL)$ are given in Appendix A, in order to facilitate switching between the two cases.

With this specification, we emphasize the impact of transport costs (via agricultural expansion) on forest harvesting. In reality, distance may also have an impact on agricultural productivity. While not directly included, it is implicitly considered in the concavity of the agricultural production function. Moreover,

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[4] We implicitly assume here that the BAU scenario is of common knowledge. We thus avoid the issue about the definition and estimation of the BAU scenario, which is a major issue in the REDD debate (Busch et al. 2009; Meridian Institute 2011).

[5] In many contexts, this type of transport cost is likely to be a function of total land cleared in the village rather than just the land cleared by the household. Nevertheless, as in a classic externality problem, the household considers only its own impact on transport costs in the first-order conditions. Our results are thus robust to this hypothesis.

we can consider our results to be valid as long as distance costs have a greater impact on forest harvesting than on agriculture, and forest harvesting productivity stays lower than agricultural productivity.

We can therefore specify expected net return in the following way:

$$\max_{L,l} Y(l,L) = A(l,L) + I(\bar{l} - l - kL) - cL. \qquad [4]$$

If the cross-derivative of the net return function is negative (positive), then land and labor are substitutes (complements). A fair assumption to make is complementarity in agricultural production, namely, $A_{lL} > 0$ (as in the case of a Cobb-Douglas function with two inputs, for instance). In contrast, due to distance costs, land and agricultural labor generate substitution in the net return function through illegal harvesting: $I_{lL} < 0$. Thus the question is how strong this complementarity is in agriculture, compared to the substitution in illegal harvesting implied by distance costs. Indeed, if distance costs are sufficiently large, land and labor may become substitutes in the net return function. It follows that land and labor are complements (substitutes) in the net benefit function if $A_{lL} + kI_{ff} > 0$. It also follows that the value of $k$, as well as the cross-derivatives will determine whether the factors are complements or substitutes. Land and labor are complementary if distance cost ($k$) is sufficiently low:

$$Y_{lL} = A_{lL} + (kI_{ff}) > 0,$$

$$k < \frac{A_{lL}}{-I_{ff}}. \qquad [5]$$

We summarize this result in Proposition 1:

*Proposition 1:* For low distance costs ($k < A_{lL}/-I_{ff}$), production factors are complements in the net return function. As distance costs increase ($k > A_{lL}/-I_{ff}$), production factors become substitutes up to the point at which illegal harvesting is abandoned ($\bar{k} = k > (\bar{l} - l)/L$).

An illustration on the influence of distance costs on factor complementarity is given in Figure 1.

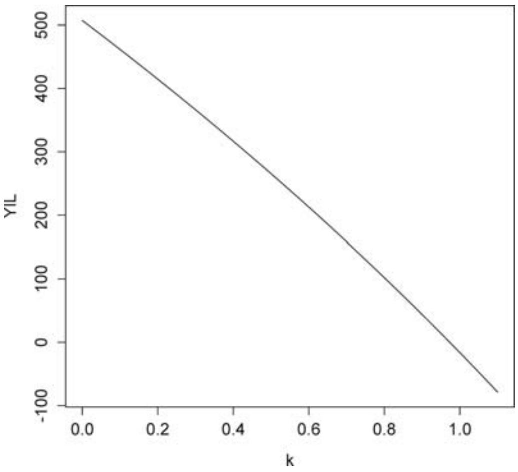

FIGURE 1
Production Factors Tend to Be Complements (Substitutes) When Distance Costs Are Low (High)

To illustrate our simple model, we run simulations using more specified functions.[6] The agricultural production function is calibrated based on the work by Marchand (2012), who estimated this function for the Brazilian Legal Amazon. The author estimated an aggregate agricultural production function as a translog function using not only land and labor, but also cattle and purchased inputs. As we in this paper consider only land and labor, we plug the average amount of cattle and purchased inputs into the calibrated function. We obtain the following form (values of the coefficients are given in Appendix B):

$$\begin{aligned} A(l,L) = {} & K \cdot (l)^{\beta 1} \cdot (l^2)^{\beta 2} \cdot (l \cdot cattle)^{\beta 3} \cdot (l \cdot inputs)^{\beta 4} \\ & \cdot (L)^{\beta 5} \cdot (L^2)^{\beta 6} \cdot (L \cdot cattle)^{\beta 7} \cdot (L \cdot inputs)^{\beta 8} \\ & \cdot (L \cdot l)^{\beta 9}. \end{aligned} \qquad [6]$$

Concerning the illegal harvesting return function, we adopt a simpler functional form:

$$I(l) = z \cdot (\bar{l} - l - lL)^{\sigma}. \qquad [7]$$

Several studies (Wunder 2001; Angelsen and Wunder 2003; Delacote 2009) observe that extraction of forest products provides low re-

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[6] Simulations are performed using R (R Development Core Team 2012).

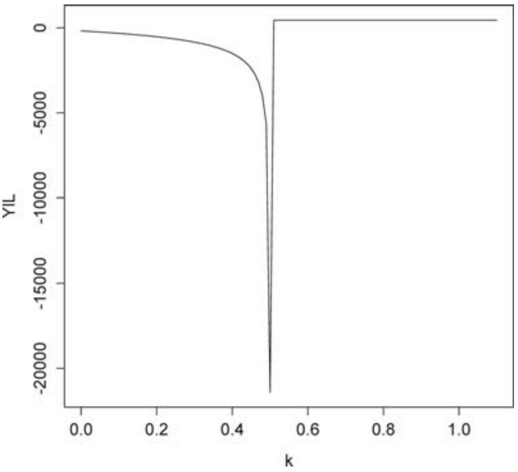

FIGURE 2
Corner Solutions Arise When Distance Costs Are Sufficiently High

turns to labor. In our calibration, we thus set the marginal labor productivity in illegal harvesting lower than in agriculture.

The first simulation (Figure 1) shows that the cross-derivative of the net return function decreases with and is very sensitive to distance costs. More specifically, when we consider lower productivity on illegal harvest, the threshold $\bar{k}$ arrives quickly, and Figure 2 shows that corner solutions, that is, labor becoming unproductive in illegal harvesting due to distance costs, may arise quickly as distance costs increase. This result suggests that the two more likely situations are when factors are complements in the net return function, and when factor substitutability leads to corner solutions in which households focus on agriculture and abandon illegal harvesting.

## III. REDD: ADDRESSING DEFORESTATION AND FOREST DEGRADATION

In our model we have one instrument to address deforestation and another one to address forest degradation. Many conservation programs being implemented are for the conservation of forests in general, such as the two biggest current PES programs in Costa Rica (see Arriagada et al. 2012) and Mexico (see Alix-Garcia, Shapiro, and Sims 2012). While recognizing that some policies aim to address both deforestation and degradation simultaneously, we also find it useful analytically to consider two different policy instruments. Deforestation and forest degradation are normally driven by different activities. The former is driven by the expansion of crop and cattle production, while the latter is driven by nonsustainable harvesting of forest products, such as collection of fuelwood (including for charcoal production) and timber (e.g., Dokken et al. 2014). Supply-chain policies, for example, will address specific products that are linked to either deforestation or forest degradation. Further, measuring and enforcing policies related to changes in forest area (deforestation) is also easier than measuring changes in the carbon per hectare (degradation).

### A PES Scheme to Avoid Deforestation

To reduce deforestation, the government offers to pay households for environmental services, so that they are compensated for reducing their agricultural expansion. We assume that the PES contract focuses only on agricultural expansion and does not consider illegal harvesting. Indeed, PES schemes are likely to function or be implemented only where property rights are in place and respected, and to focus on legal activities and not on the informal sector.

We consider the following PES scheme. The regulator (government) has full information about the BAU level of deforestation $L^{\text{BAU}}$. Estimating the accurate level of BAU deforestation is a critical issue, but that discussion is not the purpose of this paper (Angelsen 2008). The household announces how much land it will convert, $L^{\text{PES}}$. The payment to compensate avoided deforestation is then simply proportional to the difference between the two variables: $r(L^{\text{BAU}} - L^{\text{PES}})$. $r$ is the amount paid to the household per unit of land that is not deforested.[7] We assume perfect

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[7] Note here that the PES may become a tax if $L^{\text{PES}} > L^{\text{BAU}}$, which is somehow contrary to the voluntary nature of PES schemes. However, this case should not happen in our model, since agents are necessarily better off decreasing

monitoring: the policy maker can check with certainty the actual deforestation rate, and agents do not cheat on the PES contract. An interesting extension would be to consider imperfect information about the BAU baseline, or in the monitoring of actual deforestation. Clearly, getting information on BAU deforestation for individual households is a nontrivial task.

We do not discuss explicitly the price-setting in the PES scheme, *r*, which is considered as given and constant. In reality, *r* could be calibrated based on different considerations. First, households may be paid individually according to their opportunity costs. In this case, the policy maker, in order to minimize the cost of the policy, only ensures that households are just marginally better off with the policy than without it. Second, a fixed price may be offered to all households, so that they reduce deforestation. In this case, households self-select: they accept the PES if and only if it makes them better off. Finally, the PES can be set in order to compensate for the value of the environmental service, for example, the carbon sequestered in nondeforested forests. Leplay et al. (2011) compare those different PES models for price-setting, while Delacote et al. (2014) show how the objectives of the PES project manager influence the price-setting.

### Addressing Illegal Harvesting: Improved Control Quality

We make the implicit assumption that labor allocated to forest harvesting increases forest degradation and carbon emissions, in other words, that the harvest rates are beyond sustainable levels. To reduce forest harvesting, the government implements measures to control it. For example, households may be randomly inspected and have to pay a fine if they are convicted of illegal harvesting. It follows that a household keeps the return from illegal harvesting only if it is not controlled and convicted. $\alpha$ is the exogenous conviction probability times the fine, which is proportional to the amount of illegal harvesting. The parameter then describes the control quality and can be seen as an indicator of institutional efficiency: a larger $\alpha$ corresponds to more effective institutions, while, for example, corrupted civil agents may be related to a low $\alpha$. The policy maker may thus choose to invest resources in order to increase control efficiency $\alpha$. Expected return from illegal harvesting is thus $(1-\alpha)H(l,L)$.

This policy can also be given a broader interpretation. Not all nonsustainable harvesting of forest products may be illegal. The policy can then be interpreted as a tax on forest products, internalizing the externality of excessive forest harvesting. More generally, it can be related to any policy that lowers the price of forest products, for example, promotion of more efficient cooking stoves that reduce the demand for (and price of) charcoal.

### The Household Factor Allocation with the REDD Policy

The household's maximization problem with the two REDD policies in place becomes

$$\max_{L,l} Y(l,L) = A(l,L) + (1-\alpha)H(l,L) - cL + r(L^{\mathrm{BAU}} - L). \quad [8]$$

$l^{\mathrm{PES}}$ and $L^{\mathrm{PES}}$ are implicitly defined by the first-order condition:

$$A_l = (1-\alpha)I_l, \quad [9]$$

$$A_L + (1-\alpha)H_L = c + r. \quad [10]$$

Labor allocation is made so that marginal productivity of labor in agriculture equals expected marginal productivity of labor in illegal harvesting, factoring in the risk of being caught and fined. Land allocation is made to equalize the marginal productivity of agricultural land and marginal cost of land clearing plus the PES.

## IV. DIRECT AND INDIRECT IMPACTS OF THE REDD POLICY

The policy maker has two policy choice variables: it can increase the payment in the

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their deforestation rates. At the extreme, they could choose $L^{\mathrm{PES}} = L^{\mathrm{BAU}}$, and they would get the same return as under BAU.

PES scheme, by adjusting $r$; or it can increase the quality of control on illegal harvesting, by adjusting $\alpha$. The first variable plays on the household's land use choice (equation [10]), while the second variable plays on labor allocated to illegal harvesting (equation [9]). However, both policy choice variables ($r$, $\alpha$) have an indirect impact on the other households' choice variable ($l^{\text{PES}}$, $L^{\text{PES}}$, respectively).

## Direct Impacts of the Policy on Deforestation and Illegal Harvesting

Comparing equation [3] and equation [10], we easily see that deforestation is smaller when the PES scheme is implemented than in the BAU case. We can infer more precisely the influence of the level of the payment $r$ on deforestation by using the implicit function theorem:

$$\frac{\partial L^{\text{PES}}}{\partial r} = \frac{1}{A_{LL} + (1-\alpha)H_{LL}} < 0. \qquad [11]$$

The direct effect of the PES is straightforward: increasing the amount offered to households increases the opportunity cost of deforesting for the agents. The decrease in deforestation is larger when the net return function is more concave in $L$, that is, if the marginal productivity of land decreases rapidly. This should be the case in places where land is of heterogenous quality. In contrast, deforestation would be less sensitive to the PES when land is of homogenous quality. As an extreme case, deforestation may completely cease if the PES is set in order to completely cover the net return to agricultural production.

Second, it is also readily seen that increasing the quality of control on illegal harvesting will decrease labor allocated to the illegal activity:

$$\frac{\partial l^{\text{PES}}}{\partial \alpha} = \frac{H_l}{A_{ll} + (1-\alpha)H_{ll}} > 0. \qquad [12]$$

Here again, the effect is clear cut: if controlling illegal harvesting becomes more efficient, expected return for the illegal activity decreases, which again decreases the incentive to allocate labor to that activity. Labor allocation to agriculture $l^{\text{PES}}$ thus increases. We summarize these results as follows:

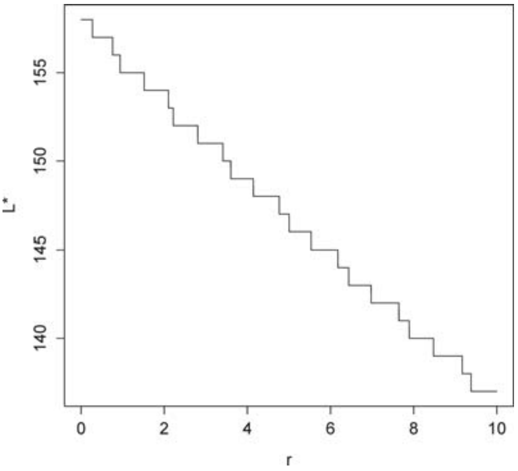

FIGURE 3
Increasing Payments for Environmental Services Decreases Deforestation When Production Factors Are Complements

*Proposition 2:* Increasing the payment for avoided deforestation will decrease deforestation, while increasing the control quality decreases labor allocated to illegal harvesting and thereby forest degradation.

Note that we consider prices to be exogenous (and implicit in the agricultural and forest harvesting functions). In general, endogenous prices would dampen the effects of the policies in our model in the area under the policy regime. For example, implementing PES would limit the agricultural land area, reduce supply of agricultural crops or beef, boost local prices of these products, and thereby limit the effectiveness of the policy. In addition, endogenous prices would add another channel of leakage: higher output prices could give incentive to increase production though deforestation (or illegal harvest) in other regions. An early study of such leakages, using a computable general equilibrium model, is Cattaneo's (2001).

Our simulations focusing on distance costs give an illustration of Proposition 2. Figures 3 and 4 show the direct influence of the PES

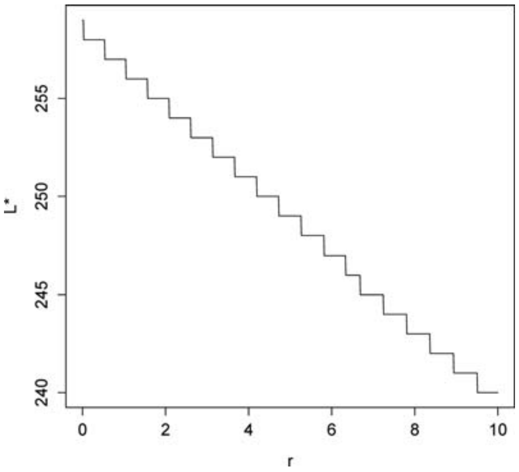

FIGURE 4
Increasing Payments for Environmental Services Decreases Deforestation When Production Factors Are Substitutes

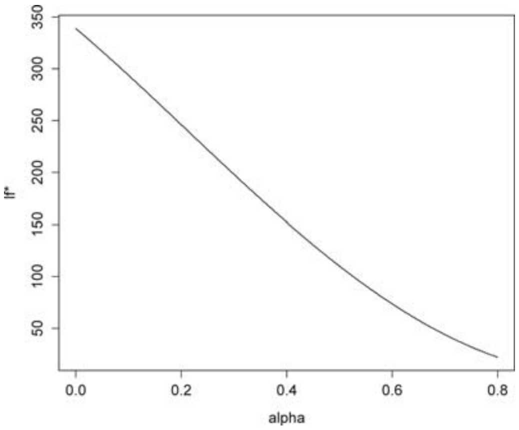

FIGURE 5
Increasing the Control Quality Decreases Illegal Harvesting When Production Factors Are Complements

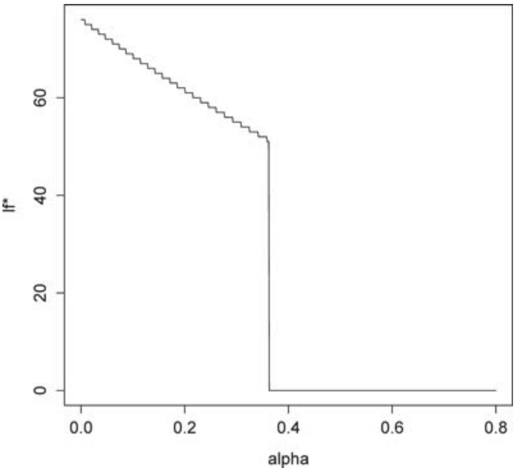

FIGURE 6
Increasing the Control Quality Decreases Illegal Harvesting When Production Factors Are Substitutes

on deforestation in the case in which factors are complements and substitutes, respectively. Similarly, Figures 5 and 6 illustrate the direct impact of improving control quality on illegal harvesting. Figure 6 also suggests that increasing the control quality rapidly brings corner solutions in the substitution case. Indeed, it is easy to see that $\alpha$ has a multiplicative effect on distance costs and thus makes corner solutions happen faster.

### Indirect Impacts of the Policy on Deforestation and Illegal Harvesting

Both policy instruments have also an indirect effect, which needs to be factored in. PES has an influence on the land use choice, which has an influence on labor allocation. Similarly, the control efficiency has an influence on labor allocation, which has an influence on land use.

Considering the impact of the PES scheme on illegal harvesting is equivalent to considering the impact of the PES scheme on labor allocation. By reducing agricultural expansion, the PES scheme may lead either to intensified agricultural production, or to free some labor that is allocated to illegal harvesting, or a combination of the two. In the first case, more labor is required in agriculture, and less labor is available for illegal harvesting. In the second case, the PES scheme leads to a shift in labor allocation, from agriculture to illegal harvesting.

The indirect impact of the PES on labor allocation can be expressed as follows:

$$\frac{\partial l^{\mathrm{PES}}}{\partial r}=\frac{\partial l^{\mathrm{PES}}}{\partial L^{\mathrm{PES}}}\frac{\partial L^{\mathrm{PES}}}{\partial r}$$
$$=-\frac{A_{lL}+(1-\alpha)H_{lL}}{A_{ll}+(1-\alpha)H_{ll}}\frac{1}{A_{LL}+(1-\alpha)H_{LL}}. \quad [13]$$

The second question is how a change in the quality of control on illegal harvesting will affect the level deforestation under the PES scheme. Using the implicit function theorem, we see that

$$\frac{\partial L^{\mathrm{PES}}}{\partial \alpha}=\frac{\partial L^{\mathrm{PES}}}{\partial l^{\mathrm{PES}}}\frac{\partial l^{\mathrm{PES}}}{\partial \alpha}$$
$$=-\frac{A_{Ll}+(1-\alpha)H_{Ll}}{A_{LL}+(1-\alpha)H_{LL}}\frac{1}{A_{ll}+(1-\alpha)H_{ll}}. \quad [14]$$

We see from equations [13] and [14] that the indirect effect of the PES depends on the cross-derivative of the net returns of agriculture and illegal harvesting.

*Proposition 3:*

- Increasing the PES indirectly increases (reduces) illegal harvesting if land and labor are complements (substitutes) in the net return function: $A_{lL}+(1-\alpha)H_{lL}>0$ $(A_{lL}+(1-\alpha)H_{lL}<0)$.
- Improving the control quality on illegal harvesting indirectly increases (decreases) deforestation if land and labor are complements (substitutes) in the net return function: $A_{lL}+(1-\alpha)H_{lL}>0$ $(A_{lL}+(1-\alpha)H_{lL}<0)$.

*Proof:*

$$\frac{\partial L^{\mathrm{PES}}}{\partial \alpha}\leq 0 \text{ and } \frac{\partial l^{\mathrm{PES}}}{\partial r}\geq 0\Leftrightarrow Y_{lL}\leq 0\Leftrightarrow A_{lL}$$
$$+(1-\alpha)H_{lL}\leq 0\Leftrightarrow A_{lL}$$
$$+(1-\alpha)(kI_{ff})\leq 0\Leftrightarrow k\geq\frac{A_{lL}}{-I_{ff}}.$$

When the fields are far away from the main markets, or when slope and elevation are high, distance costs tend to be higher. Following Proposition 1, it is then more likely that land and labor are substitutes in the net function. In this case, increasing the PES decreases illegal harvesting, while increasing the control quality decreases deforestation.

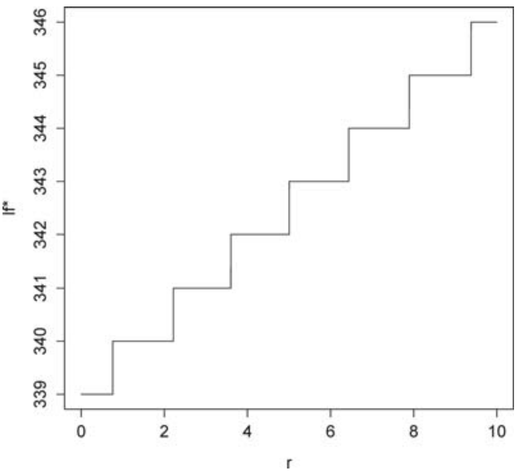

FIGURE 7
Increasing Payments for Environmental Services Increases Illegal Harvesting When Production Factors Are Complements

A PES scheme will reduce the expansion of agricultural land. If land and labor are substitutes in the net return function, this reduction leads to agricultural labor being more productive. Thus, the households intensify agriculture (and thus reduce illegal harvesting) as a feedback of this reduced agricultural expansion. In contrast, if both factors are complements, the reduction in agricultural expansion reduces the marginal productivity of agricultural labor. The household thus decreases its use, leading to an increase of illegal harvesting.

Then strengthening the REDD policy (increasing the PES and the quality of illegal harvesting control) has win-win potential, in other words, has positive feedbacks, when land and labor are substitutes in agricultural production. In contrast, the feedback is negative if land and labor are complements in agricultural production.[8] Figures 7 and 8 show

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[8] Forest products may have fairly inelastic demands in reality, as many of them are used for subsistence purposes. This inelastic demand may be related to an important concavity of the net return on illegal harvest, which can tend to reduce the extent (but not the nature) of the results of equations [10] and [11].

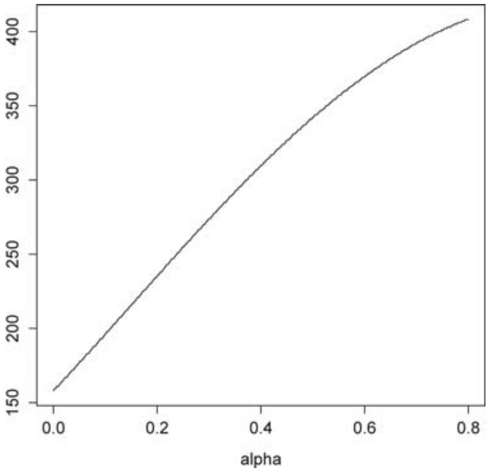

FIGURE 8
Increasing the Control Quality Increases Deforestation When Production Factors Are Complements

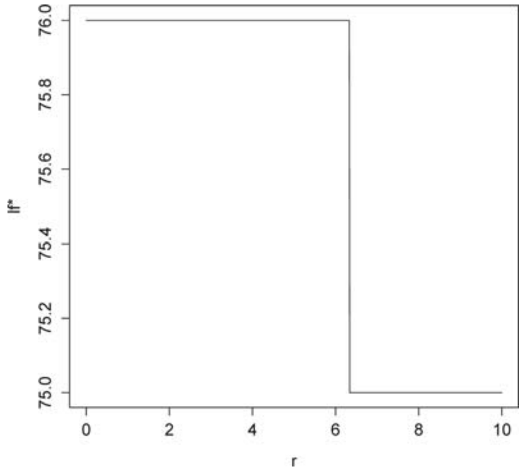

FIGURE 9
Increasing Payments for Environmental Services Decreases Illegal Harvesting When Production Factors Are Substitutes

this indirect effect of the PES and the control quality when factors are complements. In this case, one instrument focusing on one particular objective produces leakage toward the other one.

The results are different in the case of substitutability. As discussed above, we then rapidly approach corner solutions (no illegal harvesting) when distance costs increase. With high distance costs, Figure 9 shows that increasing the PES has at best a small effect on reducing illegal harvesting. Similarly, Figure 10 shows that increasing $\alpha$ rapidly brings corner solutions in which illegal harvesting is fully abandoned by the households. This implies an increase in deforestation.

## V. CONCLUSION

This paper has analyzed possible spillover effects (leakage) between the two D's in REDD policies: How do PES schemes aiming to reduce agricultural expansion (deforestation) influence nonsustainable harvesting of forest products (degradation)? How does better control of illegal harvesting impact deforestation? Our simple model demonstrates that the result depends on the nature of the relationship between land and labor. If land and agricultural labor are substitutes in the net return function, implementing PES presents policy makers with a win-win scenario: it directly slows down deforestation and indirectly decreases labor allocated to illegal harvesting. Similarly, improving the control quality directly reduces labor allocated to illegal harvesting and indirectly decreases deforestation. If land and labor are complements, which may

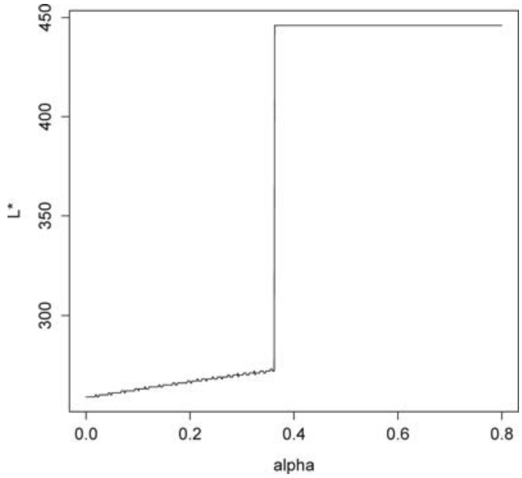

FIGURE 10
Improving the Control Quality Rapidly Generates Corner Solutions When Factors Are Substitutes

be a more reasonable empirical assumption, increasing the payment for avoided deforestation indirectly increases illegal harvesting, while increasing the quality of control indirectly increases deforestation.

We also introduced distance costs into the model, and our results bring a clear prediction. Such costs may yield a win-win scenario even if we have technical complementarity between the factors in agricultural production. It then follows that win-win outcomes (both reduced deforestation and forest degradation) are more likely in regions with higher distance costs. Moreover, our simulations suggests that a sufficiently high level of distance costs generates corner solutions in which labor allocated to illegal harvesting is no longer productive. In this case, leakage between deforestation and illegal harvesting is no longer a problem.

These results have several policy implications. First, they bring a very practical conclusion that a real policy mix of resource preservation is necessary in places where production factors are complements. PES schemes should be combined with strengthening of the control quality, to efficiently reduce indirect effects of the REDD policy. In particular, deforestation hot spots are likely to be in areas with high return to agricultural expansion, for example, caused by low distance costs, and these are exactly the areas where we are likely to face a win-lose outcome if only one policy is pursued.

Second, the PES scheme could be more effective if focused on places where distance costs are high (described by our parameter $k$) in order to get win-win outcomes. Empirically, high distance costs may be associated with low opportunity costs of deforestation (e.g., through high remoteness and lack of access to markets). In those cases of low opportunity costs, the implementation of the PES scheme presents policy makers with a more pleasant win-win scenario, in addition to the potential for larger emissions reductions due to the smaller compensation payment needed.

Third, our simulations suggest there are less likely to be synergies when increasing the control quality on illegal harvesting, due to probable corner situations in which leakage between illegal harvesting and deforestation is important. This does not suggest that increased control should not be undertaken, but serves as a warning that win-win outcomes cannot readily be assumed.

Finally, our results are based on the assumption that households have constrained access to off-farm labor markets, which makes decisions on labor allocation to different activities inseparable. Better access to labor markets and development of attractive off-farm opportunities disconnect the two activities and make the two decisions separable. Improved labor market access can help to reduce those leakage situations. This result fits well with what other deforestation models have underscored, namely, that providing better off-farm income-generating opportunities can have a major forest conservation effect.

## APPENDIX A: GENERAL CASE AND DISTANCE COST CASE

TABLE A1

Correspondence between General Case and Distance Cost Case

| General Case | Distance Cost Case | Sign |
|---|---|---|
| $H(l,L)$ | $I(\bar{l} - l - kL)$ | |
| $H_l$ | $-I_f$ | $<0$ |
| $H_L$ | $-kI_f$ | $<0$ |
| $H_{ll}$ | $I_{ff}$ | $<0$ |
| $H_{LL}$ | $k^2 I_{ff}$ | $<0$ |
| $H_{lL}$ | $kI_{ff}$ | $<0$ |

## APPENDIX B: VALUE OF THE PARAMETERS OF THE SIMULATION

TABLE B1
Parameter Values of the Numerical Illustration

| Variable | Coefficient Value | |
|---|---|---|
| $K$ | 10,499.25 | |
| $\beta 1$ | 0.709 | |
| $\beta 2$ | 0.087 | |
| $\beta 3$ | − 0.1 | |
| $\beta 4$ | − 0.098 | |
| $\beta 5$ | 0.18 | |
| $\beta 6$ | − 0.019 | |
| $\beta 7$ | − 0.021 | |
| $\beta 8$ | − 0.013 | |
| $\beta 9$ | 0.047 | |
| *cattle* | 2,750 | |
| *inputs* | 62,436 | |
| | Figure 2 | Figure 1 |
| $k$ | — | $\in [0,0.8]$ |
| $\underline{c}$ | 100 | 100 |
| $\bar{l}$ | 500 | 500 |
| $z$ | 10,604.25 | 17,848.73 |
| $\sigma$ | 0.4 | 0.5 |
| | Substitutability | Complementarity |
| Figures | 4, 6, 9, 10 | 3, 5, 7, 8 |
| $k$ | 0.1 | 0.01 |
| $\underline{c}$ | 100 | 100 |
| $\bar{l}$ | 500 | 500 |
| $z$ | 10,604.25 | 17,848.73 |
| $\sigma$ | 0.4 | 0.5 |

TABLE B2
Results of the Numerical Illustration

| | Substitutability | | Complementarity | |
|---|---|---|---|---|
| Policy | PES | Control Quality | PES | Control Quality |
| Parameters | $r \in [0,10]$<br>$\alpha = 0$ | $r = 0$<br>$\alpha \in [0,0.8]$ | $r \in [0,10]$<br>$\alpha = 0$ | $r = 0$<br>$\alpha \in [0,0.8]$ |
| Deforestation | $\in [259,240]$ | $\in [259,446]$ | $\in [158,137]$ | $\in [158,408]$ |
| Labor in illegal harvesting | $\in [76,75]$ | $\in [76,0]$ | $\in [339,346]$ | $\in [339,22]$ |

*Note:* PES, payment for environmental services.

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