ENVIRONMENTAL RESEARCH
LETTERS

Elements for the expected mechanisms on 'reduced emissions from deforestation and degradation, REDD' under UNFCCC

To cite this article: D Mollicone *et al* 2007 *Environ. Res. Lett.* **2** 045024

IOP PUBLISHING ENVIRONMENTAL RESEARCH LETTERS
Environ. Res. Lett. **2** (2007) 045024 (7pp) doi:10.1088/1748-9326/2/4/045024

Elements for the expected mechanisms on 'reduced emissions from deforestation and degradation, REDD' under UNFCCC

D Mollicone[1,5], A Freibauer[1], E D Schulze[1], S Braatz[2], G Grassi[3] and S Federici[4]

[1] Max-Planck-Institute for Biogeochemistry, Hans-Knöll-Straße 10, D-07745 Jena, Germany
[2] Food and Agriculture Organization of United Nations, Rome, Italy
[3] European Commission, DG Joint Research Centre, Institute for Environment and Sustainability, Ispra, Italy
[4] Agenzia per la Protezione dell'Ambiente e per i servizi Tecnici, Roma, Italy

E-mail: dmolli@bgc-jena.mpg.de

Received 15 August 2007
Accepted for publication 1 November 2007
Published 5 December 2007
Online at stacks.iop.org/ERL/2/045024

Abstract
Carbon emissions from deforestation and degradation account for about 20% of global anthropogenic emissions. Strategies and incentives for reduced emissions from deforestation and degradation (REDD) have emerged as one of the most active areas in the international climate change negotiations under the United Nations Framework Convention on Climate Change (UNFCCC). While the current negotiations focus on a REDD mechanism in developing countries, it should be recognized that risks of carbon losses from forests occur in all climate zones and also in industrialized countries. A future climate change agreement would be more effective if it included all carbon losses and gains from land use in all countries and climate zones. The REDD mechanism will be an important step towards reducing emissions from land use change in developing countries, but needs to be followed by steps in other land use systems and regions. A national approach to REDD and significant coverage globally are needed to deal with the risk that deforestation and degradation activities are displaced rather than avoided. Favourable institutional and governance conditions need to be established that guarantee in the long-term a stable incentive and control system for maintaining forest carbon stocks. Ambitious emission reductions from deforestation and forest degradation need sustained financial incentives, which go beyond positive incentives for reduced emissions but also give incentives for sustainable forest management. Current data limitations need—and can be—overcome in the coming years to allow accurate accounting of reduced emissions from deforestation and degradation. A proper application of the conservativeness approach in the REDD context could allow a simplified reporting of emissions from deforestation in a first phase, consistent with the already agreed UNFCCC reporting principles.

Keywords: deforestation, forest degradation, climate change, Kyoto Protocol

1. Introduction

Carbon (C) emissions from deforestation and degradation account for about 20% of global anthropogenic emissions (IPCC-WGI 2007). Since the eleventh session of the Conference of the parties to the United Nations Convention on climate change (UNFCCC) in December 2005, strategies and incentives for reduced emissions from deforestation and degradation (REDD) have emerged as one of the most active areas in the negotiations. Support for having REDD considered in the post-2012 climate change regime is building.

[5] Author to whom any correspondence should be addressed.

REDD is on the agenda of COP13 in Bali in December 2007, and some agreement is anticipated on actions that countries might take in the short term in preparation for a potential REDD instrument.

In this paper we suggest some elements for an effective long-term implementation of a REDD mechanism under the UNFCCC and for closing some gaps in forest carbon accounting. These elements are related both to environmental and political processes, reflecting some of the most critical and debated negotiation points. The proposed elements are: (a) carbon losses from forests; (b) incentives for reducing emissions and stabilizing and maintaining forest C stocks; (c) national approach; (d) data availability at national scale; (e) conservativeness approach for carbon accounting.

2. Carbon losses from forests

While current negotiations in UNFCCC are focused on reducing emissions from deforestation and forest degradation in developing countries, it should be recognized that risks of carbon losses from forests are not confined to tropical regions and developing countries, but they occur in all climate zones and also in industrialized countries. Care must be taken to ensure that GHG emissions from land use and land use change do not increase in all regions.

Deforestation means the conversion of forest to non-forest, and is associated with land use change. Degradation in general results from unsustainable management or use of forest land. Management in UNFCCC terms means any activity of humans in ecosystems. For the purpose of this paper we define 'degradation' as processes leading to a decline of carbon stocks in ecosystems at landscape level.

Degradation may be abrupt or caused by complex, often subtle and gradual processes.

There are four major processes by which the carbon stocks of forests can be changed. These are:

- Start of management in previously unmanaged forests.
- Management and management changes in existing managed forests.
- Degradation of managed or previously unmanaged forests.
- Deforestation of managed or previously unmanaged forests.

The initiation of forest management for timber production in previously unmanaged tropical forests typically depletes forest biomass C stocks by 30–70% (Sousa *et al* 2007, Gerwing and Farias 2000). In Europe, the carbon stocks in forests managed for timber production have reached a level of 100–120 t C ha^{-1}, which is below the level observed in unmanaged national parks (140–300 t C ha^{-1}).

Management interventions can lead to increased carbon sequestration (carbon 'sink') as well as to net carbon losses. Management practices can be adopted to minimize carbon losses or increase carbon sequestration. European forestry provides an example of increased storage of carbon despite wood extraction. In most European countries forest biomass has increased over the last decades, because wood extraction was lower than growth (Ciais *et al* 2007). As a consequence, European forests are net carbon sinks (Janssens *et al* 2005). This sink is not only driven by relatively low timber extraction but also by increased biomass growth due to the young age structure of European forests, nitrogen deposition (Magnani *et al* 2007), elevated concentrations of atmospheric CO_2 and increased temperatures (Wirth *et al* 2004). However, the present forest carbon sink is bound to reverse to become a net source because growing demand for compound wood, pulp and bioenergy have increased the price for small dimensioned timber.

Table 1. 10 Nations with largest primary forest (1000 ha). FAO (2006).

Nation	Area of primary forest (1000 ha)
Brazil	415 890
Russian Federation	255 470
Canada	165 424
USA	104 182
Peru	61 065
Columbia	60 728
Indonesia	48 702
Mexico	32 850
Bolivia	29 360
Papua New Guinea	25 211

Changes in technology and markets will result in a restructuring of European forest from old age class stands into young age class stands. For Germany a decrease in the harvesting rotation period from 120 years to 60 years will result in a total loss of about 10^9 m^3 of wood over the next 10 years. Converting this amount into carbon units, it is equivalent to 5% of the German annual fossil fuel emissions. This is an example how management of land can accelerate emissions to the atmosphere in an industrialized nation, and appropriate integrated policies are needed to avoid such an impact. Comprehensive accounting of the corresponding carbon stock changes will give the appropriate signal to protect and enhance carbon reservoirs.

Causes of forest degradation include, among other things, over-harvesting and unsustainable timber harvesting practices, excessive extraction of fuel wood for non-commercial purposes, and increasing forest fire frequencies (Mollicone *et al* 2006). Degradation is facilitated by illegal activities and corruption (Amacher 2006).

Degradation may eventually lead to deforestation. In a pattern seen in many developing countries, logging concessions start the process by cutting logging roads that provide access to people who move into the area in search of land for agriculture. Unplanned forest clearance occurs where slash and burn agriculture or other agricultural conversion takes place. In most tropical soils agriculture can persist only for a limited number of years after which nutrient deficiencies and aluminium toxicity set a natural end to human activities. The abandoned land is often invaded not by forest species but by aggressive grasses, such as *Imperata cylindrica*, and this process is perpetuated particularly where fires are used as a land management tool or for hunting. In some cases, this land may be reforested. However, typically it will take decades,

Table 2. Scenarios for net changes in global forest area at constant rate of deforestation (0.18% annually), and assuming that from 2008 on, the annual deforestation rate is reduced by 5% or 10% per year. Data derived and projected from FAO (2006).

Deforestation rate scenario	Indicator	Year 2000	Year 2010	Year 2020	% of forest left in 2100	Stabilization
Constant deforestation rate	Area deforested (1000 ha)	7345	7224	7092	83	<15% of forest area after 1000 years
	Change in area deforested against previous year (1000 ha)		−13.33	−13.08		
	Reduction in annual deforestation (% of area deforested in 2000)		0	0		
5% annual reduction in deforestation rate	Area deforested (1000 ha)	7345	6196	3663	95	95% of forest area after 200 years
	Change in area deforested against previous year (1000 ha)		−337	−197		
	Reduction in annual deforestation (% of area deforested in 2000)		16	50		
10% annual reduction in deforestation rate	Area deforested (1000 ha)	7345	5269	1821	97	97% of forest area after 100 years
	Change in area deforested against previous year (1000 ha)		−594.22	−203.42		
	Reduction in annual deforestation (% of area deforested in 2000)		28	75		

if not centuries, before such land will reach its original level of carbon stocks. While degradation and deforestation may take place very quickly, reforestation and forest rehabilitation is often quite slow. Thus, the process of degradation and reforestation is a classic example of the 'fast out–slow in' process (Körner 2003).

The total amount of carbon lost to the atmosphere from these processes can be large, approximately equivalent to the carbon bound in the biomass and in part of the soil. Depending on the fertility of the soil and the climatic conditions this may range between 150 and 300 t C ha^{-1} in tropical regions up to more than 600 t C ha^{-1} in some temperate forests (WBGU 1998, Schulze 1982).

At present, the reporting obligations under UNFCCC cover all the major carbon sources and sinks from forests, including forest degradation. However, under the legally binding provisions of the Kyoto Protocol, the accounting of carbon sources and sinks of annex-I parties is mandatory only for afforestation, reforestation and deforestation activities (article 3.3). This means that forest degradation may remain unaccounted for unless the party has voluntarily elected the forest management activity (article 3.4) and it is accounting for the whole forest area.

Non-anthropogenic emissions and removals in unmanaged forests are not necessarily included in the present scope of emissions inventories reported to the UNFCCC, although these forests are highly vulnerable to human-induced carbon losses in the future. This is true particularly for primary forest. According to available data, the Forest Resources Assessment (FRA) 2005 (FAO 2006) reports that about 33% of the total

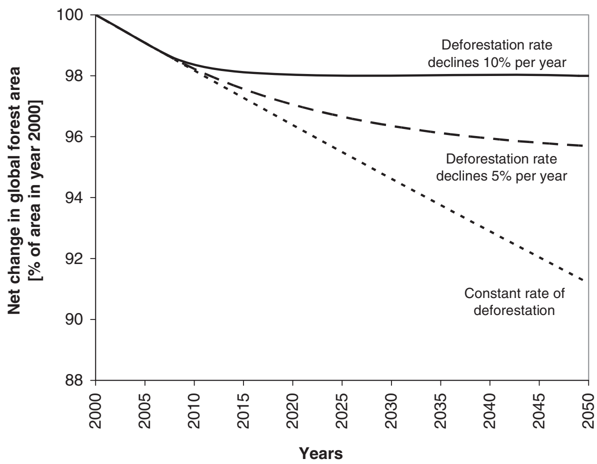

Figure 1. Scenarios for net changes in forest area at constant rate of deforestation (0.18% annually: global average for the period 2000–2005, FAO (2006)), and assuming that, from 2008 on, the annual deforestation rate is reduced by 5% or 10% per year.

forest area can be considered as primary forest. About 50% of the global primary forests are located in South America, while the other half is located in the temperate and boreal zone. Table 1 shows ten nations with the largest area of primary forest at the global scale. This table puts Brazil at the top followed by Russia, Canada and the USA before other tropical nations follow. Thus, responsibility for carbon held in these forests is not only a matter (and opportunity) for the non-industrialized countries: a high share of it rests with the industrialized world.

The GHG emissions caused by forest management, forest degradation and deforestation are all important to climate change mitigation efforts. It is quite clear that management, degradation and deforestation are continuous processes which refer to managed and unmanaged land. We suggest that a future climate agreement avoids this complicated, ambiguous distinction of terms in the future but includes them all in a broadened perspective on 'land use and land use change'.

3. Reducing, stabilizing, maintaining

The anticipated REDD mechanism aims at slowing down the rate at which the remaining primary and managed forests are degraded and deforested. This would ultimately lead to a stabilization of the remaining forest area. The necessary level of ambition is determined by two elements: how much forest would be left at stabilization? How fast can the forest area and carbon stocks be stabilized?

The extent of C losses by degradation cannot be quantified at the global level. Therefore the following scenarios only consider deforestation. The conclusions made from the scenarios, however, are equally applicable to degradation. Let us assume simple generic deforestation scenarios in which forest area monotonically declines at fixed reduction rates in deforestation. Net change in forest area is taken as proxy due to large uncertainties in forest C stocks (section 5). However, the ultimate target commodity under the UNFCCC is reduced CO_2 emission. The deforestation scenarios could be interpreted as a global goals for REDD or a global market situation in which countries successively join. Continuing deforestation at its present rate would marginally reduce the annual deforested area relative to historical forest area losses but would fall far short of halting deforestation in the long-term (table 2, figure 1). Reducing the global deforestation rate annually by 5% after 2008 (table 2, figure 1) would allow stabilization of the global forest area at 95% of its present extent (table 2, figure 1).

Following our assumption of constantly declining rates of deforestation most of the reduction in forest loss will occur in the first few years. This is in line with the success stories from, for example, Costa Rica and India. Brazil recently reduced deforestation by half by new policies. Slowing down emissions from deforestation may be a 'fast, easy and cost-effective' task at the beginning and much faster than in our '10% annual reduction' scenario illustrated in table 2 and figure 1. Reducing the global deforestation rate annually by 10% after 2008 would allow reduction of deforestation emissions by 75% by 2020 (table 2, figure 1).

We demonstrate with our simple scenarios that the present REDD mechanism sets a perverse incentive for countries to continue deforestation at only slightly reduced rates. The reason is the necessity to match implementation costs with the flow of positive incentives from REDD. Unlike the accounting of assigned amount units under the Kyoto Protocol, the REDD mechanism is set to credit emission reductions. Hence the overall volume of positive incentives achievable by a country

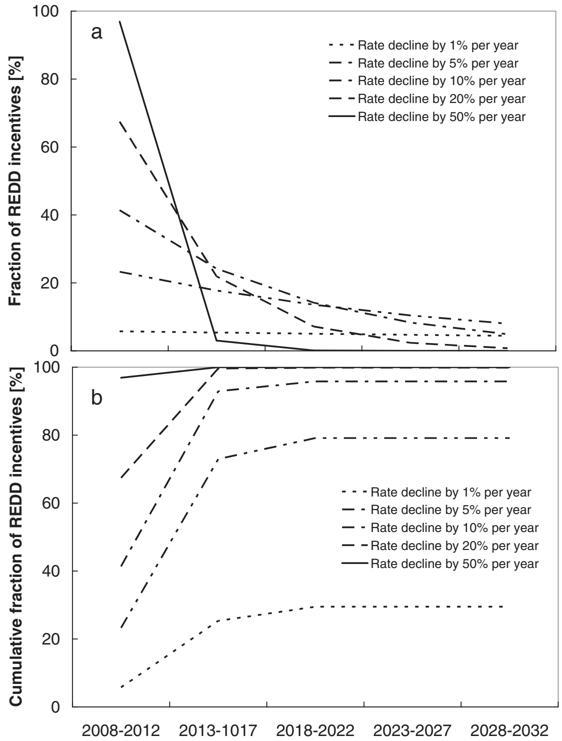

Figure 2. Scenarios for positive incentives from REDD at various ambition levels for a hypothetical country. Panel (a) shows the fraction of positive incentives from REDD obtainable in each consecutive five-year application periods. Panel (b) shows the cumulative fraction of positive incentives from REDD obtainable in consecutive five-year application periods.

is limited to its past emission level. The country needs to decide whether to receive positive incentives now or later, fast or slow, and will try to adjust the likely flow of payments with its anticipated flow of costs for REDD. We use the area not deforested as compared to the previous year as a proxy for emission reductions. High emission reduction rates at the start produce a large volume of emission reductions in the first years followed by a dramatic decline in additional emission reduction in consecutive periods (figure 2). However, long-term success in reducing forest emissions requires continuous sustained policies and measures and adequate resources. In addition, after the less costly options for reducing deforestation and forest degradation are implemented, the more difficult and costly ones—those representing higher opportunity costs—will be left. Therefore, it is expected that the costs per unit of reduced emissions will increase over time. The real challenge for REDD will be to ensure that the reduction of emissions from forests will be durable; that there will be no tendency to reverse the process. For this, it will be essential that, in addition to counteracting pressures leading to deforestation, sustainable forest management systems are put in place. Without this long-term perspective, the contribution of a REDD mechanism will ultimately be ineffective for climate change mitigation.

Any consistent reduction process must quite soon turn from a short reduction phase to a long stabilizing phase (see figures 1 and 2). Reduction and stabilization are two consecutive periods of the same track towards the conservation of the existing forest and carbon pools and thus the mitigation of climate change. The two phases need to be incorporated from the very beginning in REDD incentive schemes. The main challenge will be to modulate the incentives in relation to the different national circumstances and different stages (reduction and stabilization) of the emission reduction process.

Incentives targeted at compensating reduced emissions help to start activities, but rapidly decline over time, in particular when the start is ambitious. Other incentives are needed, e.g. payments for environmental services (Vanclay 2005), or a different target commodity under the UNFCCC, such as the conservation of C stocks, or a combination. These other incentives do not fit into the current emission trading schemes.

4. Leakage and liability

Geist and Lambin (2002) conclude in their study on deforestation drivers: 'Tropical forest decline is determined by different combinations of various proximate causes and underlying driving forces in varying geographical and historical contexts'. Each country has a unique set of drivers of deforestation and forest degradation and of appropriate policies and approaches to address them. Deforestation can be slowed down only if it is addressed through a comprehensive set of policies and measures that are compatible with the socio-cultural, economic, political and ecological conditions of the country.

Following the existing Kyoto Protocol examples, two different options could be followed in dealing with emission reduction for a REDD mechanism: the national approach and a project-based mechanism. It is worth noting that, whilst the national approach may have projects embedded in it, a project-based approach would almost certainly not provide for national coverage. From a technical standpoint, leakage is the main factor that makes a national approach preferable to a project-based one. This is because, in the absence of additional positive incentives to counteract deforestation and forest degradation outside the project area, the project activities could easily shift human pressures from the project areas to other areas, causing additional environmental and socio-economic impacts. Discounting environmental impacts on forest areas outside the project area would probably mean that project participants would not be able to claim for any positive incentives since leakage counteract the reduction in emissions within the project area. In practice, the impossibility of a project-based mechanism to guarantee that it results in an overall reduction of emissions from a country's forests makes it unsuitable for responding to the final goal of a REDD mechanism: reducing emission from forest in developing countries.

A second important factor to be considered is the liability of subjects acting in the mechanism. While a no-lose target could be agreed for a national approach mechanism since a negative performance in a certain accounting period (i.e. increase in emission from deforestation in the accounted land) could be discounted in the greenhouse gas balance of the following periods, for the project approach it should not be. Indeed, in the case of an increase in emission from the project area the related debits should be addressed on time by project participants since there are no guarantees that the project will act in the following accounting periods and so that the debits could be compensated in the future.

Anyway, the national approach in itself does not solve the problem of the displacement of deforestation from one country to another country. In this respect the REDD mechanism should include also some rules to guarantee, in some degree, a broad participation and a common liability. An option, the global baseline, has been already discussed in a previous paper (Mollicone *et al* 2006), but most probably a more agreeable solution could be the threshold rule as was used for the entry into force of the Kyoto Protocol (that rule established thresholds in term of total emissions and number of countries). This approach may minimize leakage, enforce liability and overall ensure that REDD will result in real mitigation effort.

Deforestation and degradation are correlated with corruption and governance failure (Smith *et al* 2003, Vanclay 2005). A REDD mechanism should include incentives for good governance, or even make good governance an eligibility criterion for the participation of countries. Historical forest degradation cannot be quantified yet.

5. National data availability

The global Forest Resources Assessment 2005 of the Food and Agriculture Organization provides a global dataset on forest resources, including growing stock, biomass and carbon stock, based on country submissions to the FAO. The results of this data compilation effort provide useful insights into the status of availability and accuracy of national data on forest carbon (Marklund and Schoene 2006). The conclusions include the following:

- The quality and reliability of country data are highly variable.
- The majority of countries lacks good forest inventory data; they rely on use of conversion factors and default values.
- There is weak trend data on growing stock; most countries do not have inventory data at two or more points in time.
- Reporting on carbon in soil and litter is limited.

Out of 229 countries and territories, 143 reported on carbon in biomass, and only 50 reported on carbon in litter and soil. Of 147 countries reporting time series on growing stock, 83 countries have only one figure on growing stock per hectare. Thirty-four countries provided no data, 38% of countries provided data at IPCC Tier 1 level (indicating an absence of country-specific data), 22 at Tier 2 level and six at Tier 3 level. Clearly, important gaps need to be addressed in order to make better estimates of forest carbon stocks.

The situation is particularly limiting in developing, or non-annex 1 countries, particularly in the smaller and less forested countries. As developing countries account for the large majority of deforestation globally (as indicated by the reduction in forest areas reported for FRA 2005, even if the carbon densities are uncertain), they have most to offer to

Table 3. Example of how ignoring a carbon pool may produce a conservative estimate of reduced emissions from deforestation. The reference level might be assessed on the basis of historical emissions. (1) Complete estimate, including the soil pool; (2) incomplete estimate, as the soil pool is missing. The latter estimate of reduced emissions is not accurate, but is conservative.

		Carbon stock change (t C ha^{-1} deforested)		Emissions (area deforested × C stock change, t C × 10^3)	
	Area deforested (ha × 10^3)	Aboveground biomass	Soil	Aboveground biomass + soil	Only aboveground biomass (no soil)
Reference level	10	100	50	1500	1000
Assessment period	5	100	50	750	500
Reduction of emissions (reference level—assessment period, t C × 10^3)				750 (1)	500 (2)

efforts to reduce the rate of greenhouse gas emissions from forests. These countries would also have the most to gain from a potential REDD mechanism that would provide financial incentives to countries reducing their emissions from forests. Many, if not most, developing countries, however, will need to expend considerable effort in improving their forest data collection and management systems if they are to be able to benefit from an eventual UNFCCC REDD instrument.

FAO has a programme to support national forest assessment programmes (http://www.fao.org/forestry/site/33791/en/gtm/). The experience shows that, within two to three years, a country may establish a forest monitoring system to assess the present status of forest resources, their management and uses. Within an additional three to four years, e.g. through support to a readiness phase, countries will be able to report to the UNFCCC Secretariat on emissions from forests according to the 2006 IPCC guidelines for national greenhouse gas inventories for agriculture, forestry and other land use (IPCC AFOLU Guidelines).

While data on forest carbon pools collected in the present may, with some assumptions, be used to estimate forest carbon content in forests in the past, there are more limitations on assessing historical deforestation rates connected to the availability of satellite earth observation data. There are only a few years for which there are global sets of earth observation data that can be used for assessing forest cover in tropical areas (i.e. the years 1975, 1990 and 2000). This means that accurate forest cover trend analyses are available for only a few points in time since 1975 for most countries.

6. Conservativeness approach for carbon accounting

To be fully and appropriately assessed, carbon sources and sinks in forest land require national monitoring capabilities. This represents a challenge even for industrialized countries. These technical constraints have been often used as an argument not to include these processes (or to include them only partially) in climate change mitigation efforts. Nevertheless, we point here at a practicable and easy way out of this.

Any mechanism of positive incentives for REDD will require robust estimates, both for the amount of deforested areas and for the carbon stocks in those areas. On the other hand, it requires a broad participation from developing countries to reduce the risk of emissions displacement from one country to another. Under the current UNFCCC reporting system, 'estimates of emissions should be accurate in the sense that they are systematically neither over nor under the true value, so far as can be judged, and that uncertainties are reduced so far as is practicable' (UNFCCC 2003). Whilst the capacity for monitoring the amount of deforested area is rapidly improving, in many developing countries the scarcity of reliable data on carbon stocks, especially for soil (FAO 2006), suggests that the overall estimates of emissions are not likely to be accurate. However, a simple approach—already accepted for the accounting of emissions under the Kyoto Protocol—may greatly simplify the requirements needed to get defensible estimates of reduced emissions. It is the 'conservativeness approach' (UNFCCC 2006). In the REDD context, conservativeness means that—when accuracy cannot be achieved—the reduction of emissions should not be overestimated. In practice, conservative estimates of carbon stock changes could require considerably less data than accurate estimates. For example, provided that the area deforested is reduced as compared to a reference level, if emissions from a carbon pool (e.g. the soil) are not reported, the resulting estimates of reduced emissions will not be accurate, but will be conservative (table 3).

The approach of conservativeness would help preserve the 'climate integrity' of any REDD mechanism, providing a win–win option. On the one hand, it guarantees that the economic incentives are not leading to 'hot air', thus helping to convince policy makers, donors and investors in industrialized countries. On the other hand, it helps a broad participation from developing countries, allowing them to join the mechanism even if they cannot provide accurate estimates for all carbon pools.

Furthermore, such an approach would provide a clear incentive for increasing the quality of the reporting: indeed, more complete and accurate reporting (e.g. including all carbon pools) would increase the estimate of reduced emissions, potentially allowing one to claim for more incentives. If the future REDD reporting rules will fix some minimum quality standard and will provide some guidance on the expected accuracy and cost of the different estimation methodologies, there could be envisaged a system in which—provided that conservativeness is satisfied—parties are allowed to choose for themselves what estimate/report and at which tier, depending on their own cost–benefit analysis. If a REDD mechanism starts with conservativeness, accuracy will follow.

7. Conclusions

(1) Carbon losses from deforestation and degradation represent a significant fraction of total carbon stock changes caused by mankind in developing and industrialized countries.
(2) Efforts to mitigate climate change may be delayed or even unsuccessful if land use and land use change in general, and deforestation in particular, are not addressed.
(3) A future climate change agreement would be more effective if it included all carbon losses and gains from land use in all countries and climate zones. The REDD mechanism will be an important step towards reducing emissions from land use change in developing countries, but needs to be followed by steps in other land use systems and regions.
(4) A national approach and significant coverage globally are needed to deal with the risk of leakage.
(5) Favourable institutional and governance conditions need to be established that guarantee in the long term a stable incentive and control system for maintaining forest carbon stocks.
(6) Ambitious emission reductions from deforestation and forest degradation need sustained financial incentives, which go beyond positive incentives for reduced emissions but also give incentives for sustainable forest management.
(7) Current data limitations need—and can be—overcome in the next few years to allow accurate accounting of reduced emissions from deforestation and degradation.
(8) A proper application of the conservativeness approach in the REDD context could allow a simplified reporting of emissions from deforestation in a first phase, consistent with the already agreed UNFCCC reporting principles.

Disclaimer: The views expressed in this paper may not in any circumstances be regarded as stating an official position of the European Commission.

References

Amacher G S 2006 Corruption: a challenge for economists interested in forest policy design *J. Forest Econ.* **12** 85–9
Ciais P, Nabuurs G J, Cescatti A, Piao S L, Lemaire G, Schulze E D, Liski J, Buriaud O, Zaehle S and Schelhaas J 2007 European forests: when sponges make hard wood, submitted
FAO 2006 *Global Forest Resources Assessment 2005* Food and Agriculture Organization of the United Nations
Geist H J and Lambin E 2002 Proximate causes and underlying driving forces of tropical deforestation *BioScience* **52** 143–50
Gerwing J J and Farias D L 2000 Integrating liana abundance and forest stature into an estimate of total aboveground biomass for an eastern Amazonian forest *J. Tropical Ecol.* **16** 327–35
IPCC-WGI 2007 *Climate Change 2007: The Physical Science Basis* (Cambridge: Cambridge University Press)
Janssens I A *et al* 2005 The carbon budget of terrestrial ecosystems at country-scale—a European case study *Biogeosciences* **2** 15–26
Körner C H 2003 Slow in, rapid out—carbon flux studies and Kyoto targets *Science* **301** 1242
Magnani F *et al* 2007 The human footprint in the carbon cycle of temperate and boreal forests *Nature* **447** 848–50
Marklund L and Schoene D 2006 Global assessment of growing stock, biomass and carbon stock *Forest Resources Assessment Working Paper 106* (ftp://ftp.fao.org/docrep/fao/010/ah849e/ah849e00.pdf)
Mollicone D, Eva H and Achard F 2006 Human role in Russian wild fires *Nature* **440** 436–7
Schulze E-D 1982 Plant life forms and their carbon, water and nutrient relations *Physiological Plant Ecology II. Water Relations and Photosynthetic Productivity* (*Encyclopedia of Plant Physiology* vol 12B) ed O L Lange, P S Nobel, C B Osmond and H Ziegler (Berlin: Springer) pp 615–76
Smith R J, Muir R D J, Walpole M J, Balmford A and Leader-Williams N 2003 Governance and the loss of biodiversity *Nature* **426** 67–70
Sousa C, Sales M H, Monteiro A L and Mollicone D 2007 Monitoring forest degradation: approaches and challenges to REDD *Environ. Res. Lett.* submitted
UNFCCC 2003 Guidelines for the preparation of national communications by parties included in annex I to the convention, part I: UNFCCC reporting guidelines on annual inventories *FCCC/CP/2002/8* Decision 18/CP.8
UNFCCC 2006 Good practice guidance and adjustments under Article 5, paragraph 2, of the Kyoto Protocol *FCCC/KP/CMP/2005/8/Add.3* Decision 20/CMP.1
Vanclay J K 2005 Deforestation: correlations, possible causes and some implications *Int. Forest Rev.* **7** 278–93
WBGU 1998 The accounting of biological sinks and sources under the Kyoto protocol: a step forward or backwards for global environmental protection? *Special Report, Bremerhaven* German Advisory Council on Global Change, p 75
Wirth C, Schulze E D, Schwalbe G, Tomczyk S, Weber G and Weller E 2004 Dynamik der Kohlenstoffvorräte in den Wäldern Thüringens. Mitteilungen der Thüringer Landesanstalt für Wald, Jagd und Fischerei 23, p 308