Avoiding deforestation efficiently and fairly

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VERY PRELIMINARY VERSION - PLEASE DO NOT QUOTE

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ABSTRACT. The international community recently agreed on a cost-effective mechanism called REDD+ to reduce deforestation in tropical countries. However the mechanism would probably fail to induce an optimal reduction of deforestation. The aim of this article is to propose an alternative class of mechanisms for negative externalities that is both efficient and satisfies some fairness properties. It implements the Pareto optimum as a Nash Subgame Perfect Equilibrium. It is also individually rational, it takes into account environmental responsibility. An d a weak form of environmental responsibility can also be combined with envy freeness.

1. INTRODUCTION

Deforestation in tropical countries accounts for up to 20% of global emissions of CO2. It is the second most important source of Greenhouse Gas Emissions in the world and the first one in developing countries. It is also a leading cause of loss of global biodiversity. A new scheme called REDD, for Reduction of Emissions from Deforestation and Degradation of forests, has been agreed on at the 16th COP of the UNFCCC to reward countries with low deforestation rates. The principle is to compensate developing countries that reduce their deforestation with financial incentives. However, there is still no consensus on the way such financial incentives should be calculated and allocated. The REDD transfers would be allocated per unit of real reduction of deforestation level compared to a reference level, called the baseline (see for instance Parker et al, 2008). In spirit, this is a cost-effectiveness approach of the problem: how to reach an exogenous limitation of deforestation at the lowest cost for financing countries? Not surprisingly then, the REDD program has no reason to induce a Pareto optimal reduction of deforestation (see Figuières et al, 2010).

In this paper, we propose to attack the question from a different angle. We let the goal be Pareto optimality, supplemented by additional requirements of fairness and acceptability that seem relevant for an international externality problem like deforestation, and we engineer a proposal to achieve it.

The paper is organized as follows. In Section 2 we propose a simple North-South Deforestation model that formalizes some important aspects of the problem. Section 3 introduces a class of incentive mechanisms - let us call it REDD* - directly inspired from the compensation mechanism (see Danziger & Schnytzer, 1991, Varian, 1994), and analyses its efficiency, under different assumptions regarding the structure of information possessed by countries. Section 4 addresses the crucial questions of acceptability and equity. Section 5 concludes.

2. A north-south deforestation framework

Consider m countries in the developing South with a high endowment of tropical forests. Deforestation provides land and capital for development. Let $d_i \in \left[0, \bar{d}_i\right[$, be the number of deforested hectares by country i, where $\bar{d}_i$ is its total forest area. Each country has a continuous increasing and concave technology that transforms deforestation into an index of composite economic goods and/or services[1] $s_i\left(d_i\right)$. Also, each country is endowed with an exogenous wealth y^i. Country

[1]There is an economic interest in deforestation that is not limited to timber exploitation. Forest also "compete", for instance, with agriculture and some form of tourism. Here $s_i\left(d_i\right)$ captures all the opportunity costs of preserving forest.

i's preferences are defined over the pairs (d_i, y^i), and represented by an additively separable utility function:

$$\begin{aligned} U^i(d_i, y^i) &= v_i\left(s_i\left(d_i\right)\right) + y^i, \\ &= u_i\left(d_i\right) + y^i,\ i = 1, ..., m. \end{aligned}$$

The functions $u_i\left(.\right) = v_i \circ s_i\left(.\right)$ are increasing and concave, $u_i'' \leq 0 \leq u_i'$. For instance, one could think of $v_i\left(.\right)$ as a linear transformation of the services derived from deforestation, *i.e.* $v_i\left(.\right) = \sigma_i\ s_i\left(.\right)$ where $\sigma_i \geq 0$ is a preference parameter.

As regards deforestation there is a country-specific limit d_i^{bau}, beyond which nature cannot be turned into arable lands within the time-scale captured by our static model; or put differently, for geographical, bio-physical or economic reasons the marginal utility of deforestation is zero beyond those thresholds, $u_i'\left(d_i\right) = 0,\ \forall\ d_i \geq d_i^{bau}$. Therefore, on a non cooperative basis, southern countries push deforestation up to that threshold d_i^{bau}.

The north is a block that will be treated as a single country. It is also endowed with an exogenous annual wealth y^n and it is interested in aggregate tropical deforestation, $D = \sum\limits_i d_i$, because it is linked with carbon emissions. Its preferences are captured by a utility function:

$$U^n(D, y^n) = u_n\left(D\right) + y^n,$$

which is decreasing and concave with respect to the first argument, $u_n' \leq 0,\ u_n'' \leq 0$.

This model is simple, yet it accounts for the asymmetric nature of the deforestation problem: at the business-as-usual, deforestation in the South fails to take into account of the negative externality it generates. Pareto optimal deforestation levels, denoted $(d_1^*, ..., d_m^*)$, on the contrary, would equalize the marginal benefit for the south with the marginal cost for the the North, i.e. they would solve the following system of equations (technical details are given in Appendix A):

$$u_i' = -u_n' \ , \quad i = 1, ..., m. \tag{1}$$

Pareto optimality calls for different (generally lower) deforestation levels, because of their external negative effects. But avoided deforestation represents an opportunity cost for southern countries.

3. A class of compensation mechanisms to curb deforestation

3.1. **The general design.** There is a class of mechanisms, generically referred to as "compensation mechanisms", that rests on the following logic: agents involved in an economic environment with externalities solve the social dilemma by mean of cross-subsidies (in case of positive externalities) or cross-taxes (in case of negative externalities) whose magnitude they decide by themselves. The classic reference is Varian (1994), but crucial predecessors are Guttman (1978, 1985 and 1987) and Danziger and Schnytzer (1991). These mechanisms implement first best allocations as subgame perfect Nash equilibria.

That kind of solution cannot be applied as it stands in our context of transnational negative externalities, because it would involve the developed North taxing the developing South! But a trick can be found to retain the spirit of the mechanism, while turning taxes into subsidies. The description of what we call REDD* is as follows. The North can now decide to subsidize developing countries who are willing to reduce their deforestation through a two-stage mechanism:

(1) In the first stage, the announcement stage, countries choose subvention/tax rates simultaneously. Developing country i chooses a tax rate $t_i^s \in [0, 1]$ and the North chooses a vector of subsidy rates $(t_1^n, ..., t_m^n)$, where $t_i^n \in [0, t_i^s]$ is the subsidy rate offered

to developing country i [2]. Those announced rates are collected and end up in the following formula for transfers: conditionally on the levels of deforestation to be decided at the next stage, the North would pay $T^n = \sum_i T_i^n$, with

$$T_i^n = \begin{cases} t_i^s(d_i^b - d_i) & \text{if } d_i < d_i^b \ , \\ 0 & \text{otherwise,} \end{cases}$$

and each southern country i would receive:

$$S_i = \begin{cases} t_i^n(d_i^b - d_i) - \varepsilon_i(t_i^n - t_i^s)^2 & \text{if } d_i < d_i^b \ , \\ 0 & \text{otherwise.} \end{cases}$$

This stage can be interpreted as a negotiation phase where countries discuss the correct price signal of deforestation. This is a departure from current proposals about REDD, that propose to anchor the value of avoided deforestation on the price that can be observed on the carbon market.

(2) In the choice stage, each southern country i determines its level of deforestation d_i. Transfers are then implemented.

So, under the mechanism, incomes become:

$$y^i = y_0^i + t_i^n(d_i^b - d_i) - \varepsilon_i(t_i^n - t_i^s)^2 \ , \qquad i = 1, ..., m,$$

and:

$$y^n = y_0^n - \sum_i t_i^s(d_i^b - d_i) \ .$$

3.2. **Subgame perfect Nash equilibria.** The model is solved, as usual, by backward induction. In the last decision period, developing countries choose their optimal deforestation level d_i^* which maximizes

[2] As a result, if the North chooses $t_i^n > t_i^s$, tranfers are not implemented.

their utility under the mechanism, knowing t_i^n and t_i^s. The first order condition for an interior optimal deforestation is:

$$\begin{aligned} \frac{\partial U^i}{\partial d_i} &= u_i'(.) - t_i^n = 0. \\ &\Leftrightarrow \; u_i'(.) = t_i^n \; . \qquad (2) \end{aligned}$$

With the assumptions made so far, $u_i'(.)$ can be inverted, so d_i^* is a function of t_i^n, which we can write:

$$d_i^* = d_i^*(t_i^n).$$

Applying the implicit function theorem to (2), we can deduce that the larger the subsidy rate, the lower the deforestation:

$$d_i^{*\prime}(t_i^n) = \frac{1}{u_i''} \leq 0.$$

In the first period, countries choose the tax/subsidy levels. In the South, an interior optimal decision that maximizes U^i implies the following first order condition:

$$\frac{\partial}{\partial t_i^s} U^i = 2\varepsilon_i (t_i^n - t_i^s) = 0. \qquad (3)$$

$$\Leftrightarrow \quad t_i^s = t_i^n \; . \qquad (4)$$

In the North, the first order condition for an interior solution is:

$$\begin{aligned} \frac{\partial}{\partial t_i^n} U^n &= u_n' \frac{\partial d_i^*}{\partial t_i^n} + \frac{\partial y^n}{\partial d_i^*} \frac{\partial d_i^*}{\partial t_i^n} = 0. \\ &\Leftrightarrow \quad u_n' \frac{\partial d_i^*}{\partial t_i^n} + t_i^s \frac{\partial d_i^*}{\partial t_i^n} = 0. \qquad (5) \\ &\Leftrightarrow \quad -u_n' = t_i^s \; . \qquad (6) \end{aligned}$$

Then, from (2), (4) and (6):

$$t_i^s = -u_n' = t_i^n = u_i' \; . \qquad (7)$$

This last equation characterizes all the subgame perfect interior nash equilibria. Since an interior Pareto Optimum requires $-u_n' = u_i'$, one observes from (7) that it can be reached through the mechanism.

However there could be multiple (Pareto optimal) Nash equilibria. In that case, countries would face a coordination problem.

Two important remarks about the originality of this class of mechanisms are in order:

- Under Varian's mechanism, transfers are a linear function of the amount of negative externality produced. Here transfers are a linear function of $(d_i^b - d_i)$. Thereby it rewards the deforestation effort of the South as desired by the international community rather than taxing the net deforestation level.
- Under the REDD+ mechanism, each tropical country willing to reduce its deforestation level below its reference level would receive a transfer $t(d_i^b - d_i)$ with t being the exogenous carbon price on the market. Our mechanism differs because subsidy rates are determined endogenously, so they equal the marginal cost of deforestation for the North.

3.3. **About the information structure.** The solution concept used above to describe non cooperative decisions is indicative of the information structure under which the mechanism is supposed to work: the "regulator", whatever it may be, does not have any information about countries' preferences but countries themselves know a great deal more. They know each other utility function; they know that they know that, and they know that they know that, and so on. In the terminology of game theory, there is complete information and common knowledge.

The assumption of complete information and common knowledge can be justified as an approximation for situations where there exists a sufficient degree of familiarity among countries. One may or may not subscribe to the view that this approximation is relevant for the deforestation problem. But is such an assumption really necessary? Or is it rather a convenience of presentation, a useful simplification?

Would countries play the predicted Nash equilibrium under different, less demanding, information structures?

Empirical studies have found that supermodular (when agents best responses are upward sloping) or near-supermodular games exhibit behavior of subjects that converges to the Nash equilibrium. Supermodularity is a technical property of games that ensures convergence to equilibrium under various learning dynamics, which include Bayesian learning, fictitious play, adaptive learning, and Cournot best reply (see Chen and Gazzale, 2004). This finding raises the important question of whether our class of compensation mechanisms is supermodular in the subsidies?

By inspection of (3), one can deduce:

$$\frac{\partial^2}{\partial t_i^s \partial t_i^n} U^i = 2\varepsilon_i > 0.$$

And from (5):

$$\frac{\partial^2}{\partial t_i^n \partial t_i^s} U^n = 0.$$

So the game is super-modular.

To illustrate, rule out complete information and common knowledge. Imagine that countries do not know each other's preferences; assume they are myopic and, at each announcement stage, they proceed by tatônnement to find t_i^s and t_i^n. This kind of process could correspond to an international repeated negotiation, where, at each period, each and every country i in the South and the North can adjust their subsidy level as follows:

$$\begin{cases} t_{i,t+1}^s = t_{i,t}^n \ , \\ t_{i,t+1}^n = t_{i,t}^n - \gamma \left[U_1^n(D_t, y_t^n) + t_{i,t}^s U_2^n(D_t, y_t^n) \right] \ , \end{cases} \tag{8}$$

with $\gamma > 0$ a parameter.

Along this myopic process, a southern country will match its level of transfer at $t+1$ with the one from the North at t. And the north will adjust its chosen level of transfer, if it sees that there is a marginal gain (respectively loss) from increasing (resp. decreasing) D_t. Then it will decrease (resp. increase) t_i^n proportionally.

Proposition 3.1. *Assume that countries do not know each others' preferences and that each and every country behaves myopically as defined by the above adjustement process (8). Then if the mechanism is repeated over time, it converges asymptotically to a Pareto Optimum.*

Proof. See Appendix B. ■

Asymptotically, we get the same price signal t as before, when countries were supposed to have complete information and common knowledge. Therefore the efficiency of the mechanism does not necessarily disappears when countries do not have all the information on each other's preferences. The proposed class of mechanisms implement the optimum under less restrictive informational conditions than one may think at first sight. This property remains whatever the ε_i and the d_i^b chosen, allowing us to choose baselines which satisfy some fairness properties. Various types of baselines are discussed in the next section.

4. Baselines and equity

An important topic of the international debate about financing avoided deforestation in the South is the definition of the baselines. Several possibilities are under consideration. They could be based only on historical levels of deforestation but this would promote countries that have had "bad" past behavior. They could also take into account countries' development paths so that countries that have not cleared a lot of their forest until now would be favored. For more details on possible baseline definitions see Bush et al (2009). What is more likely to happen is a mix of those two logics.

In addition, there exists an academic literature that addresses the question of equity from a more general perspective and that already gives a substantial and well organized bulk of knowledge (see Fleurbaey

& Maniquet 2011, or Clement et al, 2010, and the references therein). We will first borrow important notions from this literature and then get back to the concerns currently expressed about the design of REDD. Equipped with qualified axioms that seem relevant for the deforestation problem, it is possible to suggest different formulas for baselines. The investigation will keep in mind the asymmetric nature of information. Thus, baselines should be designed without the recourse to pieces of information on preferences not supposed to be publicly available (such as information about utility functions).

4.1. **Individual rationality.** For international issues, cooperation is problematic without a supranational authority if the contemplated solution does not guaranty each country a level of national welfare at least equal to that they enjoyed under the business-as-usual scenario. Pareto optimal allocations that are individually rational prevent such kind of objections and can be viewed not only has an equity criterion but also, on more practical grounds, as a minimal condition for acceptability.

Definition 4.1. *A Pareto optimal allocation* $(d_1^*, ..., d_m^*, y^{1*}, ..., y^{m*}, y^{n*})$ *is individually rational (IR) if:*

$$\begin{aligned} u_i\left(d_i^*\right) + y^{i*} &\geq u_i\left(d_i^{bau}\right) + y_0^i \ , \qquad i = 1, ..., m, \\ u_n\left(\sum\nolimits_i d_i^*\right) + y^{n*} &\geq u_n\left(\sum\nolimits_i d_i^{bau}\right) + y_0^n \ . \end{aligned}$$

Proposition 4.1. *Assume that the sum of baselines is not larger than the sum of business-as-usual levels, i.e.* $\sum_i d_i^b \leq \sum_i d_i^{bau}$*. Then a Pareto optimal allocation implemented as an interior subgame perfect Nash equilibrium via the REDD* mechanism is individually rational.*

Proof. See Appendix C. ■

The above proposition identifies a sufficient condition to impose on baselines in order to ensure individual rationality. It does not necessarily mean that if baselines are larger than the business-as-usual levels, IR is violated. But, clearly, being too lax on baselines has the effect of increasing the volume of transfers, at the risk of transgressing individual rationality of the north.

4.2. **No-envy.** Another criterion for equity is the no-envy test. Simply put, in our context an outcome is envy-free if no country would prefer the deforestation-income bundle of another country[3]. This concept plays an important role in the economic analysis of equity (for seminal contributions, see Tinbergen, 1946, Foley, 1967, Kolm, 1971). It has also often been discussed and criticized on several counts. It is well understood that no-envy is hard to achieve when agents have different and non transferable talents. The ethical relevance of the notion has also been questioned. If envy can be considered a nasty feeling, why should it be used to elaborate a reflexion on equity? Yet, no-envy may be proposed as a guide of justice in so far as it is indicative of social peace and, presumably, stability of the proposed state of affairs. Because of those kind of obejctions and subtleties, many refinements or weakening of the no-envy criterion have been proposed, and we are no exception.

First, because of the asymmetry between developed and developing countries, it makes sense to limit the use of this notion to southern countries. An allocation

$$\left(d_1^*, ..., d_m^*, y^{1*}, ..., y^{m*}, y^{n*}\right)$$

[3]Envy is a social sentiment that is captured in a very particular way in much of the economic literature. We follow that tradition in this paper, but we refer to Kolm (1995) for an insightful review of the issue, and where envy is modelled as a negative consumption externality.

has no-envy (NE) in the South if there exists no pair of developing countries i and j such that:

$$u_i\left(d_j^*\right) + y^{j*} > u_i\left(d_i^*\right) + y^{i*}.$$

The above notion points to an arrangement where no country in the South prefers the situation of another country. It could be criticized in our context, for it does not question the domain over which it is reasonable to use the absence of envy as a guide for equity. Some further limitations of the domain could be contemplated.

So the second weakening we propose is to discard from the domain of justice the exogenous endowment of incomes, y_0^i. Those variables can be so dramatically different from one developing country to another for reasons of size, history, geography... Although the issue of justice along the dimension of incomes could be developed at length, one can admit that redressing a feeling of envy grounded on income inequalities is far beyond the scope of REDD transfers. This seems at best a welcome consequence of those transfers, at worst a requirement not very realistic.

A modified and weaker condition of no-envy would then focus only on deforestation decisions. It would just discard the possibility that:

$$u_i\left(d_j^*\right) + y_0^i + t^*\left(d_j^b - d_j^*\right) > u_i\left(d_i^*\right) + y_0^i + t^*\left(d_i^b - d_i^*\right) \ ,$$

or simply

$$u_i\left(d_j^*\right) + t^*\left(d_j^b - d_j^*\right) > u_i\left(d_i^*\right) + t^*\left(d_i^b - d_i^*\right) \ .$$

A last refinement is in order. Clearly, small countries may not be able to achieve the same level of services derived from deforestation as those enjoyed by larger countries, for two reasons. It might be because their forest endowment is (relatively) too small, or because their technology to transform deforestation into services is (relatively) less efficient[4]. Formally, for a particular level of service $s_j^* = s_j\left(d_j^*\right)$ enjoyed by country j, there might be no admissible value of deforestation in country i that would allow to achieve that level:

$$s_i\left(d_i\right) < s_j^* \ , \quad \forall d_i \in \left[0, \bar{d}_i\right] . \tag{9}$$

Then, how could country i has a claim against a particular allocation that would allow another country j a level of deforestation, and the corresponding services, which are beyond reach for country i? Their respective situations are not commutable, for physical and/or technical reasons.

But in case another country's situation is technically within reach, i.e. $\exists d_i \in \left[0, \bar{d}_i\right]$ such that $s_i\left(d_i\right) = s_j^*$, define the function that measures the number of deforested hectares necessary to produce a given service as

$$d_i = g_i\left(s\right) \ , \quad g_i\left(.\right) \equiv s_i^{-1}\left(.\right) .$$

Finally, on that basis, a modified test for no-envy would rule out the possibility for any two country i and j that:

$$u_i\left(g_i \circ s_j\left(d_j^*\right)\right) + t^*\left(d_j^b - g_i \circ s_j\left(d_j^*\right)\right) > u_i\left(d_i^*\right) + t^*\left(d_j^b - d_i^*\right) \ .$$

Let us define that idea as REDD-restricted-envy.

Definition 4.2. *There is no REDD-restricted-envy (NRRE) in the South if there exists no pair of developing countries i and j such that:*

$$u_i\left(s_i^{-1} \circ s_j\left(d_j^*\right)\right) + t^*\left(d_j^b - s_i^{-1} \circ s_j\left(d_j^*\right)\right) > u_i\left(d_i^*\right) + t^*\left(d_j^b - d_i^*\right) \ .$$

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[4]By way of illustration, in 2005 the forest area of Solomon Islands was 18,770 km^2 (56th rank in the world), to be compared with the 366,020 km^2 (15th in the world) for Argentina, or with the 4,502,770 km^2 (1st rank) of Brazil. Source: FAO Global Forest Ressource Assessment 2005: Progress Towards Sustainable Forest Management (Forestry Paper 147, Rome 2006).

In the particular case where countries have the same technologies and differs only with respect to their endowments of forests, then $s_i^{-1} \circ s_j = 1$ and the above test becomes:

$$u_i\left(d_j^*\right) + t^*\left(d_j^b - d_j^*\right) > u_i\left(d_i^*\right) + t^*\left(d_j^b - d_i^*\right) \ .$$

If forest endowments are too different, so that inequality (9) holds, then the *NRRE* test is somewhat satisfied by default.

Proposition 4.2. *Assume that southern countries are offered the same baselines $d_i^b = d^b, \forall i$. Then, whatever the differences in forest endowments, the REDD* mechanism implements a Pareto optimal allocation and satisfies NRRE.*

Proof. First recall that for countries such that $s_i^{-1} \circ s_j\left(d_j^*\right) \notin \left[0, \bar{d}_i\right]$, then the NRRE test for such countries is satisfied by default. Otherwise, the NRRE test in the South requires that:

$$u_i\left(s_i^{-1} \circ s_j\left(d_j^*\right)\right) + t^*\left(d^b - s_i^{-1} \circ s_j\left(d_j^*\right)\right) \leq u_i\left(d_i^*\right) + t^*\left(d^b - d_i^*\right) \ , \quad \forall i, j.$$

$$\iff \quad u_i\left(s_i^{-1} \circ s_j\left(d_j^*\right)\right) \leq u_i\left(d_i^*\right) + t^*\left(s_i^{-1} \circ s_j\left(d_j^*\right) - d_i^*\right) \ , \quad \forall i, j \ .$$

Now, because $u_i'\left(d_i{}^*\right) = t^*$:

$$u_i\left(s_i^{-1} \circ s_j\left(d_j^*\right)\right) \leq u_i\left(d_i^*\right) + u_i'\left(d_i{}^*\right)\left(s_i^{-1} \circ s_j\left(d_j^*\right) - d_i^*\right),$$

an equality that is verified because the functions $u_i\left(.\right)$ are concave. ■

Results so far indicate that both individual rationality and (some form of) no-envy are compatible. This can be achieved for instance by setting the same baseline d^b to each country and in such a way that their sum is not larger than $\sum_i d_i^{bau}$. For instance $d^b = \overline{d}^{bau} = \frac{\sum_i d_i^{bau}}{m}$ would do the job.

4.3. **Environmental responsibility.** Getting back to propositions

currently discussed at the UN, there is a concern that, based on observed current deforestation behaviors, some countries are more deserving than other and should be rewarded; on the contrary some countries bear more responsibility about the environmental problem, and should be penalized. A possible measure of "environmental responsibility" could be the gap between the total possible deforestation and the BAU deforestation, $\bar{d}_i - d_i^{bau}$, that is, the contribution on a voluntary basis to pristine nature. However such a measure would attribute the same merit to countries with the same gap but with large differences in potential contributions, because some countries have much larger $\bar{d}_i$ than others. This objection is overcome if the responsibility is measured in relative terms, with the ratio:

$$M_i = \frac{\bar{d}_i - d_i^{bau}}{\bar{d}_i}.$$

Let us note $\overline{M}$ the average relative responsibility and define $\Delta M_i = M_i - \overline{M}$. From the point of view of their contributions to the environment, countries can be partitionned into two subsets, those who are deserving ($\Delta M_i > 0$) and those who are not ($\Delta M_i \leq 0$).

Two possible requirements on transfers can be formulated, where each recognizes, in a particular way, the heterogenous role played so far by countries on the deforestation problem.

Definition 4.3. *Let d be a reference vector of deforestation levels. A transfer scheme satisfies "d - Environmental Responsibility" (d-ER) if the baselines offered to "deserving" countries are at least equal to their deforestation level d_i indicated in d, whereas the baselines offered to "undeserving" countries are at most equal to d_i.*

Definition 4.4. *A transfer scheme satisfies "Incremental - Environmental Responsibility" (I-ER) if the baseline to country i is an increasing function of its departure from average relative environmental responsibility , ΔM_i.*

Note that I-ER could admit a more demanding form, by imposing that the baseline offered to country i be a strictly increasing - instead of simply increasing - function of ΔM_i.

It is easy to imagine baselines that comply both with d-ER and I-ER, and other requirements as well. Here is an example:

$$d_i^{b0} = \alpha \Delta M_i \sum_{h=1}^{m} \left(\bar{d}_h - d_h^{bau} \right) + d_i^{bau} \ , \qquad \alpha \in [0, 1]. \tag{10}$$

Proposition 4.3. *The REDD* mechanism where baselines are given by (10) satisfies PO, IR, d^{bau}-ER and I-ER.*

Proof. By construction, if the baselines d_i^{b0} are chosen, the mechanism recognizes *d-ER* and *I-ER*. Besides we already know that the mechanism implements Pareto optimal allocations. Finally, if $d_i^b = d_i^{b0}$, we have:

$$\begin{aligned} \sum_i d_i^{b0} &= \alpha \left[\sum_h \left(\bar{d}_h - d_h^{bau} \right) \right] \sum_i \Delta M_i + \sum_i d_i^{bau} \\ &= \sum_i d_i^{bau}. \end{aligned}$$

From that last equality, and by Proposition 4.1, the mechanism is individually rational. ■

4.4. **The NRRE-ER tension.** If baselines comply with *d-ER* they generally propose a differential treatment to different countries, as in the example given by (10). On the other hand, offering identical baselines to all countries can avoid restricted-envy. Notice however that identical baselines are sufficient but not necessary to rule out REDD-restricted-envy. In general, no envy is closely related, thought not identical, to equality. By and large, intuition suggests there is a difficulty to combine *NRRE* and *d-ER,* but could this tension be ascertained? At least, this can indeed be proven when the reference deforestation vector d is given by the BAU.

Theorem 4.5. *Any transfer scheme that satisfies d-ER where d is fixed at the BAU, $d = d^{bau}$, does not respect no-REED-restricted-envy requirement (NRRE) when countries are sufficiently heterogenous.*

Proof. Appendix D. ■

The transfer scheme REDD* (10) satisfies $d^{bau} - ER$ and, therefore, may violate *NRRE.* Since a compromise is to be found, one possibility is to insert non-welfarist requirements.

First let us define the mapping

$$\begin{aligned} [.]_- \quad &: \quad [-1,1] \to [-1,0]\,, \\ x \quad &\longmapsto \begin{cases} x & \text{if } x < 0 \\ 0 & \text{otherwise.} \end{cases} \end{aligned}$$

We are now in position to suggest two other formulas for baselines. The first possibility is:

$$d_i^{b1} = \alpha_i \left[\Delta M_i\right]_- * \sum_{h=1}^{m} \left(\bar{d}_h - d_h^{bau}\right) + d_i^{bau}\ , \qquad \alpha_i \in [0,1]. \tag{11}$$

Proposition 4.4. *The mechanism REDD* where baselines are given by (11) satisfies PO, IR, d^{bau}-ER and I-ER.*

Proof. By construction, it is straightforward that PO, d-ER and I-ER are satisfied. As for IR, note that, by construction too, $d_i^{b2} \leq d_i^{bau}$. Hence:

$$\sum_i d_i^{b1} \leq \sum_i d_i^{bau}.$$

Therefore, by proposition 2 the mechanism is individually rational ■

In the second possibility, baselines are constructed as follows:

$$d_i^{b2} = \alpha_i \left[\Delta M_i\right]_- * \sum_{h=1}^{m} \left(\bar{d}_h - d_h^{bau}\right) + \overline{d}^{bau} , \quad \alpha_i \in [0,1]. \tag{12}$$

Proposition 4.5. *The mechanism REDD* where baselines are given by (12) satisfies PO, IR, $\overline{d}^{bau}$-ER and I-ER. Besides, there exists a vector of weights $(\alpha_1, ..., \alpha_m)$ in the expression of baselines that guarantees NRRE (no-REDD-restricted envy in the South).*

Proof. The proof rests on a simple continuity argument. When $(\alpha_1, ..., \alpha_m) = (0, ..., 0)$ each country's baseline is equal to the average BAU and there cannot be envy in this case (remember Proposition 4.2). When $(\alpha_1, ..., \alpha_m) \neq (0, ..., 0)$, the baselines satisfy $\overline{d}^{bau}$-ER, and in this case they can violate NRRE (Theorem 4.5). Hence, there exists a particular value of α in the neighborhood of $(0, ..., 0)$ such that envy is ruled out. ∎

5. Summary

This article proposes a class of incentive mechanisms, called REDD*, to curb deforestation efficiently in tropical countries. It is derived from the Compensation Mechanism (Varian, 1994) and adapted to the context of international negative externalities where no tax can be imposed on the "polluter". In summary, the proposed mechanism allows us to choose some combinations of fairness properties, like individual rationality (IR), a form of no-envy (NRRE), an environmental responsibility (d-ER and I-ER), without losing Pareto optimality. A first interesting remark is that IR, d-ER and I-ER can be compatible. There is no unavoidable and extreme trade-off between acceptability and environmental responsibility. Ultimately, such an arrangement could allay the fears of those who, perhaps rightly, warn that setting baselines equal to the business-as-usual produces perverse incentives overtime: "If I deforest more today, tomorrow my payments will automatically be greater".

But as soon as baselines also depend on the environmental responsibility, such a calculation is no longer necessarily true. Less deforestation today will produce, ceteris paribus, a premium for tomorrow and may trigger a virtuous circle.

A tension exists however between envy freeness and environmental responsibility. The first requirement tends to favor equal baselines for all, whereas the second requirement calls for different baselines. Future research could further explore the reasonable compromise between these two requirements.

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Appendix

Appendix A. Pareto optimal allocations

Pareto optimal allocations can be found as a solution to the program:

$$\max_{\{d_i\}_{i=1}^m,\{y^i\}_{i=1}^m,y^n} u_n\left(\sum_i d_i\right)+y^n$$

$$\text{s.t.}\ \begin{cases} u_i\left(d_i\right)+y^i\geq\bar{U}^i\ , & i=1,...,m,\\ y^n+\sum_i y^i=\Omega\ . & \end{cases}$$

The Lagrangian for this problem is:

$$\mathcal{L}=u_n\left(\sum_i d_i\right)+y^n+\sum_{i=1}^m\sigma_i\left[u_i\left(d_i\right)+y^i-\bar{U}^i\right]+\lambda\left(y^n+\sum_i y^i-\Omega\right)$$

The necessary conditions for optimality read as:

$$\frac{\partial\mathcal{L}}{\partial\ d_i}=u_n'+\sigma_i u_i'=0\ ,\qquad i=1,...,m, \tag{13}$$

$$\frac{\partial\mathcal{L}}{\partial\ y^i}=\sigma_i\ +\lambda\leq 0,\qquad i=1,...,m, \tag{14}$$

$$\frac{\partial\mathcal{L}}{\partial\ \sigma_i}=u_i\left(d_i\right)+y^i-\bar{U}^i=0\ ,\qquad i=1,...,m, \tag{15}$$

$$\frac{\partial\mathcal{L}}{\partial\ \lambda}=y^n+\sum_i y^i-\Omega=0\ , \tag{16}$$

$$\frac{\partial\mathcal{L}}{\partial\ y^n}=1+\lambda\leq 0. \tag{17}$$

$$\sigma_i\left[u_i\left(d_i\right)+y^i-\bar{U}^i\right]=0\ ,\qquad i=1,...,m. \tag{18}$$

In the sequel we focus on Pareto optimal allocations that involve strictly positive values for $y^i, i = 1, ..., m$ and y^n. Hence, conditions (14) and (17) must be satisfied as equalities. Then, from (14) and (17):

$$\sigma_i \ = 1, \qquad i = 1, ..., m.$$

Using this information in (13), one can deduce:

$$u_i' = -u_n' \ ,$$

as indicated in the text by expression (1).

Appendix B. A myopic adjustment process

System (8) can be written as a matrix equation:

$$\begin{bmatrix} t^s_{i,t+1} \\ t^n_{i,t+1} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\gamma U_2^n & 1 \end{bmatrix} \begin{bmatrix} t^s_{i,t} \\ t^n_{i,t} \end{bmatrix} + \begin{bmatrix} 0 \\ -\gamma U_1^n \end{bmatrix} \tag{19}$$

To simplify notations, define:

$$\begin{aligned} t_{i,t+1} \ &= \begin{bmatrix} t^s_{i,t+1} \\ ti,^n_{t+1} \end{bmatrix}, \ A = \begin{bmatrix} 0 & 1 \\ -\gamma U_2^n & 1 \end{bmatrix} \ , \\ t_{i,t} \ &= \begin{bmatrix} t^s_{i,t} \\ t^n_{i,t} \end{bmatrix} \ , \text{ and } b = \begin{bmatrix} 0 \\ -\gamma U_1^n \end{bmatrix}. \end{aligned}$$

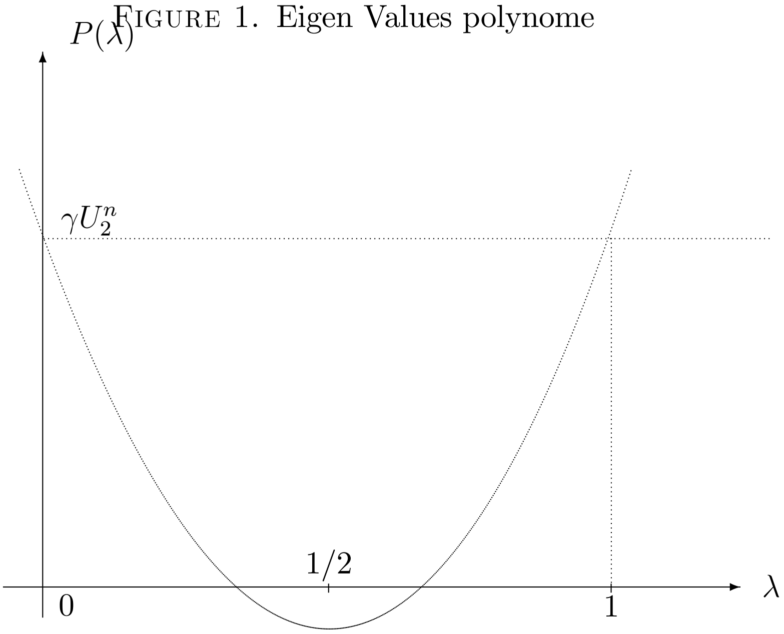
Then (19) becomes:

$$t_{i,t+1} = At_{i,t} + b \tag{20}$$

As one can check, if the optimum is reached at t, at $t + 1$ we will have $t^n_{i,t+1} = t^n_{i,t}$. Therefore Pareto Optima are stationary states of the dynamics. We can infer the stability of the stationary states by studying the transition matrix A.

The eigenvalues of matrix A, λ_1 and λ_2, solve $P(\lambda) = \lambda - \lambda^2 + \gamma U_2^n = 0$. If $\gamma < \frac{U_2^n}{4}$, the shape of P is presented in figure 1.

Figure 1. Eigen Values polynome



So $(\lambda_1, \lambda_2) \in]-1, 1[^2$ and consequently the repeated mechanism is converging to a stationary state which is the optimum. We have: $t_i^s = t_i^n = t_j^n = t$, where:

$$\begin{aligned} t &= t - \gamma(U_1^n + tU_2^n) \\ &= \frac{-U_1^n}{U_2^n} \end{aligned} \tag{21}$$

Appendix C. Individual rationality

We already know that Pareto optimality obtains under the REDD* mechanism. But individual rationality must be ascertained.

For southern countries, note that after the mechanism is introduced, each could unilaterally secure the level of utility it enjoyed under the business-as-usual scenario. It suffices to set $t_i^s = 0$. Then, because $t_i^n \in [0, t_i^s]$, necessarily $t_i^n = 0$ and $d_i^* (t_i^n) = d_i^* (0) = d_i^{bau}$ while $y^{i*} = y_0^i$. If countries unilaterally settle for equilibrium tax rates that are not zero, $t_i^{s*} \neq 0$, then it must be the case that $u_i (d_i^*) + y^{i*} \geq u_i \left(d_i^{bau}\right) + y_0^i$, $i = 1, ..., m$. Note that this inequality does not depend on the profile of baselines $(d_1^b, ..., d_m^b)$.

As for the North, because $u_n (.)$ is concave

$$u_n \left(D^b\right) \leq u_n (D^*) + u_n' (D^*) \left(D^b - D^*\right).$$

But, since at a Pareto optimal allocation $u_n' (D^*) = -t_i^s = -t_i^n = -t^*$, the above inequality reads as:

$$u_n \left(D^b\right) \leq u_n (D^*) - t^* \sum\nolimits_i \left(d_i^b - d_i^*\right).$$

When the baselines are set at the business-as-usual levels, this inequality can be re-written:

$$t^* \sum\nolimits_i \left(d_i^{bau} - d_i^*\right) \leq u_n (D^*) - u_n \left(D^{bau}\right) = WTP. \tag{22}$$

It means that, at the implemented allocation, what the north is required to pay (the left hand-side) is less than what it would accept to pay (the right hand-side) to move to the optimum, so individual rationality obtains. Would the same inequality prevail with different baselines?

When $D^b < D^{bau}$, from (22) we can deduce:

$$t^* \sum\nolimits_i \left(d_i^b - d_i^*\right) < t^* \sum\nolimits_i \left(d_i^{bau} - d_i^*\right) \leq u_n (D^*) - u_n \left(D^{bau}\right),$$

and individual rationality obtains again.

When $D^b > D^{bau}$:

$$t^* \sum_i \left(d_i^b - d_i^*\right) > t^* \sum_i \left(d_i^{bau} - d_i^*\right),$$

and it is no longer guaranteed that the WTP exceeds the transfer.

Appendix D. Tension between $\overline{d}^{bau}$-ER and NRRE

NRRE requires

$$u_i\left(s_i^{-1} \circ s_j\left(d_j^*\right)\right) + t^*\left(d_j^b - s_i^{-1} \circ s_j\left(d_j^*\right)\right) \leq u_i\left(d_i^*\right) + t^*\left(d_i^b - d_i^*\right) \ , \quad \forall i, j.$$

Rewrite this as:

$$\begin{aligned} u_i\left(s_i^{-1} \circ s_j\left(d_j^*\right)\right) &\leq u_i\left(d_i^*\right) + t^*\left(s_i^{-1} \circ s_j\left(d_j^*\right) - d_i^*\right) + t^*\left(d_i^b - d_j^b\right) \ , \quad \forall i, j. \\ u_i\left(s_i^{-1} \circ s_j\left(d_j^*\right)\right) &\leq u_i\left(d_i^*\right) + u_i'\left(d_i{}^*\right)\left(s_i^{-1} \circ s_j\left(d_j^*\right) - d_i^*\right) \qquad (23) \\ &\quad + u_i'\left(d_i{}^*\right)\left(d_i^b - d_j^b\right) \ , \quad \forall i, j. \qquad (24) \end{aligned}$$

We know that, because of concavity it is true that:

$$u_i\left(s_i^{-1} \circ s_j\left(d_j^*\right)\right) \leq u_i\left(d_i^*\right) + u_i'\left(d_i{}^*\right)\left(s_i^{-1} \circ s_j\left(d_j^*\right) - d_i^*\right),$$

But the last term of the inequality (23) is necessarily negative for some countries and may compromise the test for no-envy. Assume, without loss of generality, that country j is "deserving" ($\Delta M_j > 0$) whereas country i is not ($\Delta M_i < 0$). Then, if the baselines are chosen so as to meet d^{bau}-ER:

$$d_j^b \geq d_j^{bau} \text{ and } d_i^b \leq d_i^{bau}.$$

Assume also that $d_i^{bau} < d_j^{bau}$. So far, we can write:

$$\left|d_i^b - d_j^b\right| \geq \left|d_i^{bau} - d_j^{bau}\right| \ ,$$

and

$$\begin{aligned} & u_i\left(d_i^*\right) + u_i'\left(d_i{}^*\right)\left(s_i^{-1} \circ s_j\left(d_j^*\right) - d_i^*\right) + u_i'\left(d_i{}^*\right)\left(d_i^b - d_j^b\right) \\ \leq \ & u_i\left(d_i^*\right) + u_i'\left(d_i{}^*\right)\left(s_i^{-1} \circ s_j\left(d_j^*\right) - d_i^*\right) + u_i'\left(d_i{}^*\right)\left(d_i^{bau} - d_j^{bau}\right). \end{aligned}$$

Now because the values d_i^{bau} and d_j^{bau} are deduced from the utility functions, they can be set arbitrarily so that:

$$u_i\left(d_i^*\right)+u_i'\left(d_i{}^*\right)\left(s_i^{-1}\circ s_j\left(d_j^*\right)-d_i^*\right)+u_i'\left(d_i{}^*\right)\left(d_i^{bau}-d_j^{bau}\right)<u_i\left(s_i^{-1}\circ s_j\left(d_j^*\right)\right)\ ,$$

an inequality that implies

$$u_i\left(d_i^*\right)+u_i'\left(d_i{}^*\right)\left(s_i^{-1}\circ s_j\left(d_j^*\right)-d_i^*\right)+u_i'\left(d_i{}^*\right)\left(d_i^b-d_j^b\right)<u_i\left(s_i^{-1}\circ s_j\left(d_j^*\right)\right)\ ,$$

in violation of No-Envy.

To illustrate, consider an economy with only two countries $i=1,2$ in the South. Let their utility functions be:

$$U^i(d_i,y^i)=u_i\left(d_i\right)+y^i,\qquad i=1,2,$$

where:

$$u_i\left(d_i\right)=m_id_i-\frac{n}{2}\left(d_i\right)^2\ ,\qquad m_i,n>0,$$

And assume that the North's utility function is:

$$U^N(d_1+d_2,y^N)=k_N*\Big[m\left(d_1+d_2\right)-\frac{n}{2}\left(d_1+d_2\right)^2\Big]+y^N\ ,\quad m<0,\ k_N<1/2.$$

Levels of deforestation, at the business-as-usual scenario, are:

$$d_i^{bau}=\frac{m_i}{n}, \tag{25}$$

and thus:

$$d_i^{bau}-d_j^{bau}=\frac{m_i-m_j}{n} \tag{26}$$

Besides, Pareto optimal level are:

$$d_i^*=\frac{k_N*m+k_N*\left[m_i-m_j\right]-m_i}{n\left(2k_N-1\right)}\ , \tag{27}$$

from which we can deduce:

$$d_j^*-d_i^*=\frac{m_j-m_i}{n} \tag{28}$$

Assume that $m_j>m_i$. It is easy to check that this inequality implies $d_j^{bau}>d_i^{bau}$. Assume also that country j is deserving (say that it has a very large $\bar{d}_j$) and that country i is not.

Remember that no-restricted envy requires

$$u_i\left(d_j^*\right) \leq u_i\left(d_i^*\right) + u_i'\left(d_i{}^*\right)\left(d_j^* - d_i^*\right) + u_i'\left(d_i{}^*\right)\left(d_i^b - d_j^b\right) \leq \tag{29}$$

$$u_i\left(d_i^*\right) + u_i'\left(d_i{}^*\right)\left(d_j^* - d_i^*\right) + u_i'\left(d_i{}^*\right)\left(d_i^{bau} - d_j^{bau}\right). \tag{30}$$

Or, using (26) and (28):

$$u_i\left(d_j^*\right) \leq u_i\left(d_i^*\right) + u_i'\left(d_i{}^*\right)\left(\frac{m_j - m_i}{n}\right) + u_i'\left(d_i{}^*\right)\left(\frac{m_i - m_j}{n}\right) ,$$

an inequality that boils down to:

$$u_i\left(d_j^*\right) \leq u_i\left(d_i^*\right)$$

When, as assume above, $m_j > m_i$, it is easy to check that $d_j^* > d_i^*$ and, therefore, $u_i\left(d_j^*\right) > u_i\left(d_i^*\right)$, a contradiction to the no-envy test.