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Reducing emissions from deforestation—The ''combined incentives'' mechanism and empirical simulations

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ABSTRACT

Despite accounting for 17–25% of anthropogenic emissions, deforestation was not included in the Kyoto Protocol. The UN Convention on Climate Change is considering its inclusion in future agreements and asked its scientific board to study methodological and scientific issues related to positive incentives to reduce emissions from deforestation. Here we present an empirically derived mechanism that offers a mix of incentives to developing countries to reduce emissions from deforestation, conserve and possibly enhance their ecosystem's carbon stocks. We also use recent data to model its effects on the 20 most forested developing countries. Results show that at low CO_2 prices (~US$ 8/t CO_2) a successful mechanism could reduce more than 90% of global deforestation at an annual cost of US$ 30 billion.

1. Introduction

Our species has converted 27% of Earth's terrestrial surface (MEA, 2005) into agriculture, ranching or urban areas and we currently appropriate 24–50% of Earth's terrestrial Net Primary Productivity (Vitousek et al., 1997; Rojstaczer et al., 2001; Haberl et al., 2007). This conversion process, historically concentrated in the North, is now occurring with great rapidity in the most biodiverse and carbon rich ecosystems on the planet, the tropical forests (MEA, 2005). Home to 50–66% of Earth's species (Wilson, 1999; The Royal Society, 2003), these forests are being converted at a rate of between 6 and 12 million hectares per year (Achard et al., 2002; DeFries et al., 2002; FAO, 2006). The resulting 1–2 GtC/ emitted per year amount to 17–25% of anthropogenic GHG emissions (Baumert et al., 2005; Houghton, 2005; Nabuurs et al., 2007). Recent research suggest that the role these forests play in regulating global climate might be bigger than previously thought (Stephens et al., 2007) and will likely become even more important as alternative sinks become saturated (Le Quéré et al., 2007) while forests can continue to act as sinks throughout a century of climate-change (Gullison et al., 2007).

The financial rationale for deforestation in developing countries is clear, the alternative uses for land and timber provide higher short term financial returns than standing forests (MEA, 2005; Balmford et al., 2002; Turner et al., 2003). However, this is unlikely to be true in economic efficiency terms when global benefits, such as carbon storage, climate regulation and biodiversity are included in land use decision (Balmford et al., 2002; Turner et al., 2003; Kremen et al., 2000). This points to a failure of economic and institutional systems, related to the ''scale mismatch'' (Carpenter et al., 2006) between natural and human systems. Recent studies show that compensating developing countries for even a small portion of the global benefits their forests provide might be sufficient to greatly reduce deforestation (Stern, 2007).

For political and methodological reasons deforestation was the only major emissions source left out of the Kyoto Protocol. Therefore reductions in emissions from deforestation are not eligible for carbon credits, despite their potential to be one of the most cost effective ways of tackling climate change (Stern, 2007). After 2 years of scientific and methodological discussions, the Parties to the UNFCCC have recently affirmed the ''urgent need to reduce emissions from deforestation'', noted that it ''requires stable and predictable availability of resources'' and requested its scientific body to undertake a programme of work on methodological issues related to a range of policies approaches and positive incentives aimed at reducing emissions from deforestation (UNFCCC, 2007c).

Here we offer two contributions to this debate, based on the ongoing political and academic discussions and on analyses enabled by recently available data. First we present a compensation mechanism to provide combined incentives to developing

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countries to reduce emissions from land-use change, to conserve and possibly enhance their ecosystem's carbon stock. We then use recent data to simulate the operation of the mechanism in the top 20 developing countries by forest cover, predict the reductions in emissions for different levels of incentives, test its adaptability and compare it with other candidate mechanisms. Finally, we produce empirically estimated global cost curves of avoiding deforestation. Our simulations suggest that this mechanism would be comprehensive and flexible enough as to induce both the reduction in deforestation rates and the maintenance of forest cover over time in countries in all stages of the deforestation process.[1] Our analysis also strongly supports the idea that reducing emissions from deforestation can provide one of the most costs effective ways of combating global warming.[2]

2. Mechanism background

In the eleventh Conference of the Parties (COP 11) in December 2005 it was decided that the scientific board of the UNFCCC should examine the issue of positive incentives to reduce emissions from deforestation in developing countries (UNFCCC, 2005). A group of scientists proposed the concept of "compensated reductions" (Santilli et al., 2005). Shortly thereafter Brazil made a similar proposal that became the first official proposal for a REDD mechanism (UNFCCC, 2006). The proposed mechanism would offer incentives to countries to reduce their deforestation in comparison to a national reference level calculated from their deforestation rate in a recent snapshot of time (1990s, or early 2000s). The general formula for a historical national reference level mechanism would be

$$I_t = (\mathrm{HE} - E_t) \times P$$

where I_t is the country incentive in year t; HE is the historical annual emissions from deforestation; E_t is the emissions from deforestation in year t; and P is the incentive payment per avoided t of CO_2.

This mechanism would operate at the national level and links compensation to a country's success in reducing recent deforestation rates. Its pioneering nature set the basis for all REDD discussions, but it was soon pointed out (UNFCCC, 2007a) that targeting only a subset of countries (those countries with positive deforestation rates in the recent past) and connecting the incentive only to the annual deforested area (with no relation to total forest area) would compromise the effectiveness of the mechanism.

Attempts to address tropical deforestation in the past have systematically failed due to the "leakage" effect, i.e. a reduction of deforestation in a target area being compensated for an increase in other areas (Nabuurs et al., 2007; Santilli et al., 2005; UNFCCC, 2006, 2007a; Strassburg et al., 2007). The rapid and extensive growth in deforestation in South-east Asia after the 1998 logging ban in China (Lang and Chan, 2006) shows that deforestation also leaks across non-contiguous borders. This is hardly surprising given that the main driving force of deforestation, the expansion of croplands, responds to movements in one of the quintessential global markets.

A mechanism operating at the national level would solve the leakage within each country, a major drawback of project-based approaches (Nabuurs et al., 2007; UNFCCC, 2007b; Strassburg et al., 2007; Mollicone et al., 2007) and a major reason why these were not included in the Kyoto Protocol. But the threat of international leakage would remain.

This threat is particularly serious if an incentive mechanism that rewards only a subset of forested developing countries is put in place. An important challenge any REDD mechanism has to address is that it needs to include countries in several stages of the conversion process. Deforestation is a multicausal issue (Geist and Lambin, 2002) that has a complex relationship with development (Ewers, 2006) and varies greatly both across countries and time (FAO, 2006). Countries that are currently conserving their ecosystems for some particular reason might increase their conversion rates in the near future. That this threat would be exacerbated by distorted incentives has been pointed out by many countries (UNFCCC, 2007b).

Some developing countries responded to this proposal by suggesting that additional provisions should offer incentives to developing countries that have been conserving their ecosystems in the recent past (UNFCCC, 2006, 2007a).

A group of experts (Terrestrial Carbon Group, 2008) has suggested a mechanism that assumes that all carbon in legally, physically and economically accessible areas in the developing world would be emitted within the next 50 years. Each country would calculate its total accessible carbon and a reference level would then be constructed assuming that all the accessible carbon would be emitted at a constant rate over the next 50 years.

The more direct connection with the existing forest area (instead of past annual deforested area) is certainly more in line with the notion that there are global market forces driving deforestation and hence the need for a comprehensive global mechanism that increases the value of all standing forests without leaving a group of countries out.

An important issue related to the idea of connecting the incentives paid to the remaining forest area is the concept of "additionality", a cornerstone of the climate regime. It basically states that incentives should only be offered to avoid emissions that would happen in their absence. It has been argued that simply offering incentives to all forests in all developing countries would be a violation of this principle.

One straightforward answer to this issue would be the concept of "expected emissions" (Strassburg et al., 2007). It suggests that the fraction of its forest carbon stock that a developing country is expected to emit per year equals the fraction of all forest carbon stock in developing countries emitted per year. For instance, if the annual global emissions from deforestation rate is expected to be 0.5% of ecosystem carbon stocks in developing countries, each country would be expected to emit 0.5% of its ecosystem carbon stock per year. In addition to directly connecting incentives to the ecosystems area, this approach would make the sum of all national reference levels equal to the global reference level and any reduction below it would be additional at the global level.

These approaches that connect the incentives paid to the forest area and carbon stock, however, may suffer from an important drawback. A proposal giving all developing countries similar incentives proportionate to its forests area might work well in the long-term. But if a REDD mechanism is to work in the short term, it must also be aligned to the short-term realities of the deforestation process. And this reality is that for a multitude of reasons some countries currently have more incentives to deforest in the short term than others.

A group of scientists from the Joint Research Center (JRC) of the EC (Mollicone et al., 2007) suggested an approach where countries

[1] The recent Review on Forests and Climate Change commissioned by the UK Prime Minister (Eliasch, 2008) adopts the Combined Incentives mechanism as the example of a combined baseline and concludes that "a baseline with a flexible combination of historical rates and incentives for afforesting and low-deforesting countries is therefore the most equitable and effective type of baseline for a scheme of incentives to reduce emissions from deforestation".

[2] Throughout this article we are referring to a possible international scheme to incentivize climate change mitigation activities in natural landscapes in developing countries. This includes the reduction of emissions from deforestation, degradation, the conservation and enhancement of carbon stocks in ecosystems. On the remainder of this article the term "REDD" refers to this possible scheme, the term "deforestation" includes degradation and, as the term "forests", might also include other ecosystem types.

would be divided in two groups. High deforesting countries (deforestation rates higher than a half or a third of global average) would receive their compensation based on historical emissions and low deforesting countries would be tied to the threshold rate (half or a third of global average) as an assumed reference level.

This approach could potentially offer high deforesting countries enough incentives to induce a reduction in their deforestation rates while also offering low deforesting countries some incentive to avoid leakage in the short term. On the other hand, its short-term political feasibility and long-term sustainability might be jeopardized by some of its intrinsic characteristics. First, it connects the incentives one country would receive to the performance of all other developing countries. As shown in Strassburg et al. (2007) and in Section 3.2 of this article, this option would solve the leakage issue at all levels and might be a desirable feature in the medium to long-term. But it would limit the attractiveness of the mechanism in the short term due to very high uncertainty over the readiness of most developing countries to actually reduce their deforestation rates. Second, it uses the deforestation rates of the recent past to permanently classify countries into high or low deforesting countries in a way that introduces a permanent bias towards the first group in terms of the amount of incentives received (see Table 4).

3. Our mechanism

Recent research has allowed us to use real world data to simulate the functioning of a REDD mechanism and predict the response of individual countries to it. Through these simulations we were able to analyze the strengths and weakness of the mechanisms proposed so far, which in turn led to the development of the mechanism we present here. We believe it addresses the main issues related to REDD, fits pragmatically into the international political framework and its design ensures maximum buy-in by the participant countries. It has benefited considerably from the feedback received from two side-events dedicated to it at the meetings of the scientific board of the UNFCCC (Strassburg et al., 2007; Strassburg, 2008).

3.1. The combined incentives mechanism

In line with the majority of REDD proposals so far, the core mechanism would operate at the national level. A pure project level REDD mechanism would be extremely vulnerable to subnational leakage. In addition, the most important underlying causes of deforestation (Geist and Lambin, 2002) are either decided or heavily influenced by national governments (e.g. through interventions such as infrastructure expansion, property and use rights, tax and fiscal incentives) and are part of the long-term development strategies of each country. A REDD mechanism should seek to influence these and so the promise of sustained and predictable incentives is essential, as has been recently stated by many countries (UNFCCC, 2007b). National level REDD mechanisms are still subject to international leakage. By aiming to be comprehensive and offering incentives capable of inducing the conservation of standing forests in developing countries in every stage of the conversion process, this mechanism seeks to minimize this risk. Nonetheless, a perfect solution for the leakage issue would only be possible by connecting the incentives paid by the international community to the performance of all tropical countries as a group (Strassburg et al., 2007). An alternative global level mechanism is discussed in Section 3.2 and might be an improved alternative over the medium to long terms. However, due to the short-term uncertainties referred to before, the standard version of the mechanism presented here would operate at the national level.

The mechanism was designed to be (i) comprehensive, by including countries in all stages of the conversion process (i.e. high, low or negative past or projected deforestation rates); (ii) flexible, being capable of offering (or not) incentives to reduce deforestation and degradation and stimulate forest conservation, reforestation and afforestation activities; and (iii) adjustable, both across countries and time.

The mechanism can accommodate any source of funding. The possible alternatives (UNFCCC, 2007b) can be classified as (i) market oriented, where demand for credits is created (e.g. by expanding Annex 1 countries emission reduction targets) and these can be traded; (ii) fund-oriented, where financing countries provide the resources by taxing specific commodities or income; and (iii) a mix of both. In all these options the financing will be transformed into incentives per avoided tonne of CO_2. Our mechanism is based on this last incentive and therefore works with all these options.

It is important to note that even if the national level seems to be the most operational for a REDD mechanism, incentives also need to reach local drivers of deforestation and agents capable of implementing conservation activities on the ground. These include local governments, indigenous groups and local communities and private companies that practice sustainable management. Due to very diverse national circumstances and to sovereignty issues it is unlikely that a REDD mechanism will address the intra-national distribution of the incentives. However it has to be open and adaptable enough to cope with these diverse circumstances.

In the combined incentives mechanism each country receives two kinds of incentives simultaneously. The first is based on the "compensated reduction" concept and is an incentive to reduce its emissions in comparison with its historical emissions:

$$I1 = (\mathrm{HE} - E_t) \times P$$

The second follows the "expected emissions" concept that connects the incentive to the ecosystems carbon stock while maintaining global additionality. It is an incentive to emit less than it would emit if it followed an average behavior given by the global baseline emission rate[3]:

$$I2 = (\mathrm{EE} - E_t) \times P$$

All countries receive both incentives at the same time. The key point is the way in which these incentives are combined. By making the weight of each incentive variable, the mechanism is able to be comprehensive enough to include all countries in a single simple formula and flexible enough to combine short-term realities with long-term sustainable goals. It does so by introducing a weighting factor, α, in the sum of both incentives. So the "combined incentives" mechanism formula is

$$\mathrm{CI} = \alpha(I1) + (1 - \alpha)(I2)$$

or

$$CI = [\alpha(\mathrm{HE}) + (1 - \alpha)(\mathrm{EE}) - E_t] \times P \quad (1)$$

With α varying between 0 and 1, where HE = country past emissions; EE_i = country expected emissions; E_{it} = country emissions in year t; and P = base incentive per avoided tonne of CO_2.

Table 1 uses real world data to show the effect that different weights have on the combined baseline for the top 20 countries by forest area in the developing world. Table 4 presents the modelling results for the expected mechanism's effects for a base incentive equal to the average CO_2 market price of the EU Emissions Trading Scheme, US$ 5.63 per tonne (IETA, 2006).

[3] The global baseline emissions rate is the fraction of forest carbon stocks in developing countries emitted per year. For our 20 countries their average emissions rate (0.47%) is very close to their average deforestation rate (0.48%). The difference is due to differences in carbon content per hectare between countries.

Table 1
Combined reference levels for the top 20 developing countries by forest area.

Country	Carbon stock (Mt C)	Historical emissions (Mt C/year)	Expected emissions (Mt C/year)	Combined reference levels (Mt C/year)				
				α = 1	α = 0.9	α = 0.75	α = 0.5	α = 0
Brazil	58,794	323	274	323	318	311	299	274
DR Congo	22,378	67	104	67	71	76	86	104
China	12,214	0	57	0	6	14	28	57
Colombia	8,906	9	42	9	12	17	25	42
Indonesia	8,800	163	41	163	151	132	102	41
Peru	8,763	9	41	9	12	17	25	41
Venezuela	7,776	47	36	47	46	44	41	36
Mexico	6,976	31	33	31	32	32	32	33
Bolivia	6,372	29	30	29	29	29	29	30
Angola	4,838	10	23	10	11	13	16	23
Papua New Guinea	4,785	24	22	24	24	24	23	22
India	4,420	0	21	0	2	5	10	21
Congo	4,070	4	19	4	6	8	12	19
Gabon	3,784	4	18	4	5	7	11	18
Myanmar	3,136	42	15	42	40	35	28	15
Central African Republic	3,105	3	14	3	4	6	9	14
Argentina	2,376	10	11	10	10	10	10	11
Sudan	2,244	18	10	18	17	16	14	10
Tanzania	2,240	24	10	24	22	20	17	10
Zambia	1,134	11	5	11	10	9	8	5
Total	177,111	826	826	826	826	826	826	826

Illustrates the effect that different alphas have on the combined reference levels. The extreme value of $\alpha = 1$ makes the reference level purely based on historical emissions. As the value of α is reduced, the reference level is increasingly also influenced by the forest carbon stock in each country. The other extreme value of $\alpha = 0$ makes the reference level purely based on the forest carbon stock of each country. An important feature that guarantees perfect global additionality is that when α is the same for all countries, the sum of all countries' reference levels equates the global reference level. The global average emissions rate is found by dividing the historical emissions by the global forest carbon stock. The value (here equals to 0.46%) is then applied to each country's forest carbon stock to find that country's expected emissions. Data sources and methods are described in Section 4.

The factor α weights the incentives between historical and stock (or average) incentives by influencing each country's reference level against which their performance will be assessed. As can be seen in Table 1, a high α gives more weight to historical deforestation while with a low α the reference level is more influenced by existing forest carbon stocks. The last row in Table 1 also shows an important aspect of the mechanism that will be discussed in more detail in Section 6. By design, when the same α is used for all countries the sum of their combined reference levels is always equal to the global reference level. This guarantees perfect additionality at the global level.

The historical emissions rate of each country is fixed. The global average emissions rate used to calculate each country's EE can be fixed at the relatively constant rate of the last 25 years. That would reduce the negotiation process to choosing the value for α and, as will be discussed in Section 6, how and if it would change across countries and/or over time.

To illustrate how the mechanism works, suppose that in a given year Brazil emits half of its historical emissions, or 161 Mt C down from 323 Mt C. So if α is set at 0.75 and the incentive at US$ 20/t C, the incentives to be received would be:

$$\mathrm{CI} = [0.75(323) + 0.25(274) - 161] \times 20 = \mathrm{US\$\,3\,billion}$$

The "combined incentives" make the mechanism very comprehensive. It still offers incentives based on recent deforestation rates, so that high deforesting countries have enough incentive to reduce their deforestation rates. But it also includes an incentive for countries to keep their deforestation rates below the global average, making it attractive to countries that have been conserving their forest in the recent past. Both incentives are offered to all countries, making it unnecessary to classify them into "groups" or having different mechanisms for each stage of the conversion process. As national deforestation rates are highly variable over time, these classifications might be problematic. As both incentives are simultaneously offered, a country with high deforestation rates will have an added incentive to go below the global average while low deforesting countries also receive more if they reduce their rates even further.

3.2. An alternative global level mechanism

In the last section, we introduced the core combined incentives mechanism. It operates at national level, treating countries as independent units. By offering incentives to both reduce and avoid emissions from deforestation, the mechanism is comprehensive enough to attract countries in all stages of the deforestation process. This comprehensiveness is an important tool to minimize international leakage. A perfect answer to avoid international leakage, however, is a mechanism that relates the total amount of incentives paid each year to the global reduction in emissions from deforestation (Strassburg et al., 2007). We decided to focus this article on the national level mechanism presented in Section 3.1 as the feedback we received in the international forums discussing this issue suggested that the many uncertainties surrounding the willingness and capacity of developing countries to reduce deforestation in the short term would make it difficult politically to connect each country's incentives to the behavior of all other countries.

Still, we believe it might be desirable to present all options and in this section we show the small adaptations to the mechanism that would make it compatible with global level accounting. Even if unfeasible in the short term, it might be a desirable option for the medium to long-term as it would make the mechanism leakage-proof at all levels.

The core mechanism remains the same as presented in Section 3.1. The difference is that now the total incentive to be paid collective to all countries is calculated beforehand, as a function of the total reduction in emissions from deforestation that developing countries achieved as a group in any given year. This total reduction is simply the difference between the global reference level emissions and the global emissions in year t:

$$\mathrm{TI} = (\mathrm{GBE} - \mathrm{GE}_t) \times P \qquad (2)$$

The global baseline emissions can be initially based on the historical annual emissions from land-use change in developing countries and adapted in the future to reflect the business as usual global emissions trajectory. For instance, if the global emissions in year t are half of the baseline rate (or 2.75 G t CO_2, down from 5.5 G t CO_2) and the incentive per tonne of CO_2 is US$ 5, the total incentives to be paid in that year would be US$ 13.75 billion.

The second step distributes this total incentive across the countries and is exactly the combined incentives formula presented in Section 3.1. All countries are entitled to incentives for both reducing and avoiding emissions from deforestation and these two incentives are weighted by the factor α:

$$\mathrm{CI} = [\alpha(\mathrm{HE}) + (1-\alpha)(\mathrm{EE}) - E_t] \times P \quad (3)$$

When α is the same for all countries, the α-weighted reference level terms HE and EE of all countries sum up to the global reference level and the incentives offered are all additional at the global level.

The last step of this global level mechanism is to make the sum of all incentives paid equal to the total incentive. If all countries emitted less than their combined reference level (α(HE) + (1 − α)(EE)) then the sum of all incentives will already be equal to the total incentive. But if one (or more) country exceeds its combined reference level, then it would incur a negative value in Eq. (3) and reduce the total incentive calculated in Eq. (2). One possibility would be for this country to immediately pay this amount into the global pool and thus avoid a negative impact on all other countries' incentives in that year. If this is not the case, the other countries would have to "share the bill" and receive slightly less than what they would be entitled to in that year. In order to compensate for the excess of that country, the final incentive received by each country that remained below its reference level would be given by

$$\mathrm{FI} = \left(\frac{\mathrm{CI}}{\Sigma \mathrm{CI}}\right) \times \mathrm{TI} \quad (\text{for CI} > 0) \quad (4)$$

Each country that had a positive combined incentive for emitting less than its reference level (CI > 0) would get its share of the global pie (TI) in proportion to its share of all positive combined incentives in that year (CI/ΣCI). In other words, if a country's combined incentive represented 10% of all positive combined incentives, it would get 10% of the total incentive. The fraction of incentives each country did not receive because of the excess of other countries would be recorded as credit to be received in the future when these countries are able to pay back (possibly when they receive their next positive incentives).

On the one hand this connection to the behavior of other countries is what guarantees the leakage proof quality of the global level mechanism. On the other hand, due to short-term uncertainties mentioned before, it is the reason why such an approach was considered politically unfeasible in the short-term by some commentators. As mentioned above, one solution is for those countries that exceed their reference level to immediately pay an amount equivalent to their negative CI to the global pool. Another alternative that might be more politically feasible would be a phased approach, where countries are only included in the global calculation when they remain below their reference level for a given number of years. To complement this phased approach there could be a banking system where a fraction (say, 10%) of the positive incentives a country receives is set aside (possibly for a limited number of years) to immediately cover future negative incentives so that other countries are not affected by it.

As we said, we believe this global level mechanism is a very promising option, either immediately with a phased approach or later when the forestry sector has adjusted to a REDD mechanism (hopefully with successful reduction and avoidance of emissions in most countries). The remainder of this paper, however, will be focused on the national level mechanism presented in Section 3.1. All the modelling results would be the same for this global level mechanism if all countries remained at or below their reference level (as they would, for the case modelled).

In short, our mechanism allocates the resources from the international financing community to each country by supplying a mix of incentives for reducing emissions from deforestation and for the maintenance (and possibly the enhancement) of ecosystem carbon stocks. The question remains: How much can we reduce deforestation by such a mechanism, and at what cost?

4. Simulations

We tested the mechanism using recent data for the top 20 developing countries by forest area. These countries host 77% of all forests in developing countries. We also tested the flexible aspects of the mechanism. For comparison we included the results of other candidate mechanisms. It is important to note that the calculations described below were necessary in order to model the possible outcomes of the mechanism. If it were to be implemented, however, the mechanism's operation would only require the steps described in Section 3 and illustrated in Table 1.

Forest area and deforestation rates are available in the last Forest Resource Assessment from FAO (FAO, 2006) and listed in columns 2 and 3 of Table 4. Although neither of these variables is free of uncertainties and criticism (Ramankutty et al., 2007; DeFries et al., 2007), the FRA is the standard source. Forest area was taken directly from the FAO study, while the deforestation rate is the average of the deforestation rates for 1990–2000 and 2000–2005. Gabon was the only country without deforestation data and we used the conservative estimate of a study focused on that country (Nasi, 2001). When we extrapolate the resulting 7.7 million deforested hectares per year to the remaining 23% of forest cover (using the average deforestation rate of 0.48% p.a.) we have a total estimate of 10.1 million hectares deforested each year. This value is inside the interval found in the literature for the 1990s of 6–12 (FAO, 2006; Achard et al., 2002; DeFries et al., 2002) million ha per year.

Two other key variables necessary to estimate the individual response were obtained through more complex approaches. These are detailed in the next two sections.

4.1. Emissions per hectare

Estimating the amount of GHG emitted from deforestation is a complex task and the results vary considerably. Both deforestation rates and the emissions per deforested hectare (EpH) are subject to uncertainty. A recent review by some of the leading scientists in the field (Ramankutty et al., 2007) states that the latter are related to the uncertainties in several steps of the process, such as land cover dynamics after deforestation, the mode of clearing (e.g. slash and burn versus clean cut), the fate of the cleared carbon and the response of soil carbon. In addition to these factors other studies note that CO_2 is not the only GHG emitted in the process, with relevant quantities of the much more powerful (in terms of warming potential) methane being associate with deforestation (Fearnside and Laurance, 2004; Fearnside, 2000). Here we will assume that the conversion of one hectare emits the amount of carbon stored in its above and below ground biomass. By ignoring the fraction of carbon that can be stored in the subsequent land cover, the fraction not immediately released into the atmosphere or carbon trapped in long-term wood products, emissions will be overestimated. On the other hand, ignoring carbon emissions from soil and other GHG emissions leads to an underestimation. In the Brazilian Amazon it is likely that the last two factors dominate the

Table 2
Emission per Hectare parameter estimation.

Country	FAO (t C/ha)	GIS (base data from Potter) (t C/ha)	GIS (base data from NASA Regional Models) (t C/ha)	Average GIS (t C/ha)	Final estimate (t C/ha)	Final estimate (t CO_2/ha)
Brazil	103	142		142	123	450
China	31	94		94	62	229
DR Congo	173	154	165	160	167	611
Indonesia	67	152	115	134	100	367
Peru		127		127	127	467
India	35	102	89	95	65	239
Sudan	23	62	24	43	33	121
Mexico		109		109	109	399
Colombia	133	158		158	146	534
Angola	82				82	300
Bolivia	90	126		126	108	395
Venezuela		162		162	162	596
Zambia	27				27	100
Tanzania	64				64	234
Argentina	73	72		72	72	265
Myanmar	98	105	91	98	98	360
Papua New Guinea		165		165	165	606
Central African Republic	123	154	139	147	135	495
Congo	231	116	162	139	185	677
Gabon	167	122	232	177	172	632

first two (Fearnside, 2000). As will be seen, when compared to other studies our estimates for the EpH are on the conservative side.

The latest FRA from FAO provides estimates of the total carbon stock in forests for 16 of our 20 countries. Dividing these stocks by the forest area of each country gives the average carbon content per hectare listed on column 2 of Table 2.

These estimates, however, are admittedly imprecise (FAO, 2006). Furthermore, basing the analysis solely on such average values presents an additional problem. Carbon stocks vary greatly within each country and current and future deforestation might be concentrated in regions with carbon density considerably higher or lower than the national average. For instance, FAO average carbon content for Brazilian forests is 103 t C ha^{-1}, but deforestation is concentrated in the Amazon region where carbon concentrations are generally above 150 t C ha^{-1} (Fearnside, 2000).

To reduce these uncertainties we also followed a different approach. Potter (1999) presented a global map of biomass distribution. In order to find the average carbon content related to the areas more relevant to REDD, we used GIS techniques to combine the spatial distribution of recent (2000–2005) deforestation given by the VCC-MODIS product (Carroll et al., 2006) with the Millennium Ecosystem Assessment map of deforestation hotspots (Achard et al., 1998). We then overlaid this combined map (some 51,000 points centred on 5 minute grid cells) with the Potter (1999) biomass data in order to select the grid cells more relevant to REDD and made a country by country average. As Potter (1999) only provided estimates for above ground biomass, we used the ratio between total and above ground biomass from our FAO data (1.28) to convert Potter (1999) values to total biomass. This ratio falls between similar values used by Fearnside (2000) (1.34) and Achard et al. (2004) (1.20). The resulting estimates are listed in column 3 of Table 2.

We also overlaid this combined map over two regional maps produced by NASA for Southeast Asia and Tropical Africa (Brown and Gaston, 1996; Brown et al., 2001). The resulting estimates, also corrected for above–below ground biomass ratio (column 4 in Table 2), were averaged with the estimates from Potter's (1999) map to produce our average GIS estimate (column 5 in Table 2). These values were then averaged with FAO estimates to produce our final estimates for the Emissions per Hectare parameter for each country (columns 6 and 7 of Table 2).

When compared with the review presented by Ramankutty et al. (2007), our estimates for the EpH term are on the lower bound of the estimates available in the literature and therefore will lead to a more conservative estimate for equilibrium reductions in emissions (as the incentive per hectare, positively associated with the carbon density per hectare, is smaller).

Our resulting estimate of GHG emissions from deforestation for our 20 countries is 827 Mt of C per year. When extrapolated to the remaining 23% of forests in developing countries the total estimate is 1073 Mt of C per year. Related estimates in the literature range from 900 to 2200 Mt C. The latest study reviewed by Ramankutty et al. (2007) provides an estimate of 1100 MtC.

4.2. Opportunity costs

We also used two distinct approaches to estimate the opportunity costs of avoiding deforestation. The first one was based on the estimates presented by the Stern Review on the Economics of Climate Change (Stern, 2007). That study synthesized field information on the economic returns of the activities to which land is converted in the top eight countries by annual deforested area (responsible for 46% of annual deforestation). In addition, and crucially, the study also presented estimates for the area converted to each activity in each country.

We assumed that the average behavior of these countries represents the behavior of any one developing country. Although this is admittedly a simplification, we believe it to be a reasonable one as (i) these countries are responsible for nearly half of the annual deforested area (so the extrapolation to the other half is not overly unrealistic) and (ii) as these countries are the top eight deforesting countries it is fair to assume that their economic returns from conversion doing so are at least equal to (more likely higher than) the average of developing countries.

Table 3 lists the land fraction and returns for each of the 24 alternative uses. The land proportion was estimated by summing up the area corresponding to each use from all eight countries and dividing it by the total annual deforested area in all of them. Returns also include part of the income from one-off timber harvesting and are expressed as a net present value (30 years, 10% discount rate). Activities that provided the same return per hectare were grouped together.

Table 3
The "field approach" estimate for opportunity costs.

Alternative land use	Returns (NPV USS/ha)	% Land used	Cumulative %
Beef cattle small scale/manioc/rice	2	11.55	11.55
Cassava monoculture	18	5.75	17.30
Rice fallow	26	6.20	23.50
Dairy	154	3.51	27.02
Perennials (bananas, sugarcane pineapples)	239	0.50	27.52
Annual food crops long fallow	346	1.75	29.27
Beef cattle	390	3.06	32.33
Beef cattle medium/large scale	626	31.67	63.99
Cocoa without marketed fruit	740	0.87	64.87
Annual food crops short fallow	774	3.40	68.27
Small-scale maize and cassava	1052	1.86	70.13
Cassava monoculture	1053	0.45	70.59
Smallholder rubber	1071	9.77	80.35
Oil palm and rubber	1180	0.08	80.43
Cocoa with marketed fruit	1365	2.62	83.06
Smallholder oil palm/low-yield independent	1515	1.65	84.71
Smallholder subsistence crops	1737	1.13	85.84
Supported growers	2085	1.77	87.61
Soybeans	2135	3.82	91.43
High yield independent	2205	0.49	91.92
Oil palm supported growers	2330	0.21	92.13
Oil palm independent grower	2363	0.06	92.19
Tree plantations	2614	0.50	92.70
Oil palm large scale/government	2705	7.30	100.00

For each return value in column 2, column 4 presents the fraction of the land converted to uses that provide smaller or equal returns per hectare. The relation between these two columns is plotted in Panel 1A. Also in Panel 1A is the best-fit curve ($R^2 = 0.95$) for the 24 data points.

As will be discussed in the next section, the incentive per hectare needed to stimulate a reduction in deforestation is equal to the economic returns provided by that hectare. This curve (henceforth the "field estimate") can therefore be understood as a cost function for a REDD mechanism, relating the annual reduction in deforestation rates (y) that can be achieved to different incentives per hectare (x).

Our second approach is based on a recently available global map of economic rents from agricultural lands. Naidoo and Iwamura (2007) integrate information on crop productivity, livestock density, and prices to generate their map. As their focus was on current returns they also based the analysis on the area occupied by each crop on the mid 1990s. As a consequence, however, large wilderness areas such as the Amazon and Congo basins produced low or no returns. Following our request, they kindly provided us with a map of agricultural rents without considering the area actually occupied by each crop. Instead, this map of "potential agricultural rents" showed the rent of the most valuable crop that could be produced in each cell. As we believe that this map is more representative of the opportunity costs of a REDD mechanism, we used it as the basis for our second approach.

As Naidoo and Iwamura (2007) have used crop prices (and not profits) we needed to adjust the data to facilitate comparison with our first approach (and with current REDD discussions) that focus on incentives to compete with returns from alternative activities, not their income. We used the profit margin of 15% adopted by the Stern Review (Stern, 2007) in the cases where it was necessary to convert income to returns.

As with our second approach to estimating carbon content, we needed to focus on areas more relevant to a REDD mechanism. We therefore used a GIS to overlay the same combined distribution of recent and projected deforestation areas (some 51,000 points centred on 5 minute grid cells) and extract the corresponding agricultural return values. We used this GIS-derived data for 17 of our 20 countries to generate individual country curves of costs of avoiding deforestation.[4]

As in the case of our field estimate, we plotted the relation between each economic return and the corresponding cumulative area converted up to that point. The results for Peru are plotted in Panel 1B. We also included our field estimate on the graph for comparison.

We then averaged the general field curve from our first approach (Panel 1A) with the values for the GIS deforestation points in each country (Panel 1B, for Peru) to generate our final cost curves of avoiding deforestation for each of the 20 countries (Panel 1C, for Peru).

4.3. Modelling the equilibrium

The basic assumption in our estimation of the response of each country to the mechanism is that a country will convert a hectare if the return of doing so is higher than the incentive it receives to conserve it and vice versa. An underlying assumption is that when the mechanism is in place no country will decide to convert more than it had done previously.

Each country's reduction in emissions is equal to the fraction of emissions from the area that used to be converted to activities that generate lower returns than the incentive per hectare now offered by the mechanism. This marginal incentive can be found by

$$\mathrm{CI}_i = \{[\alpha\,\mathrm{HE}_i + (1-\alpha)\mathrm{EE}_i] - (x_{it} \times \mathrm{EpH}_{it}\} \times P \qquad (5)$$

where x_{it} = hectares deforest by country i in year t and EpH_{it} = emissions per hectare of country i on year t.

As will be discussed in Section 6, by linking the incentive offered to the actual reduction in GHG emissions, the mechanism provides two kinds of incentives. One is the incentive to reduce the number of deforested hectares and the other to reduce the emissions per hectare deforested.

To simplify the analysis, we assume that the emissions per hectare term is fixed. Therefore the only variable the country can choose each year is the number of deforested hectares (x). The

[4] Three countries (Angola, Zambia and Tanzania) were not covered by either MODIS-VCC or MEA hotspots.

marginal incentive is then the impact that one additional deforested hectare has on the total incentive a country receives.

Differentiating Eq. (5) in relation to x gives:

$$\frac{\delta \mathrm{CI}_i}{\mathrm{d}x} = -\mathrm{EpH}_{it} \times P$$

Not surprisingly, and in line with the goals of the mechanism, the incentive a country receives for each additional hectare conserved is equal to the amount of CO_2 that would be emitted multiplied by the base incentive per avoided tonne.

Therefore for each of our 20 countries we divided the per hectare cost (x-axis in Panel 1C) by that country's CO_2 Emissions per Hectare term (7th column in Table 2) to generate the relation between the base incentive offered (P) and the corresponding percentage reduction in emissions from deforestation for each given country. The 20 curves are presented in Panel 2. As can be seen, the estimates confirm the predictions that a large fraction of deforestation can be tackled with relatively low incentives. Even the sharp increase in costs for the last remaining hectares still present values at the lower end of UNFCCC estimations of viable mitigation options (up to US$ 100 per t CO_2).

There is an important last step. A country will only join the mechanism and reduce its emissions to the equilibrium rate if the total incentive it receives is higher than the total opportunity costs it would incur. One way of thinking about these costs is that they relate to the area that would no longer be converted. But this would mean that countries with current low deforestation rates would always join the mechanism, as their "current" opportunity costs are very low. This goes against the rationale of the mechanism. Countries from the Congo Basin, for instance, could decide to build highways into the heart of the forest and incentives that only cover their very low past deforestation rates would not suffice to counteract their potential conversion gains. Therefore we opted for a mixed approach. Countries with high deforesting rates had their total opportunity costs based on their current deforested areas. For countries with low deforestation rates we used the global average rate (here equals to 0.48%) to calculate their potential deforested area and this became the base for their total opportunity costs. Note that this has no influence on the equilibrium reduction or on the amount of incentive received. It is only used to check if a country would join the mechanism.

5. Modelling results and discussion

The total incentive a country would receive at its equilibrium point is given by Eq. (1). Here the relative weight α comes into play for the first time. Although it has no role in determining the equilibrium rate, it has a major role in determining whether a country joins the mechanism.

Using the average CO_2 market price of the EU Emissions Trading Scheme, US$ 5.63 per tonne (IETA, 2006), as the base incentive for illustration, Table 4 presents the outcome of the mechanism, the reduction in emissions and the combined incentives of each country and a comparison between different weights and mechanisms.

As can be seen, a high α increases the payoff to countries with high deforestation rates and means some low deforesting countries would not join the mechanism. The opposite occurs when a low α is chosen, with some high deforesting countries ignoring the mechanism. An intermediate value of α attracts all 20 countries to the mechanism. Finally, for any given α a higher base incentive increases the payoff to all countries, eventually attracting more participants even with more extreme values of α. The opposite occurs when the base incentive is reduced.

Table 4
REDD mechanism equilibrium projections.

Country	Forest area (10^6 ha)	Initial deforestation (%)	Equilibrium reduction (%)	Combined incentive (10^6 US$ year^{-1})				
				α = 0.5	α = 1	α = 0	JRC (1/2)	JRC (1/3)
Brazil	478	0.55	97.5	5,996	6,497	5,495	5,877	6,150
China	197	−1.7[a]	100.0[a]	594	0	1,187	553	386
DR Congo	134	0.3	100.0	1,763	1,379	2,147	1,247	1,305
Indonesia	88	1.85	94.5	1,935	3,200	*669*[b]	2,895	3,029
Peru	69	0.1	99.8	512	*180*[b]	844	393	274
India	68	−0.6[a]	100.0[a]	212	0	425	198	138
Sudan	68	0.8	48.7	102	179	*26*[b]	162	169
Mexico	64	0.45	93.4	619	607	632	549	574
Colombia	61	0.1	100.0	518	*183*[b]	853	397	277
Angola	59	0.2	87.1	307	174	440	194	164
Bolivia	59	0.45	86.7	522	510	533	462	483
Venezuela	48	0.6	100.0	854	960	748	869	909
Zambia	42	0.95	53.4	63	121	*6*[b]	110	115
Tanzania	35	1.05	82.1	266	401	*130*[b]	363	380
Argentina	33	0.4	88.4	191	174	207	158	165
Myanmar	32	1.35	93.5	536	824	248	746	780
Papua New Guinea	29	0.5	100.0	486	502	470	454	476
Central African Republic	23	0.1	100.0	180	*63*[b]	296	138	*96*[b]
Congo	22	0.1	100.0	243	*86*[b]	400	186	130
Gabon	22	0.1	100.0	220	*77*[b]	362	169	118
Total	1,631	(Mean = 0.48)	94.4	16,118	15,528	15,287	16,118	16,022
Emission reduction (%)				94.4	90.9	71.5	94.4[c]	94.0[c]
Participant countries				20	15	16	20	19
Incentives to high def countries in relation to low def countries (equal forest area)				+74%	+270%	−6%	+147%	+192%

REDD mechanism equilibrium projections for a base incentive of US$ 5.63. The particular case when α = 1 is similar to the mechanism proposed by Brazil (UNFCCC, 2006). Using α = 0 is similar to the mechanism we previously proposed (Strassburg et al., 2007). JRC is the mechanism proposed by the Joint Research Center (Mollicone et al., 2007).

[a] China and India have negative deforestation rates. As the default version of this mechanism does not include reforestation, their initial deforestation rate is considered equal to zero. Their equilibrium reduction is their hypothetical reduction if they had a positive deforestation rate, based on their opportunity costs curves and the base incentive of US5.63.

[b] These combined incentives are smaller than the total opportunity costs these country would incur and therefore insufficient to make them join the mechanism.

[c] The reduction obtained by the JRC mechanism would be smaller than these for the base incentive of US$ 5.63, as their marginal incentive is smaller. But these would be the reductions achieved for the total incentive listed in the cells immediately above.

In reality it is unlikely that each developing country would switch to the equilibrium deforestation rate as soon as the mechanism is in place. Although deforestation rates tend to react quite quickly to economic incentives, it might take some time for certain countries to achieve this rate. This might be particularly true where a large portion of deforestation comes from illegal activities. In order to have a positive sum in Eq. (1), high deforesting countries need to reduced their emissions below their combined reference level ($\alpha HE_i + (1-\alpha) EE_i$) before they receive their first credit. As governments can be remarkably myopic an initial "debit free" period might be agreed, so that a negative CI only becomes a debit after a certain period of time. Using an initial $\alpha = 1$ (at least for high deforesting countries) and gradually reducing it over time also solves this potential problem.

The projections presented in Table 4 show the effect that different α weights in the combined incentive have on the distribution of the incentives and consequently on the behavior of countries. Among our 20 countries, the total forest area is divided equally into high (above global average) and low deforesting countries.

The first extreme example where the incentive is entirely based on recent past behavior ($\alpha = 1$) strongly favors countries with high past deforestation, whose combined incentive is 270% higher than those of low deforesting countries. As a result, five of the latter would not join the agreement for base incentives up to US$ 5.63 per tonne of CO_2. The resulting reductions in emissions would probably be smaller than those presented in Table 4, where countries that do not join simply maintain their past behavior. Without appropriate incentives and in a context of reduced supply of deforestation-related products, a leak of deforestation to these countries would be very likely. This extreme example is similar to the Brazilian proposal (UNFCCC, 2006).

On the other hand if compensation is entirely based on the expected emissions calculated from the global average rate ($\alpha = 0$), some high deforesting countries do not receive enough incentive to "join the game" (receiving 6% less than the low deforesting countries). As a result four of them would not join the mechanism, with serious consequences for its effectiveness. This extreme option, similar to the mechanism we previously suggested (Strassburg et al., 2007), might present some advantages on the "fairness" side, but these are compromised by a lack of effectiveness.

The intermediate case presented, where both incentives have the same weight ($\alpha = 0.5$) has clear advantages over the other options. The combined incentive for high deforesting countries is still higher (+74%) than those for low deforesting ones, but this bias is much less pronounced than in the other cases. And this bias might be necessary, at least over an initial implementation period, as they would have to make "more effort" to change recent past behavior. The projections indicate that for an incentive of US$ 5.63 per tonne of CO_2 all 20 countries would join and reduce their emissions by an aggregate rate of 94.5%.

The mechanism proposed by the JCR team (Mollicone et al., 2007) would also have the participation of all countries when using the half global baseline threshold. Their emissions reduction would be smaller for the same base incentive, but the same per total incentive. Both their options, however, present a strong bias towards high deforesting countries, whose combined incentives are 147% or 192% higher than those of low deforesting countries. A country that has a deforestation rate equal to half or one third the global average would have to reduce it even further to receive any incentive. Due to its lower flexibility it would be difficult to reduce this bias over time.

6. Underlying features and flexibility

Deforestation varies considerably across time (MEA, 2005; Nabuurs et al., 2007). Basing a long-term mechanism on a snapshot of 5 or 10 years at a given point in time is unfair and potentially ineffective. Making country-by-country adjustments based on opportunity costs and future national deforestation scenarios would be highly subjective and possibly impractical. For instance, opportunity costs can change dramatically with seemingly modest governmental policy switches.

In recognition of this our mechanism provides all countries with the same basis of combined incentives. Our analysis based both on current and potential opportunity costs showed that it is capable of attracting countries with very diverse deforestation profiles. And although initially a higher fraction of the incentives might go to high deforesting countries, this bias is less pronounced than in alternative mechanisms. It makes sense that countries with higher current deforestation rates need more incentives to join the mechanism now. But taking the case of Indonesia as an example, it is hard to justify paying it approximately US$ 3 billions per year (reducing the amount received by low deforesting countries) if its emissions reduction would be the same if it received US$1.9 billions per year. And it is even harder to justify why this current high deforestation should continue to be the base for a long-term mechanism.

This brings us to one of the most interesting features of this "combined incentives" mechanism. It is possible to move from an initial configuration where current deforestation has the necessary (for all countries to join) high weight, to another where the incentive is increasingly based on the total ecosystem carbon stock of each country. Total ecosystem carbon stock is the best measure for the service of carbon storage, and its connection with total ecosystem area is a better measure for the total potential foregone benefits from alternative land uses. All it takes to make this transition is an adjustment in the weight of the "combined incentives", i.e. lowering the value of α. In this way the mechanism would initially offer higher incentives to countries that might have higher costs when reducing their high rates of deforestation. Countries with lower deforestation rates would be receiving less incentive initially, but these would rise over time. Fig. 1 illustrates what the combined reference level deforestation rate would be for a few countries, assuming an initial α of 1 constantly declining to 0 over 20 years (it shows reference levels in percent deforestation rates as these are easier to envisage, but the mechanism would work with reference levels measured in tonnes of CO_2).

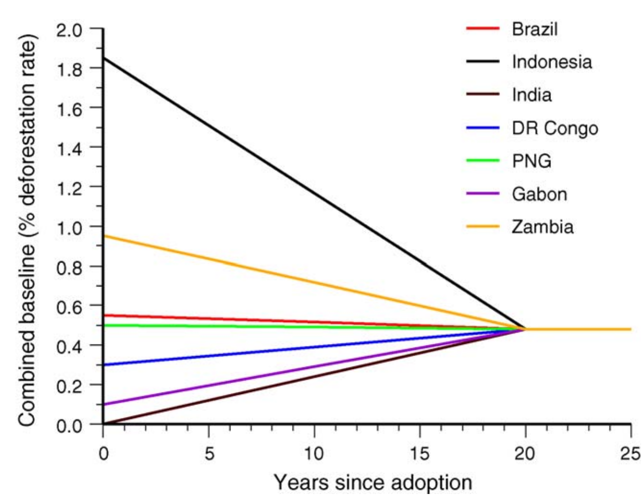


Fig. 1. An example of how a declining weighting factor alpha affects the combined baseline deforestation rate over time. The initial high value for alpha means that most weight is initially given to the historical emissions of each country. That might be a desirable option in the short-term. Declining the value of alpha over time gives increasingly more weight to existing forest carbon stock in each country, which might be a more desirable option in the medium and long terms.

Another possibility is varying α across different countries or regions. In the light of what happens to certain Annex 1 countries in the Kyoto Protocol, it could be argued that certain countries could have differentiated alphas. This option could be trickier politically. In addition, increasing a country's weighted reference level by giving it a differentiated alpha might compromise the perfect global additionality of the mechanism (unless this increase is compensated for a similar decrease in other countries' reference levels).

There are some still further interesting features included in the simple formula of the proposed mechanism. It relates the financial incentive to actual GHG emissions from deforestation, instead of relating it to the deforestation rate itself. As deforestation or partial conversion of a hectare can be done in several different ways resulting in a different volume of GHG emissions (Ramankutty et al., 2007), relating the compensation paid to the final emission provides an incentive for adopting the least damaging practice. It also provides a strong incentive for prioritizing carbon-rich vegetation (as long as safeguards are in place to maintain biodiversity), an issue of particular importance in vast areas undergoing conversion to palm-tree plantations. If current technological constraints make it impractical to measure this term directly, then it can be initially treated as a constant with regional values based on field information.

Virtually all proposals so far argue that a negative incentive should be considered a debit to be discounted from future incentives (UNFCCC, 2006, 2007a, b; Strassburg et al., 2007; Mollicone et al., 2007). The argument is that such a feature would partially address the "permanency issue" (i.e. when the international financing community pays for the service of carbon storage but the carbon is actually emitted soon after). If this becomes the political consensus, this debit system can be inserted here. Some (UNFCCC, 2007b) argue for a "banking system" where even a country that receives a positive incentive would have a portion of this set aside to cover eventual future debits. This feature can be easily included by multiplying CI by some term β (say $\beta = 0.8$, if 20% is the agreed discount).

Forest degradation might be of the same order of magnitude as deforestation (Asner et al., 2005). For this reason it has been included in the official REDD discussions (UNFCCC, 2007b). Afforestation and reforestation activities might play an important role in medium and long-term CO_2 sequestration (FAO, 2006). Our mechanism by default already includes emissions from degradation, as it is based on total emissions from land-use change. Reforestation and afforestation are not included in the default version, as they are currently covered by the Clean Development Mechanism. However due to the dismal performance of the current CDM model regarding these two activities it might be desirable to unify forestry activities under a single mechanism. This mechanism can easily account for these activities simply by considering them as negative emissions through the current emissions term (E_t).

6.1. The biodiversity synergy

The proposed mechanism has been developed in the context of the discussions taking place within the UNFCCC. Carbon storage and sequestration, however, are not the only global services provided by ecosystems. Biodiversity provides a well-known variety of direct services (MEA, 2005). To focus on just one aspect, a recent review showed that 47% of the small molecules used in cancer treatment in the US are either natural products or were directly derived from them (Newman and Cragg, 2007) and the role of these in the pharmaceutical sector has been reaffirmed (Paterson and Anderson, 2005). Furthermore there are feedbacks between biodiversity services and the carbon related ones (MEA, 2005; Nabuurs et al., 2007), with some evidence that increased biodiversity might lead to increased biomass (Bunker et al., 2005). Additional evidence suggests that biodiversity increases the resilience of ecosystems in the face of change (Hooper et al., 2005; Reusch et al., 2005; Tilman et al., 2006) and this, in the context of unavoidable climate change (Naarbus et al., 2007) is a key feature. An ideal mechanism (i.e. one that would maximize global welfare) should take these other global benefits into account in order to target more precisely and effectively areas of higher global value. A biodiversity premium can be inserted in the mechanism, simply by adding an extra weight to emissions from more biodiversity rich areas. Another alternative would be setting aside a fraction of REDD financing (say, 10%) to be applied as insurance, associated with the resilience value of biodiversity for forest carbon. It would be used to target biodiversity rich areas that would either not be protected by REDD or would need complementary financing to be conserved. Finally, although it has been developed in the context of reducing emissions from deforestation, there is no impediment to extending this mechanism to other ecosystem types, either based on their carbon content alone or including biodiversity premiums.

6.2. Additionality

Another key feature of the mechanism is that if α is the same across all countries, the sum of all countries' combined reference level would equate to the global reference level (Table 1). That would mean that even if some individual countries receive part of their compensation for "virtual reductions", this would be exactly compensated by some other countries having a reference level slightly lower than their business as usual emissions would be in that year. The aggregate sum is zero, making the mechanism hot air-proof. If it is decided that the business as usual global deforestation rates would go down (a "diminishing baseline" UNFCCC, 2007b) or up after a certain period of time, the reference level terms could be modified proportionately and the perfect global additionality would be maintained.

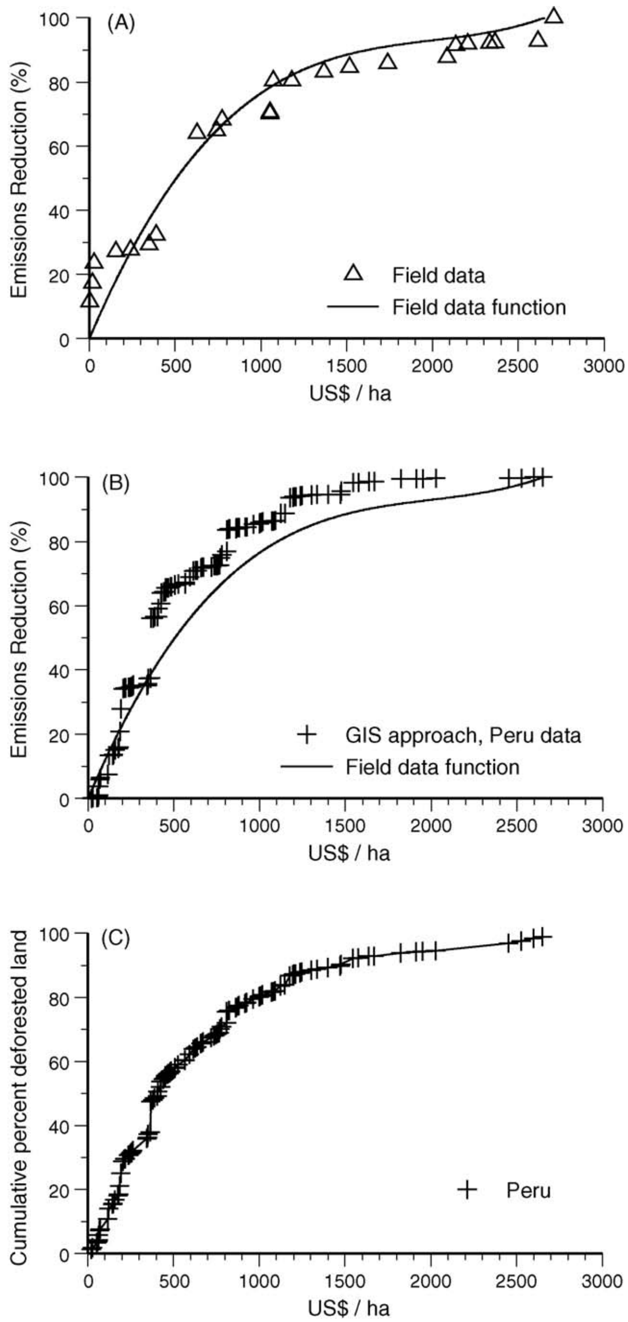
7. Global and total costs of REDD

We weighted the national estimates of our 20 countries to produce a global relation between the base incentive offered and the associated reduction in emissions from deforestation.

There are two stages involved in estimating the global costs of REDD. The first is to produce a relation between the base incentive per avoided tonne and the consequent reduction in emissions at the global level. For each country and each approach we took its relation between incentive per avoided tonne and the associated percent reduction in deforested land (from Panel 1B) and multiplied this last variable by its annual emissions from deforestation. We then have a relation between incentive per tonne and the corresponding reduction in emissions for each country. Summing all these and extrapolating the total emissions to the remaining 23% of forests in developing countries gives us a total annual emission of 3.9 Gt CO_2. Finally dividing the y-axis by the total avoided tonnes gives us a relation between the incentives offered and the resulting percent reduction in emissions (Panel 3A).

Given the fact that our "field approach" was based on data from field studies in eight countries and that our "GIS approach" is the result of combining global models of agricultural rents with remote sensing and expert opinion on deforestation patterns, the fit between them is remarkable. Even more so considering that the costs of viable mitigation options studied by the UNFCCC are US$ 0–100 per tonne of CO_2.

As the same incentive is paid to all reduced emissions, the total incentive cost is the product of the incentive per reduced tonne of CO_2 and its correspondent avoided emissions. But there are other costs that should be included in the estimate. In addition to the



Panel 1. (A) Depicts the results from our "field approach". The triangles represent the opportunity costs per hectare from the alternative land-uses listed in column 2 of Table 3 and the associated cumulative reduction in emissions from deforestation (in %). (B) Shows the results from our GIS approach for Peru and a best-fit curve ($R^2 = 0.95$). The best fit curve from Panel 1A was also plotted for comparison. (C) Shows the final cost curve for Peru, resulting from the average of results from both approaches. All costs are the Net Present Value per hectare in 2005 US$ for 30 years at a discount rate of 10%.

incentive payments a REDD initiative would incur transaction costs and the costs of protecting and managing the forests. It could be argued that the last two should be borne by the developing countries themselves, but we believe that this would contradict the rationale of REDD. As incentives would be paid so countries do not convert their forests to alternative uses, then they should include the extra costs a country would incur for conserving the forests that otherwise would be converted.

The Stern review (Stern, 2007) notes that Costa Rica's Payments for Environment Services scheme is required by law to spend no more than 7% of its budget on administering the scheme and the rest on the payments. A similar scheme in Mexico has these costs capped at 4%. As a global system would generate economies of scales, we believe the average of these two values, or 5.5% is a conservative estimate. This percentage will be added to the total costs.

James et al. (1999) present the results of a comprehensive review of conservation costs worldwide. If we average (by forest area) the cost of protection and management of forests in Latin America, Sub Saharan Africa, Developing Asia and the Pacific we get a value of US$ 3.8 per hectare per year (adjusted for 2005 US$). It is unrealistic to assume that countries can predict the exact patch of forest that would be deforested in a given year, protect it and as a consequence no deforestation would occur in the rest of its forests. On the other hand it would be an exaggeration to assume that to reduce 10% of its deforestation rates developing countries should protect and manage 100% of their forests. A reasonable intermediate solution is to associate the costs to the reduction in deforestation rates, so that to reduce its deforestation rates by 80% a country would need to protect 80% of its forests. So based on the total forest area in developing countries of 2.1 billion hectares, total management and protection costs will be the product of the percent reduction by US$ 8 billion.

The final graph showing the total costs of REDD and the associated reduction in emissions is shown in Panel 3B. For our reduction of 94.5% the total costs would be US$ 29.6 billion, of which US$ 20.9 billion are incentives, US$ 1.1 billion transactions costs and US$ 7.6 billion forest management and protection costs. The total cost per tonne of CO_2 would be approximately US$ 8.

An important observation is that the relation between the cost of REDD and its consequent reduction in emissions does not vary either due to a change in the base incentive per avoided tonne, or to a uniform change in the carbon content per hectare across all countries. The reduction achieved is a function of (i) the opportunity costs per hectare and (ii) the product of the base incentive and the emissions per hectare. In other words, if the goal is a reduction of 90% of emissions and new estimates (e.g. the inclusion of soil carbon) double the carbon content per hectare for all countries, the incentive per tonne necessary to achieve the goal is halved and the final costs remain unchanged.

8. Limitations and simplifications

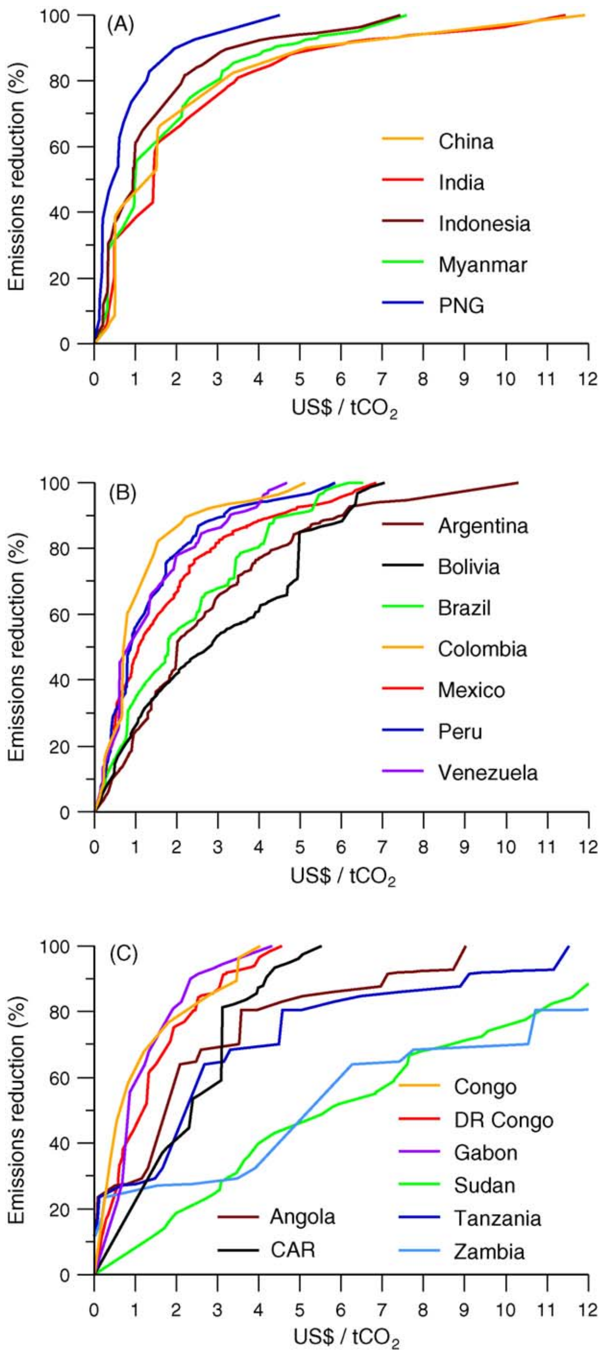
8.1. Data on emissions per hectare

We combined diverse data sources in order to choose the most representative value for each country with regard to a REDD mechanism. Our estimates carry the uncertainties of the studies used as sources. In comparison with other studies they are on the conservative side. Higher values for this variable would:

(i) lead to higher reductions in emissions for the same base incentive (pushing up the curves in Panel 2 and Panel 3A). The higher reductions in column 4 of Table 4 would increase the incentive received by the country that had its EpH increased, without affecting other countries' incentives.
(ii) not affect the relation between total costs and percent reduction in emissions (Panel 3B). As a consequence the mechanism would be more cost-effective, as the same total cost would reduce higher quantities of CO_2.

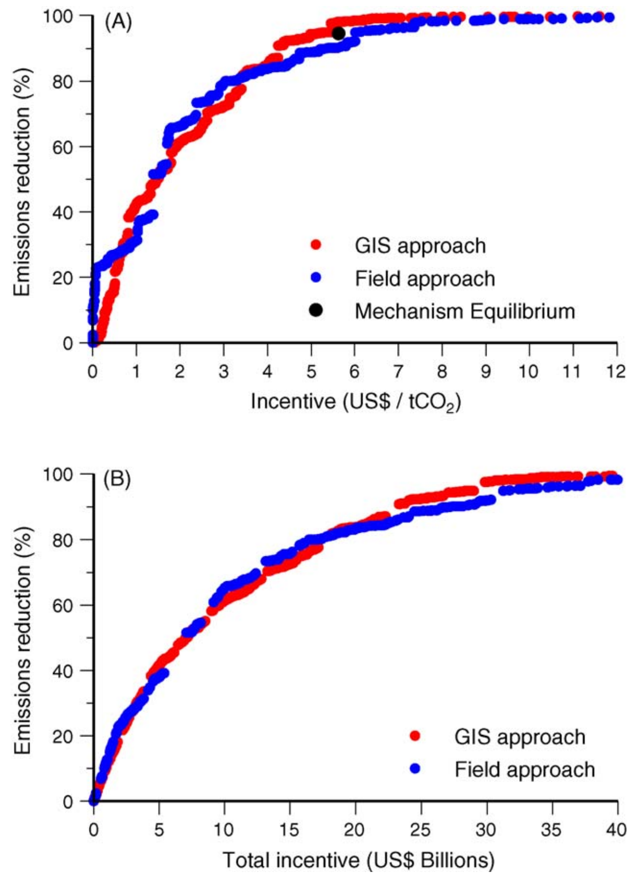
8.2. Data on annual deforested area

We used the standard FAO data for forest area and deforestation rates. Our extrapolated estimate of 10.1 million hectares deforested per year is inside the range of values found in the literature. An increase (or decrease) in the annual deforestation rates would:



Panel 2. Depicts the relationship between the base incentive per avoided tonne of CO_2 and the associated percent reduction in emissions for countries from Asia and Oceania (2A), the Americas (2B) and Africa (2C). Results are based on potential opportunity costs and current carbon density. Except for carbon-poor Sudan and Zambia all countries present a similar trend, with more than 80% of deforestation being avoided by base incentives of US$ 5/t CO_2 or less.

(i) have no influence on the equilibrium reduction in emissions for the same base incentive (column 4 of Table 4); increase (or decrease) the incentive received by the country for the same equilibrium reduction in emissions (columns 5–9 of Table 4); have a positive (or negative) marginal effect on other countries by increasing (or decreasing) the average emissions rate thus increasing (or decreasing) their expected emissions terms;
(ii) increase (or decrease) proportionally the costs of reducing the same percentage of emissions (Panel 3B), as more (or less) hectares would now have to be compensated, but would not affect the reduction per base incentive (Panel 2 and Panel 3A) nor the total costs for the same amount of CO_2 avoided.



Panel 3. (A) Depicts the global reduction in emissions from deforestation for our two approaches. National curves were averaged by national annual emissions. The figure also shows the reduction resulting from a base incentive of US$ 5.63/tCO_2 applied to our mechanism (α = 0.5). All countries would join and reduce their aggregate emissions by 94%. (B) Shows the total (incentives, transaction, management and protection) costs of reducing emissions from deforestation from our two approaches. These results are not influenced by changes in carbon density or base incentives, as one compensates the other. About 90% of emissions from deforestation can be reduced or avoid at a total cost of US$ 25 billions per year.

8.3. Data on opportunity costs

These are probably the most uncertain of the variables used, although the remarkable fit between both approaches offer some mutual support. An increase in opportunity costs would:

(i) reduce the equilibrium reduction for the same base incentive (column 4 of Table 4) and have no effect on the behavior of other countries;
(ii) decrease the reduction in emissions for the same base incentive (Panel 2 and Panel 3A) and for the same total incentive (Panel 3B).

9. Conclusions

Our estimates confirm the general consensus that REDD can be a very cost effective option for mitigating climate change. Incentives in the order of US$ 20 billion per year could curb 90% of global emissions from deforestation. The associated total cost per tonne of CO_2 of approximately US$ 8 is on the very low side of the UNFCCC estimates of mitigation options (up to US$ 100 per t of CO_2). The annual amount of CO_2 emissions reduced (3.2–6.4 Gt

CO_2) would be four to eight times the annual target of the Kyoto Protocol.

As our analysis showed, however, the way these incentives are distributed is crucial to the success of the REDD enterprise. The mechanism we presented addresses some of the most important challenges a REDD mechanism would face. We believe the mechanism is both capable of offering incentives to all developing countries to conserve their ecosystems and is able to induce reduction in deforestation rates in the short-term while keeping them low over the long-term. By including countries from all stages of the conversion process, it minimizes the threat of leakage. It also offers a mix of incentives to both reduce deforestation rates and emissions per deforested hectare. In addition its flexibility allows several financing options, the fine-tuning of incentives across countries and time, and the inclusion or not of incentives to reforestation, biodiversity conservation and other ecosystem types.

By providing substantial reductions in GHGs emissions at a very low cost, this REDD mechanism would be a powerful and cost effective tool to address what is now considered the biggest threat civilization has ever faced (King, 2007). The purely economic benefits in terms of avoided damage (Stern, 2007) far exceed its costs.

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