REDD+ as a Tool for Climate Change Mitigation and Biodiversity Conservation: Co-Benefits and Trade-Offs under Moral Hazard

Preliminary version[*]

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Abstract

Climate change mitigation through reduced deforestation and afforestation can entail biodiversity conservation as a co-benefit. However in some cases this co-benefit may be lower than usually argued. This paper aims at theoretically comparing the Reducing Emissions from Deforestation and Forest Degradation + (REDD+) scheme dedicated primarily to carbon emission reduction with another kind of contracts that would focus on biodiversity preservation. Biodiversity is modelled as a stochastic variable resulting

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from the non-observable efforts for reducing deforestation and intensifying afforestation density. The forest cover's components and the carbon density are observable ex-post. We define the contractual relationship between a developed country and a developing deforesting country in the light of the theory of incentives, with a multi-task principal-agent model under moral hazard. We compare two types of contracts: a carbon density performance-based contract and a biodiversity conservation-based contract. Because of the substitutability between the possible efforts and between the different kinds of forests, and their different biodiversity content, each kind of contract may imply different choices of reduced deforestation and afforestation efforts and different outcomes on forest coverage and biodiversity.

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1 Introduction

Climate and biodiversity are two global public goods that the international community intends to manage through two distinct conventions (Caparros and Jacquemont, 2003). In the early nineties, the United Nations Framework Convention on Climate Change (UNFCCC) has been designed to deal with climate change, while regarding biodiversity the Convention on Biological Diversity (CBD) has been set up with strategic plans. Focusing on the deforestation and forest degradation issue as one of the primary sources of carbon emissions (15-20% according IPCC (2007a, 2007b)), the Reducing Emissions from Deforestation and Forest Degradation + (REDD+) scheme has been recently promoted (since 2007) by the UNFCCC. Its goals are to assess state-of-the-art carbon stocks and deforestation levels in developing countries (mainly in tropical forests), to implement suitable public policies in these countries, and to compensate these countries based on performance achieved in reducing deforestation through monetary transfers from developed countries. Nevertheless, public policies designed to cope with deforestation at the developing country level to reduce carbon emissions may have dramatic consequences on biodiversity that need to be investigated.

While the primary purpose of REDD+ is climate change mitigation, some authors argue that it may have enormous co-benefits for biodiversity conservation. But it appears that, in several cases, it could at the contrary lower the biodiversity level, rising thus a trade-off between both objectives. Following Hanley et al. (2012), let us recall that, like for any environmental good supply, a "*cost-effective distribution of biodiversity supply effort will involve either the targeting of actions on low opportunity cost sites (Ando et al., 1998), or the use of economic incentives which encourage low-cost suppliers to offer to supply biodiversity outputs, rather than high cost suppliers (Connor et al., 2008)*". The same is true for avoiding deforestation and afforestation but the low cost suppliers of biodiversity may be different from the high cost suppliers of forest conservation efforts, as emphasized by Venter et al. (2013).

The first source of difference is due to the various impacts on biodiversity of clearing native forests and of planting new ones. Having examined data from FAO's Forest Resources Assessment 2010, Alston and Andersson (2011) have analysed changes in the spatial extent of primary forests in all countries with tropical forests during the 1990-2010 period. They found no country whose forest inventory data showed an increase in primary tropical forest areas. Only a very few countries (including China, India, and Vietnam) reported net increases of total forest cover for the 2005-2010 period, but these figures are driven by the establishment of forest plantations not by decreases in loss of primary tropical forests. This emphasizes the trade-off between two ways of reducing the decrease in forest cover.

According to the literature, native forests and plantations have different impacts on carbon density and on plant biodiversity as well as on animal biodiversity. While assessing the co-benefits of afforestation, Plantinga and Wu (2003) ackowledge that large-scale afforestation could impact biodiversity in still unknown but potentially undesirable ways. There is a plentiful science literature about the link between forestry and biodiversity and their possible discordance (Imai et al., 2009; O'Connor, 2008; Thomas et al., 2012; Matthews et al., 2002; Kessler et al., 2012; Bremer and Farley, 2010: Potts et al., 2013).

By taking account of this potential trade-off, this paper aims at comparing the different contracts that might be proposed to developing countries in order to highlight an efficient mechanism design that could both achieve climate change mitigation and biodiversity conservation.

A common feature of the biodiversity problem and the forest preservation one is that of hidden information. This hidden information may be related to the marginal supply price for the environmental service provided (Hanley et al., 2012). It is specifically difficult or costly to observe, since it depends on a large extent on various land characteristics and of local ecological conditions. But any contract (like the PES scheme) also suffers from asymmetric information about hidden actions difficult to monitor accurately, whith outcomes crucially affected by biological uncertainty.

As far as forest conservation is concerned, another issue is that forest cover can be observable and verifiable (using forest cover data derived from satellite images) but it essentially results from non-observable efforts : the effort in avoiding deforestation at the national level may suffer from the transaction costs with the private owners of the forests and of the political weakness of the national government for implementing the policy; the density of new plantations is influenced by exogenous climatic events.

Information about biodiversity assets is likely to be privately known by the landholders, as well as the opportunity costs of conservation actions. Goeschl et Lin (2004) identify four types of information failures in making conservation decisions, and this assertion can be generalized to any supply of environmental goods: biological uncertainty, natural variability, hidden individual information and monitoring issues.

Biodiversity monitoring is essential for assessing the impacts of REDD+ on biodiversity. As a matter of fact, there is so far no reliable metric of biodiversity and methods of biodiversity monitoring have not yet been established. Goesch and Lin (2004) underline that the impact of changing paterns of land-use upon biodiversity is highly complicated and research is still in progress.

As mentioned by Hanley et al (2012), "*a final feature of the biodiversity problem which is important for economic analysis is that the biodiversity benefits of a particular set of actions are stochastic from the viewpoint of the individual forest owner, since they are only partly* *a function of the actions of this agent*". Biodiversity is then both stochastic by nature and imperfectly measured. Moreover, the science literature shows that vegetal and animal biodiversity are linked to carbon density but not always monotonously (Kessler et al., 2012; Bremer and Farley, 2010).

Generally speaking, hidden information on conservation suppliers' cost type and hidden actions lead to issues of adverse selection and moral hazard, as underlined by Hanley et al. (2012). Contracts for biodiversity conservation are thus usually analyzed within a principal-agent model, mostly in a national framework where the agents are farmers. Most works assume hidden information about the conservation opportunity cost, in line with previous works about pollution regulation with hidden information about land quality (Wu and Babcock, 1993). For example, Motte et al. (2004) analyze the information issues in the implementation of incentive policies for conserving biodiversity in buffer zones of forested protected areas in developing countries. In their model, the information asymmetry has to do with the characteristics of land and specifically the user costs. They suppose that the principal and the farmers are all risk-neutral with respect to income. The farmers decide to set aside land from agricultural production under a "consistency constraint", imposing additionality over and above their behavior without the contract *i.e.* ensuring that the biodiversity conservation objective of the principal is respected within the contract.

Di Corato (2008) follows Motte et al (2004) by introducing a constraint about the surface conserved in second best in order to control for the effectiveness of the policy, in a context of risky agricultural production. Arguedas et al. (2008) take into account heterogeneity regarding both variable conservation costs and fixed costs. They find that accounting for these different kinds of conservation costs has important consequences for the efficiency of the menu of contracts targeted at the various farmer types.

Anthon et al (2010) compare the actual contracts offered for Natura 2000 forests with the optimal design of incentive contracts. They consider that biodiversity outcomes from landowner actions vary across forests, that they are unknown before a conservation contract is signed, and only revealed *ex post*. They show that the regulator should optimally offer forest owners an amount greater than their true supply price in order to induce compliance on high ecological-potential sites. They also conclude that payments should at least partly be linked to observable ecological outcomes, rather than just to the cost of actions, contrary to actual contracts. Usually specified as Payments for Environmental Services (PES), actual contracts aiming at conservation are widely analyzed, mostly from an empirical point of view (Nelson et al., 2008; Gardner et al. 2012; Gorddard R., 2008; Cordero Salas and Roe, 2011; Miteva et al., 2012; Wendland et al., 2008).

But conservation contractual agreements are characterized by moral hazard because it is difficult and costly to monitor the conservation suppliers's compliance. As mentionned by Bradsley and Burfurs (2008), this issue is exacerbated by the highly stochastic nature of environmental production. Nevertheless, it is seldom addressed in the literature. Robalinho et al. (2008) and Sanchez-Azofeira et al. (2007) demonstrate that the Costa Rica's PES program (often referred to as a forerunner to REDD programs because it pays land managers to retain tree cover on their land) had no significant short-term effect of the program on forest conservation and that most of the payments rewarded landowners with forests that had little or no alternative uses, which means that the owners would have conserved the forest regardless of the program payments. This is thus also a typical case of adverse selection due to asymmetric information about the opportunity cost.

Goeschl et Lin (2003) address the issue of conservation contracts while avoiding the usual shortcoming of the standard adverse selection literature that relies on the assumption of the costs and/or benefits of conservation actually known by the supplier. Instead, they develop a model of dual information asymmetry between the conservation agency and the contracting farmer where the farmer has some private information about his efficiency but at this information is noisy for both partners and the farmer is assumed to be in a better position to collect information about that. Moral hazard occurs since the action of information acquisition is non-observable by the principal.

Bardsley and Burfurd (2008) develop a mixed model for biodiversity procurement, incorporating multiple agents (farmers), risky agricultural production, and both moral hazard and adverse selection. The farmers are assumed to be risk-adverse with respect to the income transfers received from the principal; they can exert a non-observable effort to augment the quantity of available wildlife habitat, which endowment is privately known.

There are still few papers about the information issues arisen in the context of carbon sequestration contracts, and mainly about adverse selection situations. Chiroleu-Assouline et al. (2013) aim at theoretically grounding the Reducing Emissions from Deforestation and Forest Degradation + (REDD+) scheme as a contractual relationship between countries in the light of the theory of incentives. Considering incomplete information about reference levels of deforestation as well as exogenous implementation and transaction costs, we compare two types of contracts: a deforestation performance-based contract and a conditional avoided deforestation-based contract. Each kind of REDD+ contract implies a dramatically different information rent / efficiency trade-off, which is amplified by the implementation and transaction costs. If the contract is performance-based (resp. conditionality-based), information rents are awarded to countries with the *ex ante* lowest (resp. highest) deforestation. Mason and Plantinga (2013) show that contracts for carbon sequestration in forests that mitigate the asymmetric information problem due to private information about the opportunity costs of landowners are preferable than carbon offsets as a tool of emissions reduction policy.

Drawing inspiration from Ghatak and Pandey (2000) who analyze optimal contract choice in agriculture when there is joint moral hazard on the farmer's supply of effort and the riskiness of the cultivation technique, or from the seminal work of Holmstrom and Milgrom (1991), we develop an original multi-task principal-agent model between a Northern country and a Southern forested country, with aymmetric tasks, under moral hazard. The first one concerns the effort to avoid deforestation (compared to a baseline as defined in REDD+ contracts)[1] and the second task consists in intensifying the plantation density of newly afforested land. Both efforts are costly and non-observable while both outcomes (the newly deforested and afforested lands) may be observed, for example with existing observation satellites. These outcomes are not accurate signals of the effort levels owing to transaction cost and politi-

[1]In Chiroleu-Assouline et al. (2013), the real baseline is considered as a privately known characteristic of the developing deforesting country. The model is thus an adverse selection one.

cal difficulties to implement policies in the Southern country (for deforestation) but also to natural exogenous events such like deseases, weather or species interaction (for afforestation density). In addition to exogenous costs for the different efforts, we take account of the value represented by the cultivated land, and hence by the deforestation, for the developing country through its agricultural production. The marginal agricultural productivity of newly deforested land is assumed to be greater than the productivity of already cultivated land while the cost for afforestation also depends on the productivity of timber production in plantations. Therefore reducing deforestation and afforestation efforts entail an endogenous opportunity cost. Both opportunity costs are supposed to be common knowledge.

The vegetal and animal stochastic biodiversity indexes are supposed to be linked to carbon density and we consider different patterns. We do not consider direct biodiversity procurement efforts but only indirect ones through forest management. Instead of assuming that the Southern county is able to conceal the level of valuable biodiversity on his territory, we consider that the actual amount of biodiversity is imperfectly know by both countries, mainly because of the inherent complexity of species interactions, of the crucial role of exogenous stochastic events (diseases, pests or weather events) and of the lack of reliable scientific assessment methods. Our framework is thus a dual information asymmetry one, like in Goeschl and Lin (2003). *We put aside the issues of irreversibility and potential extinction of species, that would imply rather different modelling assumptions and we restrict the analysis to the case of stochastic biodiversity indexes normally distributed.*

The Southern country is assumed to be risk-neutral with regard to income transfers, with limited liability. We call Northern country the Principal or donor, which is assumed to be either concerned only with climate change (UNFCCC-type) or concerned only with biodiversity (CBD type). In the first case, it maximizes an expected utility function depending on carbon density in the South, through forest cover and afforestation density, for a given exogenous carbon price, and in the second case, it minimizes the risk of expected biodiversity loss in the South. In this latter case, the principal is assumed to take into account a viability objective. By assuming such an objective, we do not need to specify a utility function depending both on carbon density and (or only) on biodiversity, which would require to value the services supplied by biodiversity and to assume a given substituability between biodiversity conservation and climate change mitigation. Given the high level of scientific uncertainty about the bidodiversity indexes and the huge valuation work still to undertake, this mode of operation allows to compute for example the first-best and second-best costs of achieving a given objective in procurement of one of the public goods and to assess their consequences on the other ones, allowing then a cost-advantage analysis. The analysis is more in accordance with strong sustainability, or viability, than with weak sustainability. It allows to determine how to decouple biodiversity and carbon in REDD+ mechanism, as advocated by Potts et al. (2013).

We show then what are the differences in the induced efforts and in the carbon density and biodiversity outcomes between the two kinds of contracts. According to the values of the different parameters, the results are not identical and what would be a good choice when the Northern country is concerned only with deforestation (UNFCCC objectives) might become a worse one when concerned with biodiversity (CBD objectives). Aiming at both objectives simultanously restrict the area of the possible contracts.

The remainder of this paper is organized as follows. In Section 2, we present our theoretical Principal-Agent model. In Section 3, we design and analyse the deforestation and afforestation performance-based contract, whereas in Section 4, we design and analyse the biodiversity conservation-based contract. A full discussion is provided in Section 5, that concludes.

2 The model

There is a bilateral relationship via the REDD+ scheme between a developed (Northern) country, or a supranational funding institution centralizing contributions by developed countries, identified as the donor in the REDD+ terminology and designed here by N and a developing (Southern) country identified as the participant and designed by S, respectively hereafter the principal and the agent of the agency relationship created by the REDD+ arrangement. The developing country is assumed to be risk-neutral. At his level, the donor is unable to distinguish whether deforestation is done on forests where biodiversity issues are involved but may be concerned either with both climate change mitigation or with biodiversity conservation.

Within this relationship, their objectives can be summed up in the following way:

- The aim of N is either to reduce deforestation to mitigate climate change or to reduce the risk of critical biodiversity loss whilst delegating this task to S.
- The aim of S is to stimulate its economic growth whilst controlling deforestation and afforesting according to a set of thresholds regarding its commitment with N.

Implementing the REDD+ scheme requires designing an institutional arrangement between N and S to mitigate the occurrence of incomplete information (moral hazard on S's side) and then inefficiency in forest protection and biodiversity conservation. The contract can be described as follows (along the lines of Karsenty and Ongolo (2012)):

- N would like conservation of the forest cover, either through an overall reduction in deforestation (mainly tropical forests) or through afforestation. N proposes an institutional arrangement to S which is *a priori* capable of modifying deforestation and afforestation levels and density, but there are also opportunity costs as well as implementation and transaction costs in reducing these levels. The payment from N to cover these costs takes the form of a direct bilateral payment or via an international fund.
- N can only observe ex-post level of deforestation and afforestation, which are not an accurate signal of the efforts exerted by S because of exogenous shocks that affect their output. This is the source of incomplete information between parties.
- To create incentives to reduce deforestation, N offers a menu of contracts (take-it or leave-it offer), and if a contract is signed, N covers S' costs which alters its economic growth.

2.1 Choice variables for the Southern country

The available surface for forestry and agricultural production is assumed to be constant.[2] By assumption, the initial forest cover is exclusively composed of primary forests F_0. The distribution of surfaces of forestry vegetation terrains is known. The *ex post* deforestation level d (realized and publicly observed) depends on the country's effective effort in avoiding it (e^d). The developing country can also choose to afforest a surface f (observable) with a density a that also depends on an nonobservable effort (e^a). This density is assumed to be always less than the density of the primary forests (normalized to unity) and greater than the density of agricultural soils (normalized to zero).

We can express the land-use constraint of the available land as $F_0 + S_0 = (F_0 - d + f) + (S_0 + d - f)$: when the forestry surface decreases by $d - f$, the cultivated surface increases by the same amount. By assuming that the available land is sufficiently large to ensure that, whatever the decisions of both partners, $d < F_0$, and $f - d < S_0$, we restrict the analysis to cases where neither the cultivated land or the native forest can entirely disappear.

The carbon balance can be written as F_0 before the contract and as $F_0 - d + af$ after the contract execution.

We assume that the Southern country chooses first its avoided deforestation and afforestation efforts, $e^d \in \{0; 1\}$ and $e^a \in \{0; 1\}$. Given the expected levels of deforestation and of density of plantations resulting of these efforts, the country chooses the afforested surface (f) by maximizing its expected utility function. The agricultural output depends on the cultivated land according a production function Y assumed to be twice continuously differentiable and concave: $Y(S_0 + \theta d - f)$. The marginal productivity of land defines therefore the opportunity cost of avoided deforestation and of afforestation, which is greater for newly deforested land than for already cultivated land: $\theta > 1$ is assumed to be perfectly known both by S and by N.[3]

Because of transactions costs between the Southern government and the local landowners,

[2] We don't consider here the changes in land-use that can derive from urbanization (Plantinga et al., 2014).

[3] A forthcoming extension of our paper will consider that the opportunity cost of avoiding deforestation is only privately known by the Southern country, adding then an adverse-selection issue to our asymmetric multi-task problem.

even greater than the government is politically weak, the output of the effort of reducing deforestation is uncertain and the observed deforestation level cannot considered as an accurate signal of the effort level. We assume that, if $e^d = 1$, $d = \underline{d}$ with probability π_1 and $d = \overline{d} > \underline{d}$ with probability $(1 - \pi_1)$. In this setting, $\overline{d}$ can be interpreted as the deforestation baseline that would be realized outside the contract, and $\underline{d}$ as the contractual objective that may be not achieved because of the transaction cost. If $e^d = 0$, $d = \underline{d}$ with probability $\pi_0 < \pi_1$ and $d = \overline{d}$ with probability $(1 - \pi_0)$.

As regards the afforestation effort, it also results in an uncertain density but more because of exogenous meteorological or natural events (like deseases, or pests) than of implementation issues. In a similar manner, if $e^a = 1$, $a = \overline{a}$ with probability ρ_1 and $a = \underline{a} < \overline{a}$ with probability $(1 - \rho_1)$. If $e^a = 0$, $a = \overline{a}$ with probability $\rho_0 < \rho_1$ and $a = \underline{a}$ with probability $(1 - \rho_0)$. By assumption, the output of both efforts are independently distributed.

By assumption, the cost of exerting no effort is nil whereas the cost of exerting only $e^d = 1$ is equal to ψ, the cost of exerting only $e^a = 1$ is equal to φ and the cost of exerting both efforts is equal to χ. If $\chi > \psi + \varphi$, the efforts are substitutes and if $\chi < \psi + \varphi$, the efforts are complementary (Laffont and Martimort, 2009). We summarize these effort costs by writing the disutility of effort for the agent S as $\chi(e^d, e^a)$ such that $\chi(1, 0) = \psi$, $\chi(0, 1) = \varphi$ and $\chi(1, 1) = \chi$. In the end, the total cost of exerting an effort depends also on the opportunity cost of the maintained forestry land. Independently of the effort cost, we assume that afforestation can be desired by the Southern country because it allows to get a constant net marginal return γ per hectare (marginal return minus marginal cost)[4].

2.2 Biodiversity effects of the different kinds of forests

Since our model intends to highlight the trade-offs between climate change mitigation (positively linked to a high forestry density) and biodiversity conservation, we have to take account

[4] A more realistic assumption would be that this marginal return is the marginal productivity of the plantations, depending on their density (timber production for example). In that case, the total timber production would be expressed as $\gamma(a)f$. In this paper, we characterize the different contracts under this simplifcation assumption but we will also give some insights on the consequences of a different timber productivity when relevant.

of the differentiated effects of the forest types on both vegetal and animal biodiversity, as shown by the science literature (see Kessler et al., 2012 and Bremer and Farley, 2010). Tropical rain forests are characterized by a high carbon density which yields a low plant diversity but a very high animal biodiversity. Among plantations, the plant diversity and the animal diversity are both positively linked to their carbon density, as clear plantations may be monocultures. The main point is that because the animal biodiversity increases with carbon density but decreases for high densities while plant diversity increases monotonously, the global biodiversity might mainly follow either plant diversity or animal diversity. Our assumptions will allow us to encompass these different cases.

Moreover the afforestation effort may impact biodiversity depending on the forest types that are involved. Biodiversity is measured as a global indicator within the forests concerned, increasing as biodiversity increases. However, the link between actual deforestation or plantations and biodiversity cannot be observed by the donor, who only knows the mean value of plant and animal diversity index in each kind of forests but this effect is impacted in a probabilistic manner. This relation cannot been considered as private information for the Southern country and this is more a dual information asymmetry. As a result the biodiversity index is stochastic.

Representing the biodiversity issue is rather complex in our theoretical framework, which leads us to adopt a simplistic encompassing indicator. Since Arrhenius (1921), the scientific literature considers as a good approximation the Species-Area Relationship he proposed, relying on experimental observations. This relationship relates the number of species S to the land area of a habitat A through a power function $S = cA^z$ where z has been fund to be approximately equal to 0.25 and c is a scale parameter depending on the nature of the habitat (see Brooks et al., 2002 or Thomas et al., 2004 for applications). In our case, we consider native forests F, afforested areas f with different density a and agricultural land, that allows us to define the number of species - both vegetal and animal - in each kind of habitat after deforestation and implementation of the contract:

$$\begin{aligned} S_F &= c\,(F_0-d)^z \qquad S_f = c(a)f^z \qquad S_A = c_0\,(S_0+d-f)^z \\ \text{with} \quad c(\underline{a}) &= \underline{c}\ , \quad c(\bar{a}) = \bar{c} \qquad c > \max\{\underline{c},\bar{c}\} \lesseqgtr c_0 \end{aligned}$$

Some species may exist in different habitats, which forbids to simply add these numbers to obtain an aggregate indicator of the species richness R of the country, defined as the global number of species and, taking also into account the stochasticity of the scale parameters and thus of these estimates (denoted with a $\sim$), we can just infer that

$$\tilde{R} \leq \tilde{S}_F + \tilde{S}_f + \tilde{S}_A = c\,(F_0-d)^z + b(a)f^z + b_0\,(S_0+d-f)^z$$

Since the aggregation of diversity indexes taking account of respectives abundances (like Shannon indexes) would be even more complex if not impossible, we choose to base our analysis on this species richness indicator. More specifically, we consider that biodiversity would be at critical risk if this indicator happened to fall under a critical threshold, denoted R_{lim}. The objective of any conservation policy will then be, at least to ensure that the probability Π_B that the expected species richness $\tilde{R}$ falls below the critical threshold R_{lim}, remains lower than a threshold β considered as secure by the scientific community:

$$\Pi_B(F_0-d,a,f,S_0) = \Pr(\tilde{R} < R_{\text{lim}}) < \beta$$

From now on, we use similar notations to describe the effect of the different land areas on this probability

$$\begin{aligned} \frac{\partial \Pi_B}{\partial\,(F_0-d)}(F_0,d,a,f,S_0) &= -b \\ \frac{\partial \Pi_B}{\partial f}(F_0,a,f,S_0) &= -b(a) \qquad \text{with} \qquad b(\underline{a}) = \underline{b}\ , \quad b(\bar{a}) = \bar{b} \\ \frac{\partial \Pi_B}{\partial\,(S_0+d-f)}(F_0,a,f,S_0) &= -b_0 \end{aligned}$$

The highest the area of native forest and the highest the number of species inhabited ($b > 0$). It implies that, deforesting native forests causes, ceteris paribus, a net loss in species richness and an increase of the probability of the global stock to fall below the critical threshold. The increase of the agricultural area increases the number of species in this habitat, and thus increases Π_B, i.e. $b_0 > 0$. Afforesting also increases the number of species in afforestated land ($b(a) > 0$). But the net effects of deforestation and afforestation are ambiguous since they depend both on the relative size of the deforested land and the afforested land and on the different impacts on species richness of these different kinds of habitat. According to our assumption of a higher agricultural productivity for newly deforested land, there would be no rationale to afforest immediately after deforestation: we assume thus that any deforested land is used as agricultural land and that afforestation is limited to already existing (and stabilized) agricultural land. As a result

$$\begin{aligned} \frac{\partial \Pi_B}{\partial d}(F_0, d, a, f, S_0) &= b - b_0 \\ \frac{\partial \Pi_B}{\partial f}(F_0, a, f, S_0) &= -b(a) + b_0 \qquad \text{with} \qquad b(\underline{a}) = \underline{b}\ , \quad b(\bar{a}) = \bar{b} \end{aligned}$$

The net effects depend on the relative biodiversity content of the different habitats. Relying on the science literature mentioned above, it seems plausible to assume that $b > b_0$ such that the net effect of deforestation is negative on the number of species, increasing the probability for it to fall under the critical threshold. But there is some evidence that $b(a)$ could be, in some cases, lower than b_0, depending on whether the original land cover is grassland, shrubland, primary forest, secondary forest, or degraded or exotic pasture, and whether native or exotic tree species are planted. In this paper, we will keep things general in order to enable the analysis of all possible cases $\underline{b} \lesseqgtr b_0$ and $\bar{b} \lesseqgtr b_0$.

Our very simple model treats equally the biodiversity losses due to deforestation and the gains due to afforestation. Nevertheless, biodiversity issues arising from deforestation could also be considered as more crucial since some endemic species in native forests could disappear with their habitat. We will thus focus also on the specific critical case where the loss of species in forests induces extinction that cannot be compensated by any gain in other afforestated lands. In this setting, d/F_0 could be interpreted as the probability of extinction of endemic species, since the disappearance of native forests is likely to induce the extinction of species harboured only in S's slots. To do so, we will adopt the same framework than Rosenzweig (1995), who assumes that the objective of any conservation policy should be to minimize the risk of extinction measured according as $1 - (1 - d/F_0)^z$.

2.3 The objectives of both countries

2.3.1 The "Northern" country

The developed country N is primarily interested either in forest cover/density or more precisely in carbon density in the forest of the developing country or in biodiversity conservation. Because we take into account the debate about biodiversity valuation and the choice that should be made if one wanted to aggregate in a common utility function different objectives like carbon density and biodiversity conservation, we will alternatively study the contracts proposed by a Northern country according to different separate objectives. In each case, we assume that the risk-neutral principal operates under the same budget constraint limiting its transfers to the Southern country to an exogenous fixed amount $\bar{T}$.

In the first case of UNFCCC-type Northern country (section 3), we assume that *N's* expected welfare only depends on the carbon density of the forest cover in S, for an exogenous carbon price equal to p:

$$EW(d, a, f) = E\left[p(F_0 - d + af)\right]$$

In the second case of CBD-type Northern Country (section 4), we assume that the Northern country is only concerned with minimizing the risk of biodiversity loss in S. With the notations defined above, this objective may be summarized by minimization of the probability Π_B that the expected species richness $\tilde{R}$ falls below a critical threshold $R_{\lim}$, with a threshold β considered as secure by the scientific community.

$$\Pi_B(F_0 - d, a, f, S_0) = \Pr(\tilde{R} < R_{\text{lim}}) < \beta$$

In order to achieve its objective, whatever it is, N has to decide whether to induce S to exert both efforts, or only one of them, or none and, according this choice, to decide how the incentive contract should be designed. N proposes therefore a quadruplet of payments based on the four possible outcomes:

$$\begin{cases} (\underline{d}, \bar{a}) & \rightarrow \ \bar{t} + \bar{s}f \leq \bar{T} \\ (\underline{d}, \underline{a}) & \rightarrow \ \bar{t} + \underline{s}f \leq \bar{T} \\ (\bar{d}, \bar{a}) & \rightarrow \ \underline{t} + \bar{s}f \leq \bar{T} \\ (\bar{d}, \underline{a}) & \rightarrow \ \underline{t} + \underline{s}f \leq \bar{T} \end{cases}$$

The notations used intend to represent the desirability of the paid outcomes for N with respect to the forest cover and carbon density and we will stick to these notations throughout the paper even if the desirability of the outcomes may be different when N seeks to conserve biodiversity. Regarding plantations, the payment is proportional to the surface afforested.

2.3.2 The "Southern" country

We assume that the Southern country is risk-neutral with respect to transfers and protected by limited liability (the transfers from the Northern country are non-negative). S's gross surplus is defined by $U(d,a,f) = Y(S_0+\theta d-f)+(t+sf)+\gamma f-\chi(e^d,e^a) = u(d,a,f)-\chi(e^d,e^a)$, where $Y'(d)$ is the marginal productivity of deforested land, γ is the constant net marginal return per hectare, Y assumed to be increasing and concave, and $t + sf$ the monetary transfer in the REDD+ scheme. This setting is unusual because the costs of efforts are not only exogenous but also endogenous, since their results influence the agricultural production. Actually, the concavity of the production function introduces a kind of risk-aversion for S that might prevent the principal to implement the first-best levels of efforts under moral hazard.

The sequential programme of the Southern country is solved by using backward induction: at the second step, S chooses the surface to afforest f, for a given effort of plantation, knowing the expected deforestation according its level of effort to avoid it:

$$\max_f EU(d,a,f) = E\left[Y(S_0+\theta d-f)+t+sf-\chi(e^{d*},e^{a*})+\gamma f\right]$$

$$\begin{aligned}
& E\left[Y(S_0+\theta d-f)+\gamma f+(t+sf)-\chi(e^{d*},e^{a*})\right] \\
= \quad & \pi(e^{d*})\left[Y(S_0+\theta \underline{d}-f)+\bar{t}+(\rho(e^{a*})\bar{s}+(1-\rho(e^{a*})\underline{s})\,f\right] \\
& +\left(1-\pi(e^{d*})\right)\left[Y(S_0+\theta\bar{d}-f)+\underline{t}+(\rho(e^{a*})\bar{s}+(1-\rho(e^{a*})\underline{s})\,f\right] \\
& -\chi(e^{d*},e^{a*})+\gamma f
\end{aligned}$$

The first-order condition of this program yields:

$$EY'(S_0+\theta d-f) = E\,(s)+\gamma$$

$$\pi(e^{d*})\left[Y'(S_0+\theta\underline{d}-f)\right]+\left(1-\pi(e^{d*})\right)\left[Y'(S_0+\theta\bar{d}-f)\right] = (\rho(e^{a*})\bar{s}+(1-\rho(e^{a*})\underline{s})+\gamma \quad (1)$$

Since the marginal agricultural productivity of land is positive and decreasing, $Y'(S_0+\theta\bar{d}-f) < Y'(S_0+\theta\underline{d}-f)$, $\forall f$. One can easily show (see Appendix 6.1) that the afforested surface is lower when the Southern country has not exerted the highest effort to avoid deforestation, the land cleared by deforestation and the land lost because of afforestation being substitutes in the agricultural production function. This effect is amplified by θ: f increases with θ as it is possible to lose more cultivated land when high productivity land is gained from native forests. Moreover, the afforested surface is greater when the effort to densify the plantation has been exerted, because the expected subsidy is also greater. We can see here that in case of a timber productivity increasing with the plantation density (as suggested in footnote 4), we should replace γ with $\gamma\,(\rho(e^{a*})\bar{a}+(1-\rho(e^{a*})\underline{a})$: if the timber productivity is higher in dense plantations, the expected productivity increases with the expected subsidy and the results are qualitatively unchanged. If, on the contrary, the timber productivity is lower in dense plantations, this effect can mitigate the effect of the expected subsidy and reduce the afforested surface.

From now on, we denote $\hat{f} = \hat{f}(e^{d*}, e^{a*}, \theta)$ this optimal amount of surface afforested. However outside the REDD+ scheme, the transfers are nil, inducing zero effort to reduce deforestation and to densify plantations, so S's outside option is $EU(\underline{d}, \pi_0; \bar{d}, (1-\pi_0)\,; \bar{a}, \rho_0; \underline{a}, (1-\rho_0)) = \pi_0 Y(S_0 + \theta\underline{d} + \hat{f}(0,0,\theta)) + (1-\pi_0)Y(S_0 + \theta\bar{d} + \hat{f}(0,0,\theta)) = u_R$.

3 The contract focused on deforestation and afforestation

The developed country tries to manage the forest cover of the Southern country in order to maximize the amount of carbon stored in the forests.

In this case, unambiguously, $\underline{d}$ is preferred to $\bar{d}$ and $\bar{a}$ to $\underline{a}$, which implies that $\bar{t} > \underline{t}$ and $\bar{s} > \underline{s}$.

3.1 The incentives constraints of the Southern country

We have to write the local incentive constraints that prevent the agent S to exert only one effort and the global incentive constraint that prevents the agent from exerting no effort at all. From now on, we will call $\bar{U} = u(\underline{d}, \bar{a})$, $\bar{V} = u(\underline{d}, \underline{a})$, $\underline{V} = u(\bar{d}, \bar{a})$ and $\underline{U} = u(\bar{d}, \underline{a})$.

Using these notations allows to write S' expected utility according to the efforts exerted:

$$\begin{aligned}
EU(e^d &= 1, e^a = 1) = \pi_1\rho_1\bar{U} + \pi_1(1-\rho_1)\bar{V} + (1-\pi_1)\rho_1\underline{V} + (1-\pi_1)(1-\rho_1)\underline{U} - \chi \\
EU(e^d &= 1, e^a = 0) = \pi_1\rho_0\bar{U} + \pi_1(1-\rho_0)\bar{V} + (1-\pi_1)\rho_0\underline{V} + (1-\pi_1)(1-\rho_0)\underline{U} - \psi \\
EU(e^d &= 0, e^a = 1) = \pi_0\rho_1\bar{U} + \pi_0(1-\rho_1)\bar{V} + (1-\pi_0)\rho_1\underline{V} + (1-\pi_0)(1-\rho_1)\underline{U} - \varphi \\
EU(e^d &= 0, e^a = 0) = \pi_0\rho_0\bar{U} + \pi_0(1-\rho_0)\bar{V} + (1-\pi_0)\rho_0\underline{V} + (1-\pi_0)(1-\rho_0)\underline{U}
\end{aligned}$$

The local incentives constraints $LIC1$ and $LIC2$ are consequently written:

$$LIC1 \qquad EU(e^d = 1, e^a = 1) \geq EU(e^d = 1, e^a = 0)$$
$$\Leftrightarrow \pi_1 \left(\bar{U} - \bar{V}\right) + (1 - \pi_1)\left(\underline{V} - \underline{U}\right) \geq \frac{\chi - \psi}{\rho_1 - \rho_0} \tag{2}$$

$$LIC2 \qquad EU(e^d = 1, e^a = 1) \geq EU(e^d = 0, e^a = 1)$$
$$\Leftrightarrow \rho_1 \left(\bar{U} - \bar{V}\right) + (1 - \rho_1)\left(\underline{V} - \underline{U}\right) \geq \frac{\chi - \varphi}{\pi_1 - \pi_0} \tag{3}$$

and the global incentive constraint GIC:

$$GIC \qquad EU(e^d = 1, e^a = 1) \geq EU(e^d = 0, e^a = 0)$$
$$\Leftrightarrow (\pi_1\rho_1 - \pi_0\rho_0)\,\bar{U} + [\pi_1(1 - \rho_1) - \pi_0(1 - \rho_0)]\,\bar{V} \tag{4}$$
$$+ [(1 - \pi_1)\rho_1 - (1 - \pi_0)\rho_0]\,\underline{V} + [(1 - \pi_1)(1 - \rho_1) - (1 - \pi_0)(1 - \rho_0)]\,\underline{U} \geq \chi$$

The Southern country will accept to participate if the contract provides him an expected utility at least equal to his reservation utility:

$$PC \qquad EU(e^d = 1, e^a = 1) \geq u_R$$
$$\Leftrightarrow \pi_1\rho_1\bar{U} + \pi_1(1 - \rho_1)\,\bar{V} + (1 - \pi_1)\,\rho_1\underline{V} + (1 - \pi_1)(1 - \rho_1)\,\underline{U} \geq u_R + \chi \tag{5}$$

3.2 The first-best outcomes

Let us assume that the Northern country performs alone the two tasks, incurring only the direct effort costs. For the levels of efforts he chooses e^d_{FB} and e^a_{FB}, N expects that S will choose the amount of afforested land $\hat{f} = \hat{f}(e^d_{FB}, e^a_{FB})$ defined by $\pi(e^{d*})\left[Y'(S_0 + \theta\underline{d} - f)\right] + \left(1 - \pi(e^{d*})\right)\left[Y'(S_0 + \theta\bar{d} - f)\right] = \gamma$ from (1). N takes thus indirectly into account the opportunity costs of reduced deforestation and greater afforestation through the agricultural production loss of the Southern country. The principal's program can then be written as:

$$\max_{e^d,e^a} E\left[p(F_0 - d + af)\right]$$

$$\text{s.t.} \quad \pi(e^d)\left[Y'(S_0+\theta\underline{d}-f)\right] + \left(1-\pi(e^d)\right)\left[Y'(S_0+\theta\bar{d}-f)\right] = \gamma$$

$$\text{s.t.} \quad \chi(e^d, e^a) \leq \bar{T}$$

We will limit the analysis to internal solutions by assuming that $\bar{T} \geq \max\{\psi, \varphi, \chi\}$ so the Principal can afford any level of effort.

The principal's net benefit of choosing to let S exert a positive effort on both tasks is $W_2^{FB} = p\left[F_0 - \left(\pi_1\underline{d} + (1-\pi_1)\,\bar{d}\right) + \left(\rho_1\bar{a} + (1-\rho_1)\,\underline{a}\right)\hat{f}(1,1)\right]$ with $\hat{f}(1,1)$ defined by $\pi_1\left[Y'(S_0+\theta\underline{d}-\hat{f})\right] + (1-\pi_1)\left[Y'(S_0+\theta\bar{d}-\hat{f})\right] = \gamma$.

If N chooses to let S exert only an effort on the avoiding deforestation task, he gets $W_d^{FB} = p\left[F_0 - \left(\pi_1\underline{d} + (1-\pi_1)\,\bar{d}\right) + \left(\rho_0\bar{a} + (1-\rho_0)\,\underline{a}\right)\hat{f}(1,0)\right]$ with $\hat{f}(1,0)$ defined by $\pi_1\left[Y'(S_0+\theta\underline{d}-\hat{f})\right] + (1-\pi_1)\left[Y'(S_0+\theta\bar{d}-\hat{f})\right] = \gamma$. Clearly $\hat{f}(1,0) = \hat{f}(1,1)$, which means that the afforested surface of the first-best outcome depends only on the effort to avoid deforestation.

If, on the contrary, N chooses to let S exert only an effort on the afforestation intensity task, he gets $W_a^{FB} = p\left[F_0 - \left(\pi_0\underline{d} + (1-\pi_0)\,\bar{d}\right) + \left(\rho_1\bar{a} + (1-\rho_1)\,\underline{a}\right)\hat{f}(0,1)\right]$ with $\hat{f}(0,1)$ defined by $\pi_0\left[Y'(S_0+\theta\underline{d}-\hat{f})\right] + (1-\pi_0)\left[Y'(S_0+\theta\bar{d}-\hat{f})\right] = \gamma$. Clearly $\hat{f}(0,1) = \hat{f}(0,0) > \hat{f}(1,0)$ (same argument than in Appendix 6.1), in order to compensate the expected loss of forest cover due to the fact that S does not try to avoid deforestation.

The last case is when N decides to let S exert no effort at all, that leads to N's net benefit given by $W_0^{FB} = p\left[F_0 - \left(\pi_0\underline{d} + (1-\pi_0)\,\bar{d}\right) + \left(\rho_0\bar{a} + (1-\rho_0)\,\underline{a}\right)\hat{f}(0,0)\right]$ with $\hat{f}(0,0) = \hat{f}(0,1)$. As a consequence, $\hat{f}(0,0) > \hat{f}(1,1)$.

From these definitions, we can deduce that exerting both efforts is preferred by N to any other possibility $W_2^{FB} > \max\left\{W_d^{FB}, W_a^{FB}, W_0^{FB}\right\}$.

Exerting both efforts is preferred by N to exert only an effort on the avoiding deforestation task iff $W_2^{FB} > W_d^{FB} \Leftrightarrow p(\rho_1-\rho_0)(\bar{a}-\underline{a})\hat{f}(1,1) > 0$. This is always verified.

Exerting both efforts is preferred by N to exert only an effort on the afforestation intensity task iff $W_2^{FB} > W_a^{FB} \Leftrightarrow p(\pi_1 - \pi_0)(\bar{d} - \underline{d}) - p\left(\rho_1 \bar{a} + (1 - \rho_1)\, \underline{a}\right) \left[\hat{f}(0,0) - \hat{f}(1,1)\right] > 0$.

Exerting both efforts is preferred by N to exert no effort at all iff $W_2^{FB} > W_0^{FB} \Leftrightarrow$ $p(\pi_1 - \pi_0)(\bar{d} - \underline{d}) + p(\rho_1 \hat{f}(1,1) - \rho_0 \hat{f}(0,0))(\bar{a} - \underline{a}) > 0$.

These conditions can be rewritten as (remember that $\hat{f}(1,1) < \hat{f}(0,0)$ and $\rho_0 < \rho_1$):

$$(\rho_1 \hat{f}(1,1) - \rho_0 \hat{f}(1,1))(\bar{a} - \underline{a}) > 0$$

$$(\pi_1 - \pi_0)(\bar{d} - \underline{d}) + (\rho_1 \hat{f}(1,1) - \rho_1 \hat{f}(0,0))(\bar{a} - \underline{a}) - \underline{a}\left[\hat{f}(0,0) - \hat{f}(1,1)\right] > 0$$

$$(\pi_1 - \pi_0)(\bar{d} - \underline{d}) + (\rho_1 \hat{f}(1,1) - \rho_0 \hat{f}(0,0))(\bar{a} - \underline{a}) > 0$$

3.3 Moral hazard and carbon density contracts

Under moral hazard, the cost for the Northern country to induce both efforts is augmented by the need to pay transfers to the Southern country, under the incentive constraints and the participation constraint.

Suppose first that the Northern country wants to induce the highest effort on both task. Obviously, the best way to obtain this result is to pay a subsidy each time that $d = \underline{d}$ and $a = \bar{a}$ and zero otherwise. The transfer is thus $\bar{t} + \bar{s}\bar{f}(\underline{d}, \bar{a})$, $\bar{f}(\underline{d}, \bar{a})$.being defined as the certain afforested land if $d = \underline{d}$ and $a = \bar{a}$. The local incentive constraints are written as:

$$\begin{array}{ll} LIC1 & \pi_1 \left(\bar{U} - \bar{V}\right) + (1 - \pi_1)\left(\underline{V} - \underline{U}\right) \geq \dfrac{\chi - \psi}{\rho_1 - \rho_0} \\ LIC2 & \rho_1 \left(\bar{U} - \bar{V}\right) + (1 - \rho_1)\left(\underline{V} - \underline{U}\right) \geq \dfrac{\chi - \varphi}{\pi_1 - \pi_0} \end{array}$$

and the global incentive constraint as:

$$GIC \qquad (\pi_1 \rho_1 - \pi_0 \rho_0)\, \bar{U} + \left[\pi_1 (1 - \rho_1) - \pi_0 (1 - \rho_0)\right] \bar{V}$$
$$+ \left[(1 - \pi_1)\, \rho_1 - (1 - \pi_0)\, \rho_0\right] \underline{V} + \left[(1 - \pi_1)(1 - \rho_1) - (1 - \pi_0)(1 - \rho_0)\right] \underline{U} \geq \chi$$

In these constraints, the tranfers influence only $\bar{U}$ (and in an additional way, since we have assumed the agent to be risk-neutral with respect to tranfers) and the incentive constraints can be expressed in a simplified way, where $\bar{U}_0$ is the utility earned by S over and above the tranfers (we adopt a similar notation for the other levels of utility because in this case, they do not comprise transfers) :

$$\begin{array}{ll} LIC1 & \pi_1\left(\bar{t}+\bar{s}\bar{f}(\underline{d},\bar{a})\right) \geq -\pi_1\bar{U}_0+\pi_1\bar{V}_0-(1-\pi_1)\left(\underline{V}_0-\underline{U}_0\right)+\dfrac{\chi-\psi}{\rho_1-\rho_0} \\ LIC2 & \rho_1\left(\bar{t}+\bar{s}\bar{f}(\underline{d},\bar{a})\right) \geq -\rho_1\bar{U}_0+\rho_1\bar{V}_0-(1-\rho_1)\left(\underline{V}_0-\underline{U}_0\right)+\dfrac{\chi-\varphi}{\pi_1-\pi_0} \end{array}$$

$$\begin{array}{ll} GIC & (\pi_1\rho_1-\pi_0\rho_0)\left(\bar{t}+\bar{s}\bar{f}(\underline{d},\bar{a})\right) \geq -\left(\pi_1\rho_1-\pi_0\rho_0\right)\bar{U}_0-\left[\pi_1\left(1-\rho_1\right)-\pi_0\left(1-\rho_0\right)\right]\bar{V}_0 \\ & -\left[\left(1-\pi_1\right)\rho_1-\left(1-\pi_0\right)\rho_0\right]\underline{V}_0-\left[\left(1-\pi_1\right)\left(1-\rho_1\right)-\left(1-\pi_0\right)\left(1-\rho_0\right)\right]\underline{U}_0+\chi \end{array}$$

If we denote X_{LIC1}, X_{LIC2}, X_{GIC} the right-hand sides of the three incentives constraints, we have:

$$\bar{t}+\bar{s}\bar{f}(\underline{d},\bar{a}) \geq \max\left\{\frac{X_{LIC1}}{\pi_1}, \frac{X_{LIC2}}{\rho_1}, \frac{X_{GIC}}{(\pi_1\rho_1-\pi_0\rho_0)}\right\} \tag{6}$$

We assume that $\max\left\{\frac{X_{LIC1}}{\pi_1}, \frac{X_{LIC2}}{\rho_1}, \frac{X_{GIC}}{(\pi_1\rho_1-\pi_0\rho_0)}\right\} \leq \bar{T}$ to allow for feasible incentive contracts.

The Northern country program is now

$$\begin{aligned} \max EW(d,a,f) &= E\left[p(F_0-d+af)\right] \\ \text{s.t. } \bar{t}+\bar{s}\bar{f}(\underline{d},\bar{a}) &\leq \bar{T} \end{aligned}$$

subject to the incentive constraints summarized by (6), which is typically the same program than in the first best case, with the additionnal cost due to the transfers. Because the transfers increase N's welfare by decreasing d and increasing a, the budget constraint is binding but (6) is not necessarily binding at N's optimum.

We can notice that the susbtituability between the two kinds of forests for S and for N implies an indeterminacy for $\bar{t}$ and $\bar{s}$. By increasing $\bar{s}$, the principal will induce a higher $\bar{f}(\underline{d},\bar{a})$ but will be able to pay a lower $\bar{t}$.

If the Northern country chooses to induce only one effort, he offers a transfer $\bar{t}+\underline{s}f$ in the case of the avoiding deforestation effort and $\underline{t}+\bar{s}f$ in the case of intensifying the density of afforestation. The second-best cost of implementing effort on only one task can be computed as before (in Appendix 6.2).

Even if the setting is much more complex than in the simple multi-task model developed by Holmstrom and Milgrom (1991), the qualitative results remain: the principal decides to let the agent exert no effort at all more often than under complete information and induces both efforts less often (complete characterization to be given in Appendix 6.2).

4 The contract focused on biodiversity conservation

The developed country uses the forest cover of the Southern country as an instrument in order to minimize the risk of critical biodiversity loss. In this second case, because of the differentiated and non monotonous effect of the kinds of plantations on biodiversity, the ranking of the payments is no more obvious.

4.1 The first-best outcomes

In this case also, let us assume that the Northern country performs the two tasks himself, incurring only the direct effort costs. For the levels of efforts he chooses e^d_{FB} and e^a_{FB}, N expects again that S will choose the amount of afforested land $\hat{f}=\hat{f}(e^d_{FB},e^a_{FB})$ defined by $\pi(e^{d*})\left[Y'(S_0+\theta\underline{d}-f)\right]+\left(1-\pi(e^{d*})\right)\left[Y'(S_0+\theta\bar{d}-f)\right]=\gamma$ from (1). N takes thus indirectly into account the opportunity costs of reduced deforestation and greater afforestation through the agricultural production loss of the Southern country. The principal's program can then be written as:

$$\min \Pi_B(F_0 - d, a, f, S_0)$$
$$\text{s.t.} \quad \pi(e^d)\left[Y'(S_0 + \theta \underline{d} - f)\right] + \left(1 - \pi(e^d)\right)\left[Y'(S_0 + \theta \bar{d} - f)\right] = \gamma$$
$$\text{s.t.} \quad \chi(e^d, e^a) \leq \bar{T}$$

We still limit the analysis to internal solutions by assuming that $\bar{T} \geq \max\{\psi, \varphi, \chi\}$ so the Principal can afford any level of effort.

The afforested surface is chosen by S according to the same program than before. The notations denote exactly the same amounts than before and we express here the levels of N's objective in a similar way as in the previous case.

The principal's non monetary benefit of choosing to let S exert a positive effort on both tasks is $(\Pi_B)_2^{FB} = (b - b_0)\left(\pi_1 \underline{d} + (1 - \pi_1)\bar{d}\right) + \left[\rho_1(\bar{b} - b_0)\bar{a} + (1 - \rho_1)(\underline{b} - b_0)\underline{a}\right] \hat{f}(1, 1)$.

If N chooses to let S exert only an effort on the avoiding deforestation task, he gets $(\Pi_B)_d^{FB} = (b - b_0)\left(\pi_1 \underline{d} + (1 - \pi_1)\bar{d}\right) + \left[\rho_0(\bar{b} - b_0)\bar{a} + (1 - \rho_0)(\underline{b} - b_0)\underline{a}\right] \hat{f}(1, 1)$.

If, on the contrary, N chooses to let S exert only an effort on the afforestation intensity task, he gets $(\Pi_B)_a^{FB} = (b - b_0)\left(\pi_0 \underline{d} + (1 - \pi_0)\bar{d}\right) + \left[\rho_1(\bar{b} - b_0)\bar{a} + (1 - \rho_1)(\underline{b} - b_0)\underline{a}\right] \hat{f}(0, 0)$.

The last case is when N decides to let S exert no effort at all, that leads to N's net benefit given by $(\Pi_B)_0^{FB} = (b - b_0)\left(\pi_0 \underline{d} + (1 - \pi_0)\bar{d}\right) + \left[\rho_0(\bar{b} - b_0)\bar{a} + (1 - \rho_0)(\underline{b} - b_0)\underline{a}\right] \hat{f}(0, 0)$.

From these definitions, we can deduce that exerting both efforts is preferred by N to any other possibility iff $(\Pi_B)_2^{FB} < \min\left\{(\Pi_B)_d^{FB}, (\Pi_B)_a^{FB}, (\Pi_B)_0^{FB}\right\}$.

Exerting both efforts is preferred by N to exert only an effort on the avoiding deforestation task iff $(\Pi_B)_2^{FB} < (\Pi_B)_d^{FB} \Leftrightarrow (\rho_1 - \rho_0)\left[(\bar{b} - b_0)\bar{a} - (\underline{b} - b_0)\underline{a}\right] \hat{f}(1, 1) < 0$. That may happen iff $(\bar{b} - b_0)\bar{a} < (\underline{b} - b_0)\underline{a}$ i.e. iff $(\bar{b} - b_0)/(\underline{b} - b_0) < \underline{a}/\bar{a} < 1$. This condition is verified if only one of the net biodiversity impacts of afforestation is negative, but in case they are both positive or both negative, there are some cases where it is impossible for N to prefer exerting both efforts (e.g. when $\bar{b} > \underline{b}$).

Exerting both efforts is preferred by N to exert only an effort on the afforestation intensity task iff $(\Pi_B)_2^{FB} < (\Pi_B)_a^{FB} \Leftrightarrow (b-b_0)(\pi_1-\pi_0)\left(\bar{d}-\underline{d}\right)+\left[\rho_1(\bar{b}-b_0)\bar{a}+(1-\rho_1)(\underline{b}-b_0)\underline{a}\right]\left[\hat{f}(0,0)-\hat{f}(1,1)\right]$ 0. This second condition is always verified if $\left[\rho_1(\bar{b}-b_0)\bar{a}+(1-\rho_1)(\underline{b}-b_0)\underline{a}\right] > 0$, which is true if both net biodiversity impacts of afforestation are positive, but it may not be verified when they are both negative, or even if one of them is negative and weighted by a sufficiently high probability.

Exerting both efforts is preferred by N to exert no effort at all iff $(\Pi_B)_2^{FB} < (\Pi_B)_0^{FB} \Leftrightarrow (b-b_0)(\pi_1-\pi_0)\left(\bar{d}-\underline{d}\right)-\left[(\bar{b}-b_0)\bar{a}-(\underline{b}-b_0)\underline{a}\right]\left[\rho_1\hat{f}(1,1)-\rho_0\hat{f}(0,0)\right]+(\underline{b}-b_0)\underline{a}\left[\hat{f}(0,0)-\hat{f}(1,1)\right] > 0$.

The thresholds that determine the choice for the principal are now modified by the biodiversity indexes in the different kinds of forests.

An important result here is that, when caring about the risk of biodiversity loss, N will not always choose to exert both efforts than only the effort of avoiding deforestation, if at least one of the afforestation pratice implies a biodiversity loss compared to agricultural land.

And according to the respective biodiversity indexes and to the range of the possible outcomes in deforestation and in density of afforestation, it might happen that N would choose more often to exert no effort at all or to only seek to increase the density of afforestation without trying to reduce deforestation.

According to the values of the different parameters, all the results can now been upset (Appendix to be given 6.3) and what would be a good choice for a UNFCCC-type Northern country is concerned only with deforestation might become a worse one for a CBD-type one.

4.2 Moral hazard and biodiversity conservation contracts

Under moral hazard, in this case also, the cost for the Northern country to induce both efforts is augmented by the need to pay transfers to the Southern country, under the incentive constraints and the participation constraint. Without any additional computations, we can see that the risk premium added in this case is not modified by moral hazard that only increases N's costs. The consequences of caring only about biodiversity are then qualitatively the same under moral hazard than under symmetric information.

5 Concluding discussion

Our results enlighten the extent of the trade-off between climate change mitigation through preservation of forests and biodiversity conservation. By avoiding any specific substitutability assumption between both objectives, that would come with the specification of a utility function depending both on carbon density and (or only) on biodiversity, we allow to do without biodiversity valuation. Instead of standard cost-benefit analysis, a cost-advantage analysis may be performed by computing the first-best and second-best costs of achieving a given objective in procurement of one of the public goods and to assess their consequences on the other ones. It is particularly useful given the high level of scientific uncertainty about the bidodiversity indexes and the huge valuation work still to undertake. The analysis is more in accordance with strong sustainability, or viability, than with weak sustainability. It allows to determine how to decouple biodiversity and carbon in REDD+ mechanism, as advocated by Potts et al. (2013).

Some of our assumptions could be relaxed or changed, that might increase the accuracy of the cost valuation without introducing significant qualitative changes. Firstly, one could assume that the agricultural productivity is affected by exogenous shocks and that the Southern country is risk-adverse with regard to income transfers. The contract should thus trade off between incentives and insurance and propose a higher fixed subsidy. Secondly, or alternatively, one could add private information about these opportunity costs of forests. One should expect that the standard results apply to this case of adverse selection: an informational rent would be given to all types of Southern countries except the least efficient one and lower efforts would be asked to all types of countries except the most efficient. Introducing adverse selection is likely to increase the cost of any given ecological outcome.

6 Appendix

6.1 The impact of efforts on the afforested surface

How does the afforested surface react to the efforts exerted by the S country?

From (1), one can write than if $e^{d*} = 1$, for a given effort e^{a*}, the first-order condition writes $\pi_1 [Y'(S_0 + \theta \underline{d} - f_1)] + (1 - \pi_1) [Y'(S_0 + \theta \bar{d} - f_1)] = E(s) - \gamma$. By assumption about the efficiency of efforts, $\pi_1 > \pi_0$, which implies, since $Y'(S_0 + \theta \bar{d} - f) < Y'(S_0 + \theta \underline{d} - f)$, $\forall f$, that $\pi_0 [Y'(S_0 + \theta \underline{d} - f_1)] + (1 - \pi_0) [Y'(S_0 + \theta \bar{d} - f_1)] < E(s) - \gamma$. Therefore, the first-order condition in case $e^{d*} = 0$ is met for $Y'(S_0 + \theta \underline{d} - f_0) > Y'(S_0 + \theta \underline{d} - f_1)$ that means for $f_0 > f_1$. Let us now consider the effect of e^{a*}, for a given e^{d*}: $E(s)$ is higher under $e^{a*} = 1$ and the same argument allows to conclude that f has to be higher when $e^{a*} = 1$ than when $e^{a*} = 0$. Obviously, because of the concavity of Y, f increases with θ.

6.2 Carbon density contracts under moral hazard

TBD

6.3 Biodiversity contracts under moral hazard

TBD

7 References

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