SSD

SCIENCE FOR A SUSTAINABLE DEVELOPMENT

BE-REDDI

BELGIAN PLATFORM FOR REDD+ INFORMATION

DAUWE, T., CUYPERS, D., MEYFROIDT, P., SWINNEN, E., VANGOIDSENHOVEN, M., VERBIST, B.

ENERGY

TRANSPORT AND MOBILITY

AGRO-FOOD

HEALTH AND ENVIRONMENT

CLIMATE

BIODIVERSITY

ATMOSPHERE AND TERRESTRIAL AND MARINE ECOSYSTEMS

TRANSVERSAL ACTIONS

.be

SCIENCE FOR A SUSTAINABLE DEVELOPMENT

(SSD)

Climate

FINAL REPORT

"BE-REDDI"

BELGIAN PLATFORM FOR REDD+ INFORMATION

SD/CL/10

Promotors:

Dauwe Tom (VITO)
Meyfroidt Patrick (UCL)
Nyssen Jan (UGent)
Swinnen Else (VITO)
Verbist Bruno (KUL)

Authors:

Dauwe, T.[1], Cuypers, D.[1], Meyfroidt, P.[2], Nyssen, J.[3], Swinnen, E.[4], Vangoidsenhoven, M.[1], Verbist, B.[5]

1. VITO, unit Transition, Energy and Environment, Boeretang 200, 2400 Mol; 2. UCL, Earth and Life Institute, Chemin du Cyclotron 2, 1348 Louvain-la-Neuve; 3. UGent, Department of Geography, Krijgslaan 281, 9000 Gent; 4. KUL, Division of Forest, Nature and Landscape, Celestijnenlaan 200, 3001 Heverlee; 5. VITO, unit Remote Sensing, Boeretang 200, 2400 Mol, Belgium.

Belgian Science Policy Office
Avenue Louise 231
Louizalaan 231
B-1050 Brussels
Belgium
Tel: +32 (0)2 238 34 11 – Fax: +32 (0)2 230 59 12
http://www.belspo.be

Contact person: Aline Van der Werf
+32 (0)2 238 36 71

Dauwe, T., Cuypers, D., Meyfroidt, P., Swinnen, E., Vangoidsenhoven, M., Verbist, B., Be-REDDi. Final Report. Brussels: Belgian Science Policy, 2012 – 74 p. (Research Programme Science for a Sustainable Development)

Table of content

List of abbreviations

A/R	Afforestation/Reforestation
AAU	Assigned Amount Units
AFOLU	Agriculture, forestry and land use
BAP	Bali Action Plan
BAU	Business-as-usual
CDM	Clean Development Mechanism
CER	Certified Emission Reduction
CfRN	Coalition for Rainforest Nations
COP	Conference of the Parties
EC	Eddy Covariance
ERU	Emission Reduction Unit
ETS	EU Emission Trading Scheme
EU	European Union
FCPF	Forest Carbon Partnership Facility
GPG	Good Practice Guidelines
GPP	Gross Primary Productivity
IPCC	Intergovernmental Panel on Climate Change
LUCC	Land Use and Land Cover
LULUCF	Land Use, Land Use Change and Forestry
MRV	Monitoring, Reporting and Verification
NAMA	National Appropriate Mitigation Action
NBP	Net Biome Productivity
NEE	Net Ecosystem Exchange
NEP	Net Ecosystem Productivity
NGO	Non-Governmental Organisation
NPP	Net Primary Productivity
PAM	Policies and measures
REALU	Reducing Emissions from All Land Uses
REDD	Reducing Emissions from Deforestation and forest Degradation in developing countries
TDERU	Tropical Deforestation Emission Reduction Unit
UNFCCC	United Nations Framework Convention on Climate Change

Introduction

The United Nations Framework Convention on Climate Change (UNFCCC) was established to avoid negative impacts of climate change through prevention, mitigation and adaptation. Deforestation and degradation of forests in developing countries contributes to approximately 12 to 17% of the global annual greenhouse gas emissions (IPCC, 2007; van der Werf *et al.*, 2009). With such a large share, reducing emissions in the Land-Use, Land Use Change and Forestry (LULUCF) sector is essential in climate change mitigation. Despite of being a substantial opportunity for achieving significant greenhouse gas emission reductions, avoided deforestation projects were excluded from the Kyoto Protocol's Clean Development Mechanism (CDM), because of methodological and political reasons (Fry, 2008). Furthermore, there were concerns that including a project-based mechanism that could avoid deforestation in the CDM could result in significant leakage, permanence problems, flooding the market with cheap credits, massive offsetting through this mechanism and additionality problems (Fry, 2008). Thus, for the first commitment period, LULUCF mitigation options in developing countries were limited to CDM afforestation and reforestation projects (Schlamadinger *et al.*, 2007).

Avoiding deforestation was however not of the negotiating table and during the UNFCCC meeting in Montreal in 2005, the Coalition for Rainforest Nations (CfRN) proposed a new mechanism to deal with emissions from deforestation. Since then discussions on Reduced Emissions from Deforestation and forest Degradation in Developing Countries (REDD) have progressed considerably. The objective of a REDD payment distribution mechanisms is to support policies and measures that reduce deforestation and degradation through the transfer of revenues from international REDD funds or carbon markets to (or within) national levels. This may provide benefits of three types:

a) shared responsibility for reducing a major driver of global climate change,
b) financial payments and co-investment that exceed the economic opportunities foregone from decisions to maintain carbon stocks, and
c) co-benefits through the other environmental service functions that well-maintained forests can provide.

To ensure demonstrable results on emission reduction, REDD must be effective in targeting the wide range of agents involved in deforestation and degradation (drivers). Therefore they must incentivize and reward good performances compared to reference scenarios and adequately compensate agents that suffer losses from changed practices.

Ultimately, the objective of a REDD scheme is to scientifically, technologically and financially support developing countries to install policies and measures that reduce deforestation and degradation. To ensure verifiable emission reductions, effective forest monitoring systems must be installed in participating developing countries. These systems will have to combine remote sensing imagery and field data. A particular difficulty for developing countries will be to establish an effective and cost-efficient system to monitor and assess the progress that has been made in the different activities that are eligible under REDD.

In the end, REDD can only be successful if developing countries are able to deal with the agents that are driving deforestation and forest degradation. REDD can thus only be viewed in the larger context of agriculture, forestry and land use (AFOLU). Developing countries have the extremely difficult task to protect and conserve their forests in an age when demand for forest products and agricultural commodities will only increase due to increasing population (especially in developing countries), increased welfare (and subsequent consumption) and in some regions declined agricultural productivity due to climate changes and other environmental problems (*e.g.* soil erosion). Part of the solution could be to move from REDD to REALU (reducing emissions from all land uses), abandoning the sometimes artificial distinction between forest and non-forest. REALU would give developing countries an incentive to look at land use in an holistic perspective.

Any REDD scheme will however come with a considerable cost to developing countries. Not only costs to national or sub-national governments in implementing policies and measures (PAM) and setting up an effective forest monitoring system, but also the foregone economic benefits from further deforestation (opportunity costs). An international REDD scheme that is not able to attract sufficient funds from developed countries or international carbon markets to provide an incentive to all developing countries to keep forests intact, is deemed to be ineffective as it will lead to leakage.

In this report, a comprehensive review is given of the ***different options for the REDD building blocks*** and a ***state-of-play is given of the REDD negotiations***, up to Durban. This focuses on the progress that has been made so far in crystallizing a workable REDD scheme. The REDD discussions focus on the five essential building blocks of any REDD scheme:

- what kind of activities will be eligible and can be accounted for (*scope*);
- will REDD be project-based (such as the CDM) or will it be al (sub-)national level (*scale*);
- how will the efforts of developing countries be assessed and how will they be rewarded (*accounting*);
- how will emission reductions be monitored and reported (*MRV*);
- and where will the money come from to reward developing countries (*finance*).

Most developing countries do not have the technological and scientific capacity at this moment to monitor forests with sufficient accuracy at this stage. This could be a bottle neck for these developing countries to participate fully in a REDD scheme where payments will be results-based. Cheap but accurate forest monitoring tools are needed (Bucki et al., 2012). In this respect, the ***applicability of low resolution imagery in REDD*** is discussed.

Addressing the drivers of deforestation will be critical for national or sub-national governments of developing countries. In a globalised world, these have however become more elusive for national authorities. The potential ***undermining effect of increasing global demand for agricultural commodities on REDD*** is given. It will therefore be essential for the success of REDD that the financial and non-financial (*e.g.* ecosystem services of forests) reward for developing countries not only offsets the foregone benefits but also puts them on track of sustainable economic growth.

1. REDD+ in the UNFCCC

1.1. Policy options for REDD+

Introduction

The design and details of the REDD+ decision, require careful consideration because it will have environmental, economic and social implications in the long term (Ghazoul *et al.*, 2010). But REDD could also provide numerous co-benefits in addition to the reduction of greenhouse gas emissions (Stern, 2006). These include biodiversity and watershed conservation, renewable energy supply, food security for local communities and the maintenance of soil resources; and social benefits such as poverty alleviation and the protection of land and human rights (Dickson *et al.*, 2009). These co-benefits will be achieved if the design of the international REDD+ framework provides incentives to project developers and governments across scales.

The international design of REDD+ will need to provide incentives to all developing countries, bridging the diversity in historical deforestation rates and capacities to implement forest policies and monitor emissions.

To date governments, non-governmental organizations (NGOs) and scientists have put forward many specific proposals on the design of a forestry-based mitigation mechanism (Parker *et al.*, 2009). These proposals differ along a number of dimensions, such as the type of activities that will be included (scope), the geographical scale, the sources of funding and the approach of greenhouse gas accounting (CIFOR, 2010).

Many options have been proposed during the negotiation process and some have been placed in the background. For this analysis, we use a modular framework, drawn upon recent work undertaken by The Prince's Rainforest Project and The Global Canopy Programme (Parker *et al.*, 2009), consisting of five building blocks, representing the key constituents of any future international REDD mechanism *e.g. scope*, *geographical scale*, *accounting mechanism*, *monitoring, reporting and verifying (MRV) scheme* and *financing mechanism* (Figure 1). Using this framework as a guidance, the options for each building block that have emerged are compared.

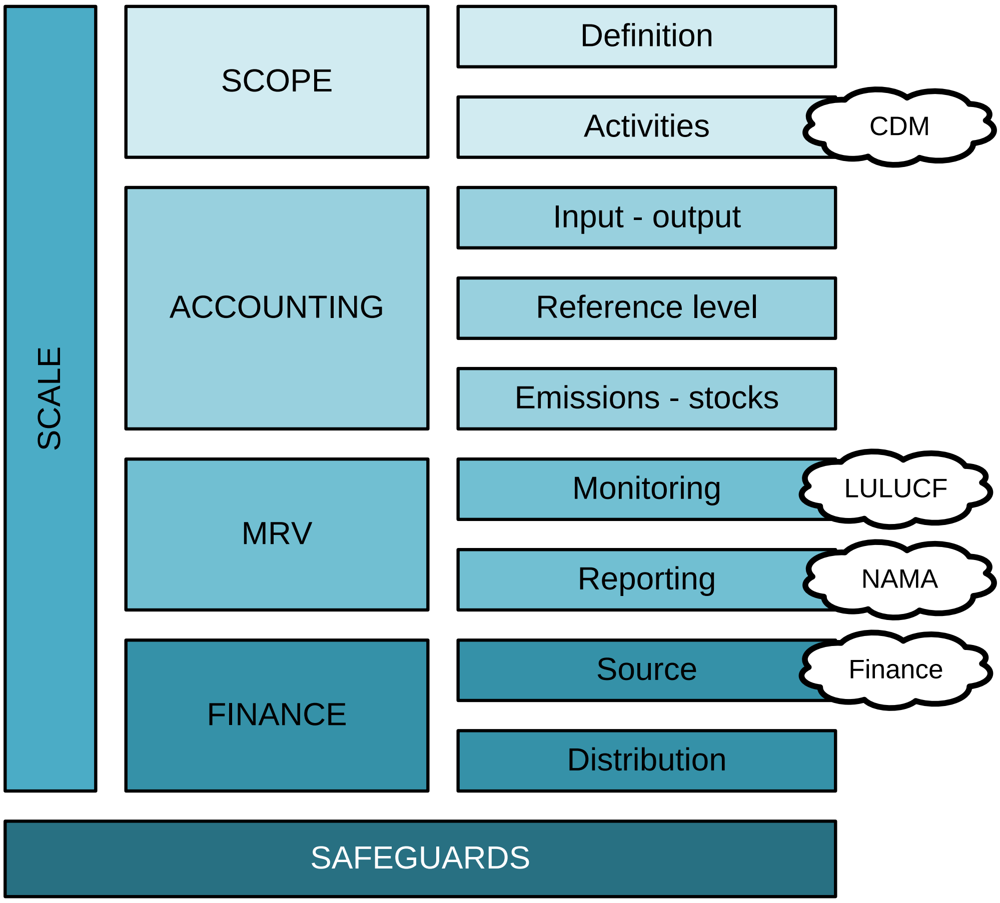

Figure 1. Essential building blocks and elements of any REDD+ scheme. Links with other climate change discussions are outlined.

The scope of REDD

Definitions

An important aspect is what is meant with forest (see also section 2.1). In total, there are over 890 different definitions of forests (Lund, 2005) and this has a significant impact on assessment of forest area (see Colson et al., 2009). The definition used in the UNFCCC is an area of more than 0.5–1.0 ha with a minimum “tree” crown cover of 10–30 %, with “tree” defined as a plant with the capability of growing to be more than 2–5 m tall. However, it also includes young stands of natural regeneration, all plantations which have yet to reach the required crown density or tree height, and areas normally forming part of the forest area which are temporarily unstocked as a result of human intervention (such as harvesting or natural causes) but which are expected to revert to forest. It would be logical that this definition (used in the Kyoto Protocol) will also be used in REDD+. However, this forest definition could lead to perverse incentives as it makes no distinction between natural forests rich in biodiversity and monoculture plantations. The inclusion of safeguards in REDD+, which include forest ecosystem services, has to some degree avoided the need of a more restrictive forest definition. However, not only a clear definition of a forest is needed, but also for all other activities that are eligible under REDD+ (Sasaki and Putz, 2009; Simulu, 2009).

What kind of activities?

One of the key questions regarding REDD concerns the scope of land use and forestry activities that developing countries could undertake to contribute to climate change mitigation (Angelsen, 2008). Since the beginning of the negotiation process in, 2005, there has been considerable interest in expanding this list of activities (Lawlor *et al.*, 2010). The increasing number of activities included in the scope reflects the history of the policy debate, in which, at first, only avoiding deforestation (RED) was recognised as an important goal, to which avoiding forest degradation (REDD) was quickly appended. The additional elements making up REDD+, *i.e.* the conservation of forest carbon stocks, sustainable forest management and the enhancement of forest carbon stocks entered the debate at COP 13 in, 2007 (Herold and Skutsch, 2011). More recently, suggestions were made to expand the scope beyond forestry-based activities to also include CO_2 and other greenhouse gas emissions from agricultural and other non-forest lands. This approach, which is based on a full land-based accounting of agriculture, forestry and land use (AFOLU), is termed 'Reducing Emissions from All Land Uses (REALU) or REDD++ (Van Noordwijk *et al.*, 2009). In the latter, all transitions in land cover that affect carbon storage are included, whereas in a REDD+ mechanism, developing countries can implement various activities that are voluntarily chosen from a list provided by the UNFCCC.

The first reason for expanding the list of activities was the recognition that forest degradation is a significant source of carbon emissions. Because the UNFCCC defines a forest as an area with a minimum crown cover of 10–30%, forests can be significantly degraded before they are considered deforested. Thus, without the inclusion of avoiding forest degradation as a goal, the integrity of the mechanism would be jeopardised. A second aim of broadening the scope was to minimise the potential for the displacement, or "leakage", of emissions to land uses not included in the scope. The additional activities making up the '+' would allow countries with varying rates of deforestation and levels of forest cover to participate, which will improve not only the international equity of the mechanism but also prevent shifting of deforestation activities to countries with low deforestation rates. Including agriculture, wetlands, peatlands and grasslands in the scope makes the mechanism even more effective at minimising leakage, because all displacements of emissions among sectors and land categories, including non-forest biomes, will be covered under AFOLU accounting (Lawlor *et al.*, 2010). A third reason is the potential for maximising the climate contributions from the land-use sector by not only reducing negative changes but also by enhancing positive changes and, in the case of AFOLU accounting, additionally reducing emissions from agriculture (Lawlor *et al.*, 2010).

However, broadening the scope also has some drawbacks. First, it increases complexity, particularly for measuring and monitoring, because four of the above-mentioned activities are not land-use change processes, as they constitute forest land that remains forest land, *i.e.* existing forests undergoing degradation, conservation, sustainable management and/or the enhancement of forest carbon stocks (GOFC-GOLD, 2009). Second, the UNFCCC does not have officially adopted definitions of forest degradation, sustainable forest management or the enhancement of forest carbon stocks (Griscom *et al.*, 2009). The lack of universally agreed-upon definitions of these terms will cause complications when REDD is implemented on the ground (Sasaki and Putz, 2009). Third, uncertainty remains regarding the question of whether the term 'enhancement of forest carbon stocks' includes forest restoration only on lands already classified as forests or also includes the forestation of non-forest land (Angelsen *et al.*, 2009b). A challenge associated with including afforestation/reforestation (A/R) is that it is already part of the CDM under the Kyoto Protocol. Excluding A/R, however, risks fragmentation of the overall forestry architecture (Angelsen, 2008). A last concern is that an expanded list of creditable activities can lead to the conversion of natural forests into plantations, because the UNFCCC definition does not recognise different biomes and, importantly, does not distinguish natural forests from plantations (Sasaki and Putz, 2009; Lawlor *et al.*, 2010).

This definitional problem would be resolved in an AFOLU approach, because all transitions in land cover that affect carbon storage would be included (Van Noordwijk *et al.*, 2009). Furthermore, REDD++ avoids fragmenting the framework into separate systems for different land-use categories. However, the work leading to an integrated AFOLU framework will be complicated (Angelsen, 2008). For this reason, including all carbon sources and sinks related to land use is supported as the ultimate objective of a future REDD mechanism but may be too complex to implement in the short term (UNFCCC, 2009).

The accounting mechanism specifies how emission reductions (ERs) and/or carbon stock enhancements are measured (Parker *et al.*, 2009). The following sections show the steps and the options for designing such an accounting mechanism for REDD.

Accounting Basis

As a first step, the basis on which payments or credits would be made must be defined. Payments can be based either on the inputs needed to achieve a specific outcome or on the actual outcome (Angelsen, 2008). Input-based schemes suggest that financial benefits should be provided on the basis of developing countries' implementation of policies and measures (PAM) to reduce emissions from deforestation and forest degradation, as in, for example, the 'Compensated successful efforts' proposal of Combes-Motel *et al.* (2009). Under an output- or performance-based approach, financial incentives are provided proportionally to the results achieved by REDD actions (Angelsen, 2008). Payments would be granted for additional carbon sequestration or reduced emissions relative to a reference level calculated over a specified reference period (Santilli *et al.*, 2005; Plantinga and Richards, 2008).

An advantage of the input-based approach is that deforestation levels need not be measured, whereas output-based approaches require a measurable output, ruling out certain countries that currently lack adequate technical capacity and institutions for these measurements (Alvarado and Wertz-Kanounnikoff, 2007). However, because financial benefits would be directly conditional on services delivered, such output can easily be connected to compliance markets, accommodating all sources of financing (see xxx), whereas input-based approaches can only be financed through a fund (Angelsen, 2008; Tacconi, 2009). Input-based programs would have some advantages in terms of lower transaction costs and the opening of separate negotiations regarding international forest sequestration and energy emissions (Aldy and Robert, 2008). An important limitation of the input-based approach is that it may be difficult to assess the likely impacts of many of the PAMs that countries might use to address the drivers of deforestation. Furthermore, reductions in greenhouse gas emissions could probably not be measured with sufficient certainty. The implementation of such PAMs should therefore be measured, reported, and verified using non-greenhouse gas metrics (Daviet, 2009).

Setting Reference Levels in an Output-Based Approach

A reference level can be defined as the level of a specified output (*e.g.* an emission or a carbon stock level), either at a point in time or over a period of time, that could be used to measure performance and/or award credits (Angelsen, 2008; Havemann, 2009). The reference level could be the same as a business-as-usual scenario (BAU), indicating a prediction of future emissions without REDD. However, proposals have been made to set the crediting reference level above (in the case of carbon stocks) or below (in the case of emissions) the BAU (Angelsen, 2008). Different proposals have been put forth for defining the key characteristics for setting reference levels, including the output and the reference period. These variables are explained in the next paragraphs.

Defining output

The output can be defined either as an emission (or a flow), as a carbon stock or as a combination of the two (Plantinga and Richards, 2008; Angelsen *et al.*, 2009a). In the flow- or emission-based approach, only the net changes in carbon stocks for specific periods are used to calculate credits (Angelsen, 2008). In this case, the reference level indicates greenhouse gas emissions from deforestation and forest degradation in the absence of additional efforts to curb such emissions (Griscom *et al.*, 2009). As an alternative or complement to the emission-based approach, suggestions have been made to connect incentives directly to the amount of forested area or forest carbon stock, regardless of a country's past deforestation rates. The 'stock-flow' approach uses an reference level based on historical emissions but relies on a second instrument, *i.e.* a stabilisation fund, which provides payments for stocks but is not associated with credits. A fraction of the payments for reductions is withheld to raise funds to be distributed to forest countries in the form of payments for forest stocks (Cattaneo *et al.*, 2010).

An emission-based approach was used in the Kyoto Protocol, making its application in REDD a natural step (Angelsen, 2008). However, opponents have pointed out the methodological challenges associated with emission-based approaches including data quality and availability, leakage control (Prior *et al.*, 2007), and equity concerns such as accounting for early efforts in forest conservation (Cattaneo *et al.*, 2010). Arguments in favour of the stock-based approach are the likely greater carbon effectiveness (Ashton, 2008) and the greater willingness of the private sector to pay (Prior *et al.*, 2007). A risk of the stock-based approach is that payments could be made to forest areas that are not under threat, undermining the additionality of the mechanism (Angelsen, 2008).

Base Period

A reference level can be calculated based either on historical data or on projections of emission scenarios in the absence of a REDD mechanism. One of the earliest proposals for a mechanism to reduce emissions from deforestation, the 'Compensated Reduction' proposal of Santilli *et al.* (2005), suggested that reference levels should be based on a country's average rate of emissions due to deforestation over a recent historical period. This idea is reflected in other national proposals, although the reference periods differ among them; *e.g.* Santilli *et al.* (2005) suggested using a five-year average, whereas in other proposals, the reference period is ten years.

Developing countries are in different phases on the forest transition curve, a single method for setting the reference level and assessing emission reductions therefore cannot provide incentives to all.

Historical deforestation rates are one of the best and easiest predictors of future deforestation in the short and medium terms (Angelsen *et al.*, 2009b). They are also able to demonstrate "actual" reductions relative to past emissions from deforestation (Parker *et al.*, 2009). However, the historical approach also has some important limitations. First, historical reference levels will be difficult to establish with accuracy in countries with limited comparable (across years) and/or unreliable high-resolution historical deforestation data (CIFOR, 2010). Second, because deforestation dynamics and the timing of deforestation differ greatly among countries and even within countries, the reference period chosen to estimate an reference level will make a great difference (Corbera *et al.*, 2010). Regarding overall equity, this methodology is likely to provide incentives only for countries with high historical rates of deforestation (Alvarado and Wertz-Kanounnikoff, 2007). In addition, when positive incentives are extended only to these historically high-deforestation countries, there could be an exacerbated threat of the leakage of deforestation activities to countries with historically low deforestation rates, including "high-forest, low-deforestation" (HFLD) countries (Cattaneo *et al.*, 2010). Finally, this approach does not recognise potential changes in national circumstances over time such as changes in the rates deforestation and economic growth (Parker *et al.*, 2009). In particular, if there is evidence that deforestation is likely to decline in any of the large remaining tropical forest areas, a major risk is the creation of emission allowances that are not additional, *i.e.* that are "hot air", which undermines the environmental integrity and credibility of REDD (CIFOR, 2010; Corbera *et al.*, 2010).

Several proposals have attempted to address the limitations of the historical approach by the use of an adjustment factor for the historical deforestation rate in establishing reference levels. To address differences among countries, incorporate potential changes in national circumstances and address the potential for leakage, two main options have been proposed. The first is extending reference levels that are higher than the historical values to countries with historically low deforestation rates, and the second suggestion is to apply a development adjustment factor to the historical reference level (Parker *et al.*, 2009).

In the first approach, countries with high rates of deforestation would be rewarded for reducing these emissions under a crediting reference level set relative to their historical deforestation rates. In contrast, countries with low rates of deforestation would gain credits for preventing emissions growth relative to reference levels that are elevated based on assumptions of increased future rates of deforestation (Cattaneo *et al.*, 2010). One option is to use the reference emission rate indexed to the global deforestation rate for countries with little or no historical deforestation, as suggested in the 'incentive accounting' proposal (Mollicone *et al.*, 2007). Countries with deforestation rates of less than half the global average would use the historical global deforestation rate as their national RL, whereas countries with higher deforestation rates would use their national historical reference level (Mollicone *et al.*, 2007). As an alternative, Strassburg *et al.* (2009) proposed a 'combined incentives' mechanism, in which incentives allocated to an individual country are determined by a formula that combines a measure of individual country performance against their own historical reference level, and performance against a global RL. In this approach, different scenarios are generated by differing the weights put on historical global deforestation and national deforestation for different types of countries (Strassburg *et al.*, 2009).

In the second option a development adjustment factor is applied to the historical reference level to reflect predicted changes in future drivers of deforestation and which takes into account national circumstances such as forest cover, income (Gross Domestic Product) per capita, demographic trends, agriculture and infrastructure development (UNFCCC, 2007; Parker *et al.*, 2009). Adding a growth cap to the reference scenario allows for certain amounts of deforestation to occur for the purpose of a country's socio-economic development (Angelsen, 2008).

A general advantage of these measures is the upward adjustment of the national reference level for countries with lower-than-average historic deforestation rates as an incentive for maintaining these low rates, which will make it more attractive to these countries to participate in REDD (Murray, 2008). By including countries at all stages of the deforestation process, it will minimise the threat of leakage and increase the overall effectiveness and equity of the mechanism (Alvarado and Wertz-Kanounnikoff, 2007; Strassburg *et al.*, 2009). Nevertheless, the risk of "hot air" remains with the use of an adjustment factor to the historical reference level. When setting global deforestation rates to define national reference levels, many countries are likely to receive reference levels above their emissions in a BAU scenario, eventually giving a sum of national reference levels higher than the global reference level. This increases the possibility of generating more credits than emission reductions at the global level, compromising additionality (Angelsen, 2008; Mur,ray, 2008; Busch *et al.*, 2009). The 'combined incentives' mechanism is the only option that addresses this problem by setting the sum of national reference levels equal to the global reference level through a flexible combination of global and national reference level determination.

A projected reference level reflects future emissions from deforestation, usually based on past deforestation, and projections for key social, economic, political and technological variables (Eliasch, 2008). They aim is to predict how deforestation rates are most likely to change in the future, employing simulations of change in land use and land cover (LUCC) models (Alvarado and Wertz-Kanounnikoff, 2007). Ashton *et al.* (2008) have proposed a 'forward-looking' reference level that uses the fraction of the volume of terrestrial carbon stock estimated to be at risk for emission in the long run, based on biophysical, economic and legal considerations.

If it were possible to predict when and where deforestation would occur without an incentive scheme, additionality would be maximised (Eliasch, 2008). However, LUCC models carry the risk of inaccuracy given the uncertainties regarding the evolution of direct and indirect causes of deforestation, including the evolution of agricultural commodity prices, biofuel markets and the production of timber goods (Alvarado and Wertz-Kanounnikoff, 2007). Conversely, their ability to incorporate country-specific circumstances such as drivers of deforestation makes this approach very attractive to countries in different stages of the deforestation process, minimising the risk of leakage (Huettner *et al.*, 2009). Still, calculating reference levels based on future projections demands sufficient technical capabilities, and the complexity of LUCC models limits their transparency and clarity to policy makers (Huettner *et al.*, 2009).

Monitoring, Reporting and Verification Scheme

Monitoring

To participate in REDD, countries will need to establish a (national) MRV system to estimate anthropogenic forest-related greenhouse gas emissions from sources and removals by sinks. Such a system should support the MRV requirements under the UNFCCC, so that such estimations are based on a common international methodological approach for MRV in REDD (Maniatis and Mollicone, 2010). Until now, the proposed options for estimating forest-related greenhouse gas emissions within a REDD mechanism are restricted to the most recent Good Practice Guidance (GPG) (2003) and Guidelines (2006) of the Intergovernmental Panel on Climate Change (IPCC), although other carbon-estimating methods exist, *e.g.* the CDM methodologies and the Voluntary Carbon Standard methodologies (Bird *et al.*, 2010). Because the latter two have not been submitted to the UNFCCC, only the application of the IPCC GPG and Guidelines are assessed here.

The IPCC GPG and Guidelines refer to two basic inputs used to estimate greenhouse gas inventories: activity data and emission factors. To represent activity data or changes in areas of different land categories, three different Approaches are defined. These range from the collection of non-spatial country statistics to spatially explicit land-conversion information, derived from sampling or wall-to-wall mapping techniques in the third Approach (Angelsen *et al.*, 2009b). Secondly, the emission factors refer to the emissions or removals of greenhouse gases per unit of activity and can be measured as changes in carbon stocks in the various carbon pools of a forest, *e.g.* aboveground biomass, belowground biomass, litter, dead wood and soil organic carbon. There are three Tiers of data for emission factors in the IPCC GPG and Guidelines, representing increasing levels of analytical complexity and data requirements, ranging from default values to actual inventories, using repeated measures of permanent plots to directly measure changes in forest biomass and/or well-parameterised models in combination with plot data (IPCC, 2006).

The benefits of using these methods as the basis for REDD are that they have been developed and reviewed by experts, they have already been accepted in UNFCCC negotiations and they have been tested during the initial phase of the Kyoto Protocol (Olander *et al.*, 2008). However, monitoring for REDD would require identifiable and traceable land conversion, and only Approach 3 will accommodate this (Baker *et al.*, 2010). Furthermore, although moving from Tier 1 to Tier 3 increases the accuracy and precision of the greenhouse gas estimates, it also increases the complexity and the costs of monitoring (Maniatis and Mollicone, 2010). According to DeFries *et al.* (2007), the capacity for deforestation monitoring is well advanced in a few developing countries and is a feasible goal for most others. Nevertheless, an assessment of current monitoring capabilities conducted by Herold (2009) emphasised that the majority of countries have limitations in their abilities to provide a complete and accurate estimation of greenhouse gas emissions and forest loss. Consequently, given the differences in ecology, institutions and technical capabilities among countries, no single MRV system will apply to all developing countries (Baker *et al.*, 2010). A tiered system would provide some flexibility for differences in technical capability among countries (Olander *et al.*, 2008). However, Tier 1 estimates, based on default values, can have uncertainties as large as 70% (Angelsen *et al.*, 2009b). Clearly, substantial improvements (at least to Tier 2) over that value will be required if the participating countries are to meet international compliance standards (Baker *et al.*, 2010).

Financing Scheme

Generating financing for REDD activities at an adequate and sustainable scale is crucial for creating incentives and payment systems for government actions and specific projects to reduce emissions that overcome the drivers of deforestation and forest degradation (Evidente *et al.*, 2009). The Eliasch Review (2008) on financing global forests estimated that US$ 17–33 billion must be invested annually to halve greenhouse gas emissions from deforestation by 2030. Once generated, this financing must be distributed among the participating countries. The generation and the distribution of payments can be seen as two more-or-less independent mechanisms. For this reason, the two mechanisms will be addressed as two sub-building blocks of the overall financing scheme.

Finance Sources

The source of finance refers to the type of economic instrument that the mechanism uses to generate revenue (Parker *et al.*, 2009). Recognising the varied interests and institutional capacities of countries, various proposals are being discussed as potential financing sources (Evidente *et al.*, 2009). These sources can be classified into three main instruments: fund-based instruments, market-based instruments and combinations of the two instruments in hybrid approaches.

In the fund-based system, incentives for REDD would be paid by a fund, which could be made up of voluntary financial contributions or provided through market-linked instruments. The emission reductions generated in this approach cannot be purchased as offsets by developed countries to meet their national targets (Skutsch and McCall, 2010).

A first fund-based option for providing REDD financing is for governments, financial institutions or private entities to voluntarily contribute to a fund, which can then be distributed to participating developing countries to aid and reward their efforts to reduce emissions from deforestation and forest degradation (Evidente *et al.*, 2009). The manner in which these contributions are resourced can take a variety of forms, ranging from, *e.g.* bilateral or multilateral commitments to a global mechanism (Daviet *et al.*, 2007; Evidente *et al.*, 2009). A voluntary fund-based approach offers three advantages: first, it allows for differentiation among types of forests, policies and programs by taking into account each country’s particular circumstances; second, it decouples carbon accounting and quantification issues from Annex I parties’ emission-reduction targets; and third, it provides the required up-front payments for capacity building and the implementation of REDD activities (Daviet *et al.*, 2007). The major arguments against a solely fund-based mechanism are that it is unlikely to be able to generate funding at the required scale to effectively provide support for emissions reductions activities and that funding will be difficult to continue over the long term (Evidente *et al.*, 2009; Corbera *et al.*, 2010). For this reasons, market-linked instruments have been proposed. These instruments raise revenue indirectly from the (carbon) market through a variety of mechanisms (Parker *et al.*, 2009). For example, proposals have been made to tax carbon-intensive commodities and services in Annex I countries and to set a levy on the sale of Assigned Amount Units (AAUs) or on transactions involving Emission Reduction Units (ERUs); this revenue would be placed into a carbon fund (Corbera *et al.*, 2010). Such a levy on an auction process, either at the international level, as proposed in Norway, or at the national level, as in Germany's "International Climate Initiative", could generate revenues at the necessary scale, and would ensure additional emission reductions to existing commitments (Parker *et al.*, 2009). However, these market-linked instruments would depend on the existence of a sound long-term (carbon) market to produce a predictable flow of funds and could be politically difficult to negotiate (Corbera *et al.*, 2010).

Market-based approaches generally refer to a mechanism whereby participating developing countries are able to create and sell emission-reduction credits. There are three types of market-based instruments: compliance-based markets, separate markets and voluntary carbon markets.

The first market instrument creates incentives that are linked to compliance with developed countries' commitments to greenhouse gas emission reductions. In this option, the forest emission-reduction credits sold by developing countries would be fully fungible in the global carbon market and used for compliance by either governments that have binding targets under a post-2012 climate change agreement or by companies in trading systems such as the EU Emission Trading System (ETS) (European Commission, 2008). According to several authors, including Corbera *et al.*, (2010) and Pedroni *et al.*, (2009), market instruments are the most significant sources of funding, because carbon offset markets have the potential to assure long-term, continuous and predictable flows of finance for REDD. However, concerns exist that a direct integration of REDD into carbon markets may result in a destabilisation of these structures. The introduction of potentially large volumes of low-cost credits could create market disruptions and increase price volatility (Ogonowski *et al.*, 2007; Angelsen, 2008). It would also weaken the incentives for abatement in developed countries and could result in a significant delay of mitigation actions by the most important emitters (Wertz-Kanounnikoff and Tubiana, 2007; CIFOR, 2010).

A market-based REDD+ scheme could generate the flow of money needed to make REDD+ a success but it will need to be imbedded with great care in an overarching carbon market to avoid that low-cost REDD+ credits delay mitigation actions in developed countries and in other sectors.

Various options have been put forward to reduce the risks of integrating REDD into carbon markets including the adoption of deeper emission-reduction commitments by developed countries, limiting the supply of REDD credits into the market and controlling the interchange ability of REDD credits in the form of separate but linked markets or the creation of a new trading unit (Angelsen, 2008; CIFOR, 2010). In a separate market, REDD credits are linked to existing emission-reduction credits in other countries and sectors but have varying degrees of fungibility (*i.e.* tradability) (Parker *et al.*, 2009). Examples of separate markets for REDD are the 'Dual-markets approach' (Ogonowski *et al.*, 2007) and the 'Tropical Deforestation Emission-Reduction Mechanism (TDERM)' proposal (Hare and Macey, 2007). The latter involves the creation of a special trading unit, the Tropical Deforestation Emission Reduction Unit (TDERU), which would represent both emission reductions and other ecosystem services. Developed countries would take on commitments to purchase TDERUs as part of their overall emission-reduction commitments (Hare and Macey, 2007).

A third market mechanism, for which the procedures are not as lengthy, costly or binding, consists of voluntary carbon offset schemes. These make it possible to sell carbon credits to individuals, companies or entities (large towns, institutions, etc.) wishing to compensate for emissions linked to their activities (Karsenty, 2009). Although the voluntary carbon markets are playing a pioneering role in market-based initiatives to foster investment in REDD, they are unlikely to mobilise sufficient funding to finance widespread REDD adoption (Angelsen *et al.*, 2009b).

General concerns about market-based approaches are related to the required upfront financing for capacity building and separate financing necessary to address the broader social and political factors that contribute to deforestation such as land tenure and indigenous peoples' rights, enforcement and monitoring capabilities and coherent economic and agricultural policies (Peskett *et al.*, 2008; CIFOR, 2010). Further concerns are related to fears that a market is incompatible with forest conservation and that it will have a negative impact on ecological and other forest values. At a higher level, there is concern that in a market mechanism, the more powerful players may benefit most, both within and among countries, as has been the case in CDM. Countries which have relatively good forest inventory data and sufficient technical capacity, *e.g.* Brazil and Mexico, will be able to take advantage of a REDD market quickly, whereas others may fall behind (Skutsch and McCall, 2010).

Noting that both market and non-market systems have their limitations, various combinations have been explored in attempts to use the strengths of each system (Evidente *et al.*, 2009). As a first hybrid funding option, the type of financing could depend on the type of action being undertaken. In this dual system, contributions from government funds would finance government activities—improving forest policies and governance, land-tenure reform and indigenous rights, agricultural and economic policies, among others—while market-linked or market financing would direct resources to people and communities to provide incentives and to support activities that directly result in emission reductions at the ground level (Viana, 2009).

A second hybrid funding option that has gained significant support during the negotiation process is the 'phased approach'. Due to the different levels of institutional capacity and development in the developing countries, a REDD framework should be implemented in three phases. The First Phase, *preparation and readiness,* includes the development of national strategies or action plans, policies and measures and capacity building. This is followed by a Second Phase that focuses on the implementation of PAMs, addressing the drivers of deforestation and demonstration activities for emission reductions. The Third, and last, Phase includes the full implementation of a greenhouse gas -based instrument that rewards performance on the basis of quantified forest emissions and removals with respect to an agreed-upon reference level (UNFCCC, 2009). In this scenario, the sources of financing vary according to the phase of REDD implementation, starting with activity-based payments, mainly provided through non-market based funds, with a transition to result-based payments in the Second Phase. In the latter, financing may come from either funds or market sources. An option to finance the intermediate phase is the creation of a separate market for REDD, because this will still provide incentives for the private sector to invest while allowing a REDD market to stabilise before any full-scale linking with the post-2012 global carbon market (Ogonowski *et al.*, 2007). When institutions develop sufficient capacity for monitoring and demonstrating emissions reductions, countries could proceed to a full implementation phase, in which payments will be entirely based on results and financing by compliance markets becomes feasible (Angelsen *et al.*, 2009b; UNFCCC, 2009). The advantage of the phased approach to REDD lies in its flexibility (Angelsen *et al.*, 2009b); countries can participate according to their capacity and have incentives to progress from one stage to the next. This means that a wide range of tropical-forest countries will be able to take part in REDD. Countries with sophisticated MRV systems and sound institutional frameworks may start at Phase Three. Other countries with less sophisticated MRV systems can start at Phase One or two but have incentives to move towards more sophisticated systems so that they can graduate to Phase Three. The incentive for graduating from phase one to phase three is that by doing so, countries generate a more reliable income from REDD (Angelsen *et al.*, 2009a).

Distribution System

The second sub-building block of the financing scheme explores the different options for delivering climate financing to developing countries and the equality of the distribution of REDD revenues across countries. In general, equity concerns are addressed implicitly in the reference level methodology (Parker *et al.*, 2009). Examples are adding a development factor to the reference level or the ‘combined incentives’ and the ‘incentives accounting’ approaches. There are, however, also mechanisms to redistribute revenues independent of the methodology used to set the reference level. One mechanism withholds a proportion of the revenues for emission reductions (as a levy or tax), which feed into a fund for REDD countries in the form of stock payments (Cattaneo, 2009). In both of these approaches, the revenue required to support HFLD countries is generated from the mechanism itself (Parker *et al.*, 2009). Potential disadvantages of these approaches are the distorting effect that redistribution could have on incentives to reduce emissions in countries with high rates of deforestation (Parker *et al.*, 2009). As an alternative, an additional distribution mechanism or “stabilisation fund” was proposed, which would use additional funding, generated outside the REDD mechanism, to address leakage and equity concerns in HFLD countries. The revenue for a stabilisation fund could come from a variety of sources including voluntary funds or innovative financing mechanisms such as the auctioning of allowances or levies on shipping or aviation (Parker *et al.*, 2009).

Scale

The scale of REDD refers to the geographic scale at which eligible REDD activities will be implemented, MRV will be performed and an international funding mechanism will provide incentives for REDD activities. Four main options for the scale of REDD are proposed: the project level, the sub-national level, the national level and an integrated approach (Angelsen, 2008; Cortez *et al.*, 2010).

Several countries, such as the United States and Colombia, have firmly expressed being in favour of a project-based approach, similar to that of the CDM (Calmel *et al.*, 2010). In this approach, incentives flow directly to project developers based on performance against a project reference level. Although each project will not necessarily coincide with a governmental jurisdiction, a sub-national implementation of REDD nevertheless indicates that incentives will flow to a sub-national government entity such as a state, municipality, province or district based on their performance compared with a sub-national reference level (Cortez *et al.*, 2010). In the national approach, a country would be required to establish a national strategy and will receive payment if their emissions are reduced in comparison with the national reference level. A national emissions monitoring system would also be established to verify that these emission reductions are additional (Calmel *et al.*, 2010). The principle of the national approach is that the beneficiary of the carbon credits generated is the country, which would be responsible for distributing them among the concerned stakeholders in accordance with procedures established during the preparation phase (Calmel *et al.*, 2010). An ‘integrated approach’ to REDD has been proposed as an option for creating incentives for action at multiple scales (Cortez *et al.*, 2010). Under an integrated approach, sub-national activities are integrated into a national accounting framework (Angelsen, 2008). Both projects and/or sub-national and national activities can be started immediately (Pedroni *et al.*, 2009). The national government would set up a national accounting framework and establish a nationwide monitoring system. Simultaneously, implementation of REDD+ activities would also occur at the sub-national level, led by local/regional governments, communities, NGOs or private developers (Cortez *et al.*, 2010). Different versions of an integrated approach have been presented. In the 'transitional approach', the sub-national level is seen as an intermediate phase. Developing countries would be able to decide on their initial level of participation in this mechanism according to their particular circumstances and interests (Pedroni *et al.*, 2009). However, in the case of an implementation of activities at the sub-national level, a country would need to scale up to a national approach as they strengthen their capacity and improve governance. Transition to a national approach would be obligatory, either within an agreed time frame or when an agreed percentage of forest area is covered by REDD activities (Angelsen, 2008). In the 'nested approach', the sub-national level continues to exist and can still be credited after a national accounting framework has been established (Cortez *et al.*, 2010).

The decision on the scale of the REDD mechanism involves a trade-off between the capacity of a developing country to participate in the scheme, which may depend on, *e.g.* data availability, institutional and financial capabilities and the potential risks of leakage. Implementation at a lower scale, *i.e.* projects and sub-national activities, would initially be easier than national approaches and would accommodate different national circumstances and account for intra-national heterogeneity in the capacity to implement REDD projects (Myers, 2008). Conversely, opponents of these lower-scale approaches note that they face greater challenges in addressing leakage and permanence than do national-level approaches (Cortez *et al.*, 2010). However, the national-based approach does not entirely solve the leakage problem, because the issue of international leakage remains as emissions could shift from participating to non-participating countries (Corbera *et al.*, 2010).

A second challenge is to find a balance between triggering the policy reforms required to address land-use change drivers and to involve a broad scope of stakeholders and so sustain a long-term success. Because the causes of land-use change are many and variable and, in some cases, are even linked to national-level policies, the involvement of national governments is essential to achieve the necessary large-scale systemic policy reforms (Eliasch, 2008; Virgilio *et al.*, 2010). Furthermore, given the magnitude of emissions, the implementation of REDD at only low levels risks having a small impact and is not likely to address the broader drivers (Myers, 2008; Virgilio *et al.*, 2010). Conversely, according to Cortez *et al.*, (2010), a greater participation by actors with direct control over land-use decisions, including sub-national governments, indigenous peoples and forest-dependent communities, and landowners/users, can be motivated by providing direct incentives for sub-national activities. Nevertheless, the national approach addresses sovereignty issues by creating country ownership, and it would give governments the flexibility to establish a broad set of PAMs to reduce deforestation and forest degradation (Angelsen, 2008). In addition, a national approach can be aligned with national development strategies, possibly bringing long-term development benefits (Angelsen, 2008; Eliasch, 2008).

A third issue in the scale debate is the question of cost efficiencies versus the generation of the significant up-front capital needed to enact REDD programs. While a national approach enjoys significant economies of scale such as lower transaction costs and lower MRV costs, many potential private-sector investors are hesitant to invest up-front capital in national programs because of concerns over controlling risks, lack of transparency, poor governance and corruption, among others (Cortez *et al.*, 2010).

Regarding social equity, because incentives must reach local actors in the deforestation process, the implementation of national approaches as an exclusive instrument to provide incentives to reduce emissions from deforestation in developing countries could have negative intra-national equity implications (Eliasch, 2008; Corbera *et al.*, 2010). Although some developing countries may have transparent systems for benefit sharing already in place, others, however, lack the institutional capacity and legal safeguards to ensure that a centralised REDD scheme would equitably allocate resources to local actors (Costenbader, 2010).

An integrated approach to REDD has the potential to address many of the drawbacks of pure national or sub-national approaches by accounting for in-country leakage, engaging national governments, and taking advantage of certain economies of scale, while also motivating sub-national actors to participate in REDD and attracting greater private investment. An integrated approach may also provide for a more transparent distribution of the benefits from REDD, because local actors could own and transact credits directly rather than relying on a national system of benefit sharing (Cortez *et al.*, 2010). Further, the sub-national activities provide important learning opportunities for countries to test options for building national capacity and institutions regardless of whether or not the sub-national level would be an intermediate phase (Virgilio *et al.*, 2010). However, a nested approach may be more difficult from an institutional point of view, because the sub-national and national accounting systems would need to be harmonised, and a framework for transferring REDD incentives across scales must be defined (Angelsen, 2008; Corbera *et al.*, 2010). Furthermore, risk-management mechanisms would need to be developed to mitigate the risk of revenue loss by sub-national entities in the case of national-scale non-performance (Cortez *et al.*, 2010).

Conclusion

The negotiation process for an international REDD mechanism has so far resulted in a series of proposals on policy approaches and positive incentive mechanisms. The latest decision document for a REDD+ mechanism, adopted at COP 16 in Cancun, Mexico (UNFCCC, 2011), represents a key step in achieving an overall land use and forestry-based mitigation framework. Although some decisions were made about REDD in Cancun, e.g. the scope of REDD and its scale of implementation, the negotiation of a forestry-based mitigation mechanism will be a continuous process. This paper is intended to inform this ongoing negotiation process regarding the inclusion of REDD within a future climate change agreement.

By dividing the REDD mechanism into five modular building blocks, an attempt was made to provide a complete overview of the proposed options for each building block, including those that have been placed in the background of the current negotiations. The assessment herein shows that these options face several design and implementation challenges in terms of mitigation potential, abatement costs, environmental risks and benefits, social equity and institutional feasibility. As a result, when assembling the overall REDD framework, all these implications will involve trade-offs to enable the design of a sustainable international REDD framework that will deliver effective, efficient and equitable results and that will be feasible for all developing countries.

1.2. REDD+ negotiations: a state-of-play

From Montreal to Copenhagen

At the 11th Conference of the Parties (COP11), Papua New Guinea and Costa Rica submitted on behalf of the Coalition for Rainforest Nations (CfRN) a proposal to establish a mechanism called 'Reducing Emissions from Deforestation in developing countries (RED)' under the UNFCCC (Lawlor *et al.*, 2009). The CfRN was established several months before the COP, and unites countries aiming to promote a more sustainable use of tropical forests. The aim of the RED mechanism would be to curb or limit deforestation and its related greenhouse gas emissions, by providing economic incentives to developing countries to keep their forests intact (Karsenty, 2008). Discussions were initially limited to reducing emissions from deforestation, but expanded quickly to include forest degradation (REDD) (Verchot and Petkova, 2009).

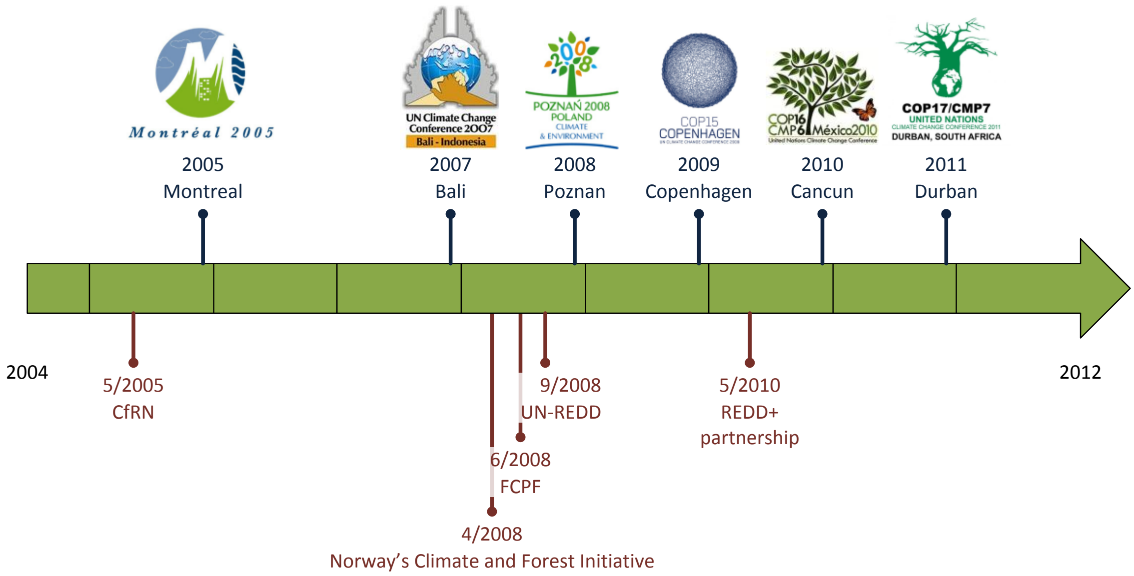

Figure 2. Timeline of the most important UNFCCC meetings and initiatives with respect to REDD+ [CfRN Coalition for Rainforest Nations, FCPF Forest Carbon Partnership Facility].

The principle of REDD was accepted at COP13 of the UNFCCC held in December, 2007 in Bali. The Parties agreed in the Bali Action Plan (BAP) that a REDD scheme should be one of the building blocks of a new climate agreement (as part of the Ad-Hoc Working Group on Long-term Cooperative Action). Further, the BAP encourages Parties to expand the scope beyond deforestation and forest degradation and to explore options to include forest conservation, sustainable management of forests and the enhancement of forest carbon stocks (UNFCCC, 2007). These new activities were expressed as the "+", and since then, 2008 COP14 in Poznan REDD+ is officially defined as 'reducing emissions from deforestation and forest degradation in developing countries, and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries'.

In the BAP, the Parties to the UNFCCC decided to launch a negotiation process for a post-2012 climate change agreement scheduled to be concluded at the COP15 in December, 2009. This agreement should also include financial incentives for forest-based climate change mitigation actions in developing countries. At COP15 in Copenhagen in, 2009 however, countries could not find a common ground for an overall legally-binding climate change agreement only for a general Copenhagen Accord. REDD+ was one of the few issues though on which significant progress was made and is the only mitigation action specifically mentioned in the Copenhagen Accord. In paragraph 6 of the Accord, the Parties to the UNFCCC:

"recognize the crucial role of reducing emission from deforestation and forest degradation and the need to enhance removals of greenhouse gas emission by forests and agree on the need to provide positive incentives to such actions through the immediate establishment of a mechanism including REDD-plus, to enable the mobilization of financial resources from developed countries."

The Cancun agreement

At COP15, negotiations on REDD+ had progressed considerably and a REDD+ decision text was ready to be included in an overarching post-2012 climate regime. The failure to reach such an agreement however, allowed some Parties to reflect on the language or to reposition themselves for strategic reasons in the broader process. To avoid an open confrontation at COP16, a compromise text was drafted which was acceptable for all Parties except the Plurinational State of Bolivia. They refused to cooperate and came up with a proposal explicitly ruling out the development of carbon markets and offsetting, and emphasizing the integrity and multifunctionality of ecological systems. This isolated Bolivia and their attempt to include stronger language on the treatment of ecological systems in the text failed. The compromise text would form the basis for the REDD+ decision which was adopted by the COP as part of the AWG-LCA decision. This was an important step as it already consolidated some of the issues for which a decision is needed.

1) Drivers of deforestation
   The first paragraph of the REDD+ decision "*"Encourages all Parties to find effective ways to reduce the human pressure on forests that results in greenhouse gas emissions, including actions to address drivers of deforestation;"* underlines the role of both developing and developed countries as drivers of deforestation.

2) A REDD+ global target
   Some parties, including the EU, and NGOs have argued that an overarching goal for REDD+ should be written in the preamble. Such a statement would be a good indicator to assess the effectiveness of REDD+. A quantitative objective however did not make the REDD+ text. Instead, a more general reference to the Conventions' objective was written in the preamble: *"Parties should collectively aim to slow, halt and reverse forest cover and carbon loss, according to national circumstances, consistent with the ultimate objective of the Convention"*. This refers to the objective of the Convention aiming for a stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. In the Copenhagen Agreement this objective was translated as a limit of 2°C global warming above pre-industrial levels.

3) A phased approach
   There are considerable differences among developing countries, not only in forest cover and historical deforestation rate, but also in capacities to implement REDD+. A phased implementation approach is therefore necessary, allowing countries to go through the process of policy design, stakeholder consultation, and consensus building, testing, and evaluating in accordance with their national circumstances (Angelsen *et al.*, 2009a). Since this approach had gained significant support throughout the negotiation process leading up to Copenhagen and further to Cancun, a phased implementation of REDD+ activities is now provided in the Cancun agreement.
   The first phase includes the development of national strategies or action plans, policies and measures, and capacity-building. These action plans should also address the drivers of deforestation and forest degradation, land tenure issues, forest governance issues, gender

considerations and other safeguards. This is followed by a second phase in which national policies and measures and/or national action plans will be implemented. This could involve further capacity-building, technology development and transfer and results-based demonstration activities. In a third and final phase results-based actions should be fully measured, reported and verified (MRV). The phased approach however does not imply that all Parties will have to start in the initial phase. The choice of the starting phase depends on the specific national circumstances, capacities and capabilities of each developing country Party and the level of support received.

4) The scope of REDD+

The REDD+ decision in Cancun appears to be very conclusive: "*encourages developing country Parties to contribute to mitigation actions in the forest sector by undertaking the following activities, as deemed appropriate by each Party and in accordance with their respective capabilities and national circumstances:*

- *Reducing emissions from deforestation;*
- *Reducing emissions from forest degradation;*
- *Conservation of forest carbon stocks;*
- *Sustainable management of forests;*
- *Enhancement of forest carbon stocks."*

However, it is not very clear on what is understood under these activities. For instance, enhancement of forest carbon stocks could include conversion of natural forest to forest plantations or even palm oil plantations as these classify under forests according to broadly used forest definitions as for example the current UNFCCC definition of 'forest' as adopted for LULUCF activities under the Kyoto Protocol. According to the Marrakesh Accords only three quantitative indicators are needed for a vegetation type to qualify as a forest: a minimum area, tree crown cover and height (or potential to reach a certain minimum height) (UNFCCC, 2001).

Not all activities have to be implemented, but only those deemed appropriate by each developing country and in accordance with their respective capabilities and national circumstances. This implies that Parties do not necessarily have to include all five activities in their REDD+ strategy. There is considerable emphasis in the REDD+ text that activities should be voluntary and looked upon in the bigger picture of sustainable development, adaptation to climate change and poverty reduction.

5) Scale

One of the most contentious issues, going into the Cancun REDD+ negotiations was the scale on which: (i) a strategy should be developed; (ii) a monitoring scheme should be deployed; and (iii) the accounting should be done (the reference level).

A compromise was found in an interim measure which allows for subnational reference levels and monitoring, in accordance with national circumstances and if this is deemed appropriate. So although the ultimate objective of REDD+ is a national REDD+ scheme, subnational accounting will be possible for a limited period of time. It is still unclear how long this interim measure can last and down to what geographical scale accounting can be done. The text does not explicitly mention nor exclude project levels and it does not state that for example national monitoring should be a prerequisite for entering the results-based actions phase. The discussions on the scale of REDD+ are closely linked to the finance issue and more specifically the link to a market approach. Project-level accounting, for instance is closely linked to a carbon market approach.

There is a small nuance in the treatment of sub-national scales between the scale for reference levels and the monitoring scale. While for the reference levels national or sub-national approaches can be used, the monitoring system allows for sub-national monitoring and reporting, but still in combination with a national monitoring system. This is merely because of problems experienced with remote sensing of typically very clouded rainforest areas. The limited duration of the latter was solved with a footnote stating that financing of the results-based phase requires national monitoring systems.

6) MRV
For estimating anthropogenic forest-related greenhouse gas emissions, forest carbon stocks and forest area changes, developing countries are requested to use as a guidance the most recent IPCC guidance (2003) and guidelines (2006) as a basis (UNFCCC, 2009a). To do so accurately and precisely a national (or sub-national) monitoring system, that uses a combination of remote sensing and ground-based forest carbon inventory approaches, has to be established.

7) Accounting
The decision on methodological issues related to REDD+ in Copenhagen specified that reference levels should be determined transparently, taking into account historical levels, and adjusted for national circumstances. This issue however has not been resolved in Cancun.

8) REDD finance
For an effective REDD+ mechanism with broad developing country participation, sufficient capacity building, technology development and transfer, and (financial) resources will be necessary (Angelsen *et al.*, 2009a; Stern, 2006). Developed country parties are urged to support developing countries during the first and second phase of REDD+ implementation, through bilateral and multilateral channels. This includes the implementation of national policies and measures and action plans and results-based demonstration activities, also including the consideration of the safeguards. Additionally, relevant international organizations and stakeholders are invited to contribute to REDD+ activities and their coordination.
For the financing of the last phase of REDD+, the full implementation of results-based actions, a final decision has been delayed by requesting the AWG-LCA to explore different options. This implies that all kind of finance options are still open: from funds (*e.g.* bilateral, multilateral and the Copenhagen Green Climate Fund), over market-linked approaches to market-based approaches, or private finance (which are not necessarily carbon markets), or a combination thereof. On the financial approach, positions are very divergent and linked to Parties' experiences from carbon trading and CDM, ongoing pilot projects and prior investments (whether or not already being credited in the voluntary carbon markets). The EU for example has been struggling with its emission trading scheme, which showed high price volatility (Buchner and Ellerman, 2007), windfall profits and, recently internet fraud (Reuters, 2011). The state of California on the other hand, have established a REDD agreement with Chiapas (Mexico) and Acre (Brazil) in December, 2010 to open their cap-and-trade system for REDD+ credits (Reuters, 2010). One of the concerns of opponents of the market-based approach is that if REDD+ carbon credits would be used to offset industrial emissions in annex I countries, this would not lead to significant global emission reductions. Therefore, a market-based REDD+ scheme should be accompanied with more stringent reduction targets for industrialized countries to be in line with the global emission reductions needed to limit global temperature increase to 2°C.

9) Safeguards in REDD+: biodiversity, ecosystem services and indigenous people.
Only if the REDD+ mechanism is correctly designed and implemented, perverse incentives or actions that might be beneficial from a mitigation point of view, but that are not necessarily

sustainable in the long run, could be avoided. For instance, REDD+ could undermine the rights of indigenous peoples and local communities, could lead to conversion of natural forests to monoculture and/or non-native species plantations or could lead to international displacement of deforestation and related emissions (leakage). Forests, with all their ecosystem services that are beneficial to the local, regional and global REDD+ community (Gonzalez *et al.*, 2005), are not just carbon storehouses and therefore cannot be treated as other sectors where mitigation will have to take place. To address these issues, the text states that safeguards should be promoted and supported (see Box 1). These safeguards should make REDD+ actions complementary to or consistent with the objectives of national forest programs and international conventions and agreements. This links the UNFCCC to, among others, the United Nations Convention for Biological Diversity (UNCBD) and Convention to Combat Desertification (UNCCD), the 2 other Rio Conventions.

Box 1. Safeguards in REDD+

In Annex I of the AWG-LCA draft decision /CP.16 the safeguards are listed that should be promoted and supported when undertaking REDD+ activities. These are:

(a) Actions complement or are consistent with the objectives of national forest programs and relevant international conventions and agreements;
(b) Transparent and effective national forest governance structures, taking into account national legislation and sovereignty;
(c) Respect for the knowledge and rights of indigenous peoples and members of local communities, by taking into account relevant international obligations, national circumstances and laws, and noting that the United Nations General Assembly has adopted the United Nations Declaration on the Rights of Indigenous Peoples;
(d) The full and effective participation of relevant stakeholders, in particular, indigenous peoples and local communities, in actions referred to in paragraphs 70 and 72 of this decision;
(e) Actions are consistent with the conservation of natural forests and biological diversity, ensuring that actions referred to in [paragraph 70 of] this decision are not used for the conversion of natural forests, but are instead used to incentivize the protection and conservation of natural forests and their ecosystem services, and to enhance other social and environmental benefits;
(f) Actions to address the risks of reversals;
(g) Actions to reduce displacement of emissions.

With respect to the protection of biodiversity, REDD+ actions should be consistent with the conservation of natural forests and biological diversity. REDD+ therefore should not be used for the conversion of natural forests. It should rather be used to incentivize protection and conservation of natural forests and their ecosystem services, and to enhance social and environmental benefits. It is estimated that 60 million indigenous peoples are totally dependent on forests for their livelihoods (WorldBank, 2008). An estimated 350 million people from indigenous and local communities depend for their livelihoods on forests (Krishnaswamy and Hanson, 1999). The United Nations Permanent Forum on Indigenous Issues has already warned that a forest protection scheme, such as REDD+, could increase land tenure conflicts and even result in eviction of forest people from their traditional land, practices that are already taking place at the moment (UN, 2009). Therefore, the REDD+ text now specifies that the knowledge and right of the indigenous people and local communities should be respected, taking into account the UN declaration on the rights of Indigenous Peoples. This is an important improvement compared to previous texts which did not contain this reference.

Essential is that the safeguards should only be promoted or supported. Consequently, the text as it is, does not force Parties to actually implement them. There are, however, some additional references to the safeguards, which will make it difficult for developing countries to ignore them. Developing countries are requested to address not only the safeguards mentioned in annex I but also land tenure and forest governance issues, gender considerations and the drivers of deforestation and forest degradation. Secondly, most developing countries will need support from developed Parties with the development of national strategies and plans, effective policies and measures and capacity building. This capacity building will not only relate to carbon MRV but also to the consideration of the safeguards. Developed countries will therefore also have an opportunity and responsibility to put sufficient emphasis on the safeguards. The work program for the SBSTA on REDD+ also contains 'developing guidance for a system for providing information on how the safeguards are being addressed and respected'. Nevertheless, full MRV of the safeguards was not included in the final text, although it was on the negotiating table. The feasibility of monitoring, reporting and verification of some safeguards was questioned, although progress is being made under REDD+ supporting initiatives to develop minimum standards and guidance on monitoring (UN-REDD and the World Bank's Forest Carbon Partnership Facility, FCPF). For other parties this was also a sovereignty issue. A compromise was found in 'a system for providing information on how the safeguards are being addressed and respected throughout the implementation of the activities'. For some observers and the Plurinational State of Bolivia the safeguards are not sufficiently guaranteed, and they fear that the Cancun REDD+ agreement will not be able to protect the valuable ecosystem services, the biodiversity or the rights of indigenous people. Also some Parties were in favour of stronger language on the safeguards, but the level of ambition was reduced as a compromise.

COP17 in Durban: progress on how to measure REDD+

During the COP17 in Durban some progress was made in two building blocks: accounting and safeguards. Importantly though no progress was made on REDD+ finance.

1) Safeguards
   The decided guidance on systems for providing information on safeguards. Importantly, the implementation of the safeguards and the information on how safeguards are being addressed and respected should support national strategies or action plans and be included in all phases of implementation, where appropriate.

2) Reference levels
   Most progress was made on forest reference levels and/or forest reference emission levels (expressed in tonnes of carbon dioxide equivalent per year). These reference levels will be used as benchmarks for assessing each country's performance in implementing REDD+ activities. The decision reaffirms that reference levels shall be established based on historic information and adjusted for national circumstances. This would allow countries with historically low deforestation rates to take into account potential future increases in deforestation when setting their REDD+ reference level and should ensure incentives to these countries to keep deforestation and forest degradation low. This is important to keep leakage limited. In principle this also applies to countries were historic data are likely to overestimate future deforestation and forest degradation, *e.g.* countries with high deforestation rates and low remaining forest cover. In this case, the adjustment of the reference level should avoid the creation of "hot air" (Figure 3). How this should be done is not specified, but the forest reference emission levels and/or forest reference levels should be accompanied with transparent information and details of the national circumstances that were included to adjust the reference level. This allows for a technical assessment of the data, methodologies and assumptions that were used, including the carbon pools that were considered and the forest definition used.
   The Durban outcome also acknowledged differences in capabilities of developing countries and reference levels may be improved in a step-wise approach, by incorporating better data, improved methodologies and, where appropriate, additional carbon pools. The Cancun agreement already highlighted that this would require additional support to developing countries, both financial and technical. Although the ultimate objective is to have national reference levels, subnational reference levels may be elaborated as an interim measure,

even if this covers less than the entire national territory or forest area. This could open the door for Parties to exclude areas where deforestation and degradation are particularly high or difficult to reduce.

There are still some outstanding issues that need to be resolved though. For one, it is not specified over which time period historic information should be considered. Several proposal have been done in this respect, but are not included in a decision yet. This is especially relevant for countries that have seen deforestation rates change (both positive and negative) in recent years. And although it is recognised and agreed upon that reference levels should be updated periodically based on new information, trends and methodologies, the time frame to do so has not been decided.

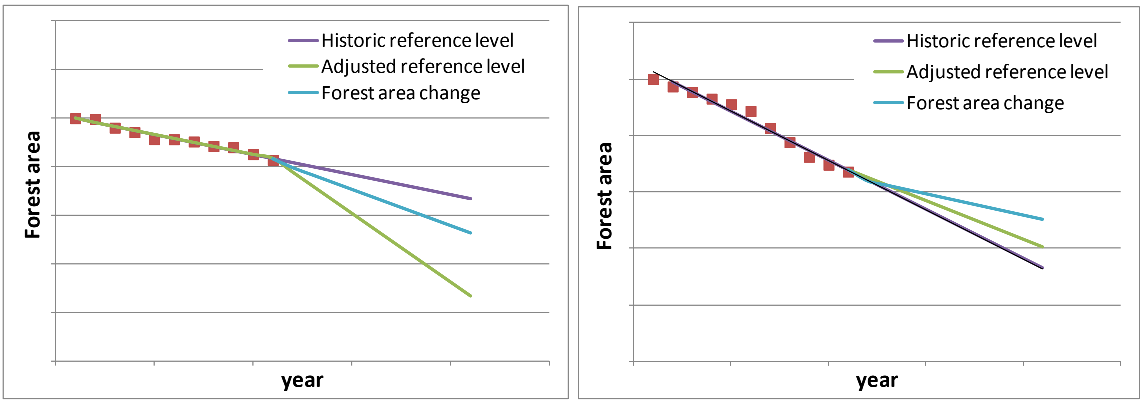

Figure 3. Adjusted reference levels in a) cases were the reference level based on historic data only underestimates future deforestation trends; b) cases were the reference level based on historic data only overestimates future deforestation trends. The difference between blue and green line denotes the accounted impact of REDD+.

3) REDD+ Finance

For most observers, the outcome of Durban with respect to financing REDD+ was the most disappointing. No real progress was made and the options of both public and private sources for financing results-based REDD+ were kept open. In the text that was adopted by the COP, both market and non-market mechanisms are specifically referred to. As the REDD+ mechanism needs to fit in a new post-2020 climate change agreement, it is not surprising that this piece of the puzzle can only be solved when the shape and form of the post-2020 climate regime is more clear.

Agriculture

Developing countries that partake in REDD+ activities, need to identify the drivers of deforestation and forest degradation in order to set-up effective PAMs, both within and outside the forestry sector. Agriculture is by far the most important direct driver of deforestation. Increasing population sizes and welfare, increased use of bio-energy and the negative impacts of climate change on agricultural productivity in certain areas may have effect on REDD+. The effectiveness of REDD+ therefore depends also on agricultural policies. Mitigation and adaptation in the agricultural sector are discussed under the topic 'sectoral approaches' of the AWG-LCA, together with emissions from international air and maritime transport. The discussions on the latter topic are very difficult, because developing countries that depend heavily on export for their economic development (such as China) oppose cutting emissions in this sector. This also gridlocked discussions and progress on agriculture for a considerable time. In Durban however, an opening was made that allows the development of agriculture in the UNFCCC.

General outcome

The most important result after COP17 was that the two-track approach of the BAP was abandoned. It was decided at Durban that the AWG-LCA would be terminated and replaced by a new negotiation track, the AWG-Durban Platform for Enhanced Action. The DPEA should result to a protocol, legal instrument or agreed outcome applicable to all Parties, the latest, 2015 and to entry into force in 2020. This instrument should thus cover both developed and developing countries on a pathway to reduce emissions and keep the impact of global change limited.

Conclusion

The international framework of REDD+ is taking form and shape. The progress that has been made, has already resulted in both large scale international (e.g. FCPF) and local project-based initiatives. Apart from outstanding technical and political issues, there are still two major challenges:

a) REDD+ needs to be imbedded in an overarching climate agreement that ensures additional global emission reductions and sufficient financial resources for developing countries. Without it, the potential of REDD+ as mitigation tool will be largely untapped;

b) REDD+ needs to be implemented on a national scale across countries and continents. A CDM scenario, where only a few countries benefit, will undermine REDD+ as it will result in leakage of deforestation. Although the design of REDD+ can facilitate this, governments at different levels will have to install and enforce effective forestry policies, secure tenure rights and ensure a fair sharing of the benefits of REDD+. This poses a big challenge for many developing countries.

2. How can REDD+ be sustainable

2.1. Imbedding REDD+ in the forest REALU'ty

The Coalition of Rainforest Nations has been successful in highlighting the importance of tropical forest since the international climate change negotiations in Montréal in December, 2005 (COP11). At the COP15 negotiations in Copenhagen in December, 2009, most observers agreed that REDD was one of the topics where most progress has been made. A remaining problem is that negotiators mainly focus on (rain)forests, although no REDD working definition for forest has been formulated. The current UNFCCC definition formulated for CDM afforestation and reforestation projects (CDM A/R) excludes vast areas with limited forest cover, often situated in the dry tropics.

Forest definition and leakage

Up to now, a forest definition has not been agreed upon for REDD+ within the UNFCCC. What does exist since COP7, the Marrakesh negotiations in, 2001, is a definition for the CDM A/R where forest is defined as "a minimum area of land of 0.05-1.0 hectares with tree crown cover (or equivalent stocking level) of more than 10-30 % with trees with the potential to reach a minimum height of 2-5 metres at maturity in situ." In addition "a clearcut area that is temporarily unstocked, but that is expected to revert to forest" is also considered forest.

The UNFCCC definition of a forest is not inclusive enough. Areas of open forest or dry forest are not included, which could lead to leakage.

Sasaki and Putz (2009) have criticised this definition because large quantities of carbon and other environmental benefits will be lost when natural forests are severely degraded or replaced by plantations but technically remain "forests". Verchot *et al.* (2007) calculated the effect of different tresholds for 4 countries and showed that under the CDM a higher lower limit of tree cover would allow countries to maximize their participation and flexibility. In a REDD framework the effect would be the opposite, while anyway forests (generally dry forests) of less than 10–30 % cover would remain excluded (Figure 4). In addition, an important drawback of almost any forest definition is that it would exclude trees outside the forest (*e.g.* on farms).

The ICRAF-led ALLREDDI project (Accountability and Local Level Initiative to Reduce Emission from Deforestation and Degradation) revealed that in Indonesia, about a third of the emissions from land use change take place outside state forest land, without even including the large emissions from peat lands. The current Indonesian REDD plans only consider state forest land. Even if the current REDD approach for Indonesia is 100 % successful, net emission reductions would be obtained earliest after 6 years because of a shift of emissions to areas currently not recognised as forest (Ekadinata *et al.*, 2010).

Biodiversity

Dry forest degradation is not only relatively neglected in the current international REDD policy debates, but is poorly represented in pilot programs as *e.g.* led by UN-REDD. It is undeniable that many of the worlds' biodiversity hot spots are in what can be considered rainforest. However, the current focus on areas that are rich in both carbon and biodiversity, risks to go at the detriment of dry forest and other vegetation types. This has *e.g.* been reported from Brazil, where deforestation in the Cerrado is now higher as in Amazonas, and only 2.2 % of its area is under legal protection (Klink and Machado, 2005). On the voluntary carbon market certified emission reductions (CER's) that also preserve biodiversity usually get higher prices than emission reductions without co-benefits. To include this in a post-Kyoto arrangement, steps should be made to better integrate the Convention of Biological Diversity (CBD) into current and future REDD approaches.

Ecosystem carbon and REALU: an alternative approach

REALU (Reducing Emissions from All Land Uses) makes the unfruitful discussion about forest definitions redundant. There is probably no single definition of forest that can apply in the continuum of landscapes with trees (Van Noordwijk and Minang, 2009). A better option would be to consider 'ecosystem carbon', rather than forest carbon alone (Guariguata *et al.*, 2009). The emphasis should be on monitoring persistent declines and increases of carbon stocks over time, based on the Intergovernmental Panel on Climate Change (IPCC) methodologies. Zomer *et al.* (2009) have shown the large amount of biomass and carbon stored in trees in both dry land areas and in agricultural domain.

Mitigation …

What many developing countries (and especially the least developed ones) can offer on the global carbon market is largely land use based carbon. A large part of the developing countries have up to now been reluctant, or even opposed, to a full carbon accounting. Lack of capacity is often cited as the major reason, which is likely also why up to now so little 0 10 30 50 100 % Percentage tree cover

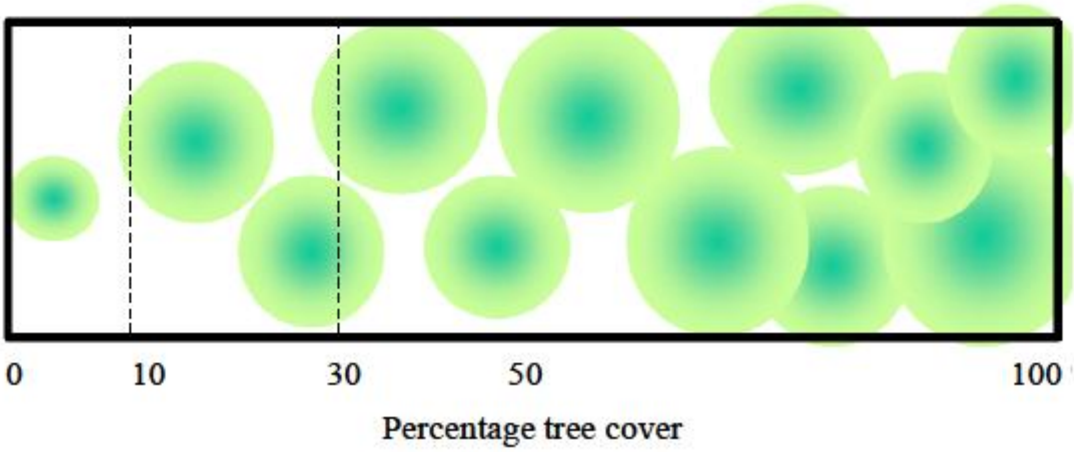

Figure 4. Continuum of tree cover from 0-100 % and the range of thresholds that is used across the globe in defining forest on the basis of tree cover (adapted from Van Noordwijk (2001)). Using tree cover as a major threshold means picking an arbitrary cut-off point.

CDM projects have been realised in these countries. The needed capacity is not only for monitoring, reporting and verification (MRV), but also for effective linking to the global market. Recent research in Ethiopia (Mekuria *et al.*, 2010) has quantified the potential of converting degraded grazing lands into tree covered exclosures to restore soil fertility and to sequester carbon from the atmosphere. Over a period of 30 years, sequestered carbon dioxide was 246 Mg/ha, total soil nitrogen increased by 7-9 Mg/ha and additional available phosphorous stocks amounted to 40 kg/ha. For a period of 30 years, a real interest rate of 8.1 % and assuming a price of 18 € per ton CO_2, the Net Present Value of the exclosure's ecosystem services was about 28 % higher than for wheat, the best alternative production (3188 vs. 1600 €/ha. Carbon revenues alone added up to only about 44 % of the net revenues of wheat production. This indicates that (i) carbon market revenues alone would not generate sufficient incentives to establish additional exclosures, and (ii) if all benefits are taken into account and financially rewarded, exclosures are competitive to alternative land uses. Mekuria et al (2010) identified substantial opportunities to mobilize the local communities. It is important to note that over those 30 years 90-95 % of the sequestered carbon is soil carbon!

… and poverty reduction by adaptation

Dry land forests are often more degraded and void because they are more densely populated, generally by rural poor. Climate change adaptation is a priority for most developing countries. In dry areas like the Sahel, trees do not only sequester carbon, but also redistribute water over different soil layers improving the growth of grasslands and crops. As a matter of fact, saving carbon is not the top priority for smallholder farmers, but increased tree cover and agroforestry practices (using *e.g.* nitrogen fixing trees or exclosures) have the potential to increase and stabilise harvests, and deliver the ecosystem services farmers really need, while offering also opportunities to store carbon for the global community (Akkinifesi *et al.*, 2009).

Development programs aimed at improved food security should explore ways to increase tree cover adapted to local conditions and achieve both mitigation and adaptation as part of the same integrated strategy.

Monitoring-Reporting-Verification

Most developing countries do not have comprehensive forest inventory data, raising the question on how reference scenarios can be created. Remote sensing based methodologies have improved significantly, albeit that in cases of low intensity forest timber harvesting, fuelwood collection, forest degradation, etc. direct monitoring will remain needed. Community based monitoring in the Sahel, India, Nepal and Tanzania have shown very promising results, also realising the above mentioned adaptation co-benefits (Skutsch *et al.*, 2009; Skutsch and Ba, 2010). In dry areas sequestered carbon is dominantly soil carbon. It is definitely more difficult to measure than aboveground biomass, so there is an urgent need to invest more into research for this carbon pool (Rossi *et al.*, 2009).

Conclusion

The inherent problem of defining a forest (biophysical vs. legal) seriously undermines any REDD+ approach. The current focus of the international REDD+ negotiations on forest carbon alone and especially on countries with high forest cover or high deforestation induces risks of large-scale leakage, especially in dry land forests and trees outside the 'forest'.

An ecosystem carbon approach through REALU (Reducing Emissions from All Land Uses) overcomes this leakage problem and also has a large potential for integrated adaptive development, where mitigation goes hand in hand with food security, biodiversity and poverty reduction.

ODA could help to acquire the needed capacity for REALU with integrated programs that focus on increased food security, better land use management, climate change mitigation and adaptation. In dry areas forest protection and/or increased tree planting will not only improve local development and climate adaptation.

Proven mitigation could help fund this tree planting and forest protection. A simplified carbon accounting system for developing countries, even temporary, until these countries have developed sufficient institutional capacity, will lower the entry point of LDC's to engage in REALU. This could be developed in accordance with the currently developed tiers 1, 2 and 3 for REDD+.

3. Potential of low resolution optical remote sensing imagery

Introduction

The IPCC guidelines to estimate and report emissions from deforestation rely on five land use conversions that imply deforestation for which methodology and conversion factors are provided. Currently, most IPCC reporting in the GPG-LULUCF or GPG-AFOLU is based on national forest inventories as the good practice guidance. This is often a time consuming and expensive approach. In addition the focus of national inventories is often on forests of (high) commercial value with intensive management. These GPG's form currently the basis for setting up MRV systems for the REDD+ framework. Approaches to assess national-level carbon emissions from deforestation and degradation require the assessment of the area of forest (or cleared forest) (areas) and the amount of carbon stored in the forests (stocks). The measurement system described in the GPG uses three tiers that range from coarse resolution data using general equations to substantially refined local data used in sophisticated models (Olander *et al.*, 2008).

Forest surface area estimates are often derived from high resolution images such as Landsat (30m resolution*, e.g.* Achard *et al.*, 2007). These data have been widely used for mapping of land cover and vegetation. The strength lies in the good spatial resolution to capture landscape details, but it has low temporal resolution (biweekly to monthly acquisition). It is considered the best practice in the sourcebook on REDD+ (GOFC-GOLD, 2009). Due to the relatively high spatial resolution, national wall-to-wall mapping and long-term carbon accounting for a country like Indonesia takes a high amount of resources and can only be reasonably conducted as multi-year analyses (*e.g.* 5-year or a decade). The Forest Resource Assessment uses this approach to assess globally the forest cover every 5 years (FAO *et al.*, 2009).

The most simple way to estimate carbon stocks is using biome-average data sets where a single representative value of forest carbon per unit area is applied to broad forest categories or biomes (*e.g.* Achard *et al.*, 2002, Kindermann *et al.*, 2008, Eva *et al.*, 2012). These values, combined with the areal extent of forests, provide the carbon stock. A more detailed method is to derive stocks from ground-based forest inventory data using allometric relationships assessed statistically between tree properties, such as tree diameter at breast height and tree height, and destructive harvest measurements (*e.g.* Chave *et al.*, 2005). This method often suffers from inappropriate sampling schemes and insufficient data set size which can lead to incomprehensible national inventories from which carbon stocks cannot be estimated with sufficient accuracy (Gibbs *et al.*, 2007). Moreover, it is anticipated that field data are unlikely to be sampled adequately for monitoring of carbon stocks (Goetz *et al.*, 2009), because these inventories are a time consuming and costly activity.

Upscaling of land cover maps derived from Landsat data into carbon accounting to comply with IPCC's Tier 3 mapping has as well been implemented. A good example is Indonesia. ICRAF through the ALLREDDI project, conducted nationwide land cover mapping and landscape carbon estimation using Landsat images as the main data source for Indonesia for the years 1990, 2000, 2005 and, 2010 (Ekadinata *et al.*, 2011). Landscape carbon estimation was based largely on land cover maps produced with hierarchical object-based classification. Land cover maps were combined in a geographical information system with other biophysical parameters, elevation, eco-regions and the carbon database (based on national forest inventory) as the lookup table (Hardja *et al.*, 2011; Ekadinata *et al.*, 2011). Still, the resulting multi-year products bear uncertainties with regard to carbon stock variations within one time-series. Nevertheless, the approach has been considered optimum considering various aspects with regards to data availability, time and cost.

A number of authors discuss the capabilities and limitations of these classical methods to assess above-ground biomass against various remote sensing imagery sources such as SAR, lidar and optical data (*e.g.* Goetz *et al.*, 2009, Gibbs *et al.*, 2007). Despite the fact that RS data are often perceived inadequate for assessing above-ground biomass, they conclude that classical approaches are insufficient without using remote sensing as additional information. Moreover, the approach using satellite imagery could be used to obtain estimates of above-ground biomass in all categories of LULUCF reporting. The largest contribution for carbon stock mapping is expected from lidar, but currently there are no operational systems that provide consistent data sets for large areas. On the other hand, optical RS often underestimates biomass due to dense canopy closure (Houghton *et al.*, 2007). Nonetheless, Gibbs *et al.* (2007) acknowledge that these sensors are operational, and provide long term and consistent time series.

Carbon stocks have been derived from low resolution optical data by calibrating the reflectance values directly to field estimates of above ground biomass using “machine learning” techniques with various success (*e.g.* Houghton *et al.*, 2007, Baccini *et al.*, 2008 and Blackard *et al.*, 2008). Advantages of this approach are the higher spatial detail in above ground biomass estimates, more consistent estimates through time, independence from the determination of land cover types and an increased probability of acquiring cloud free observations for the entire area (*e.g.* Goetz *et al.*, 2009).

Another way to use low resolution optical sensors for carbon estimation is to monitor continuously the vegetation production through the estimation of Net Primary Production (NPP) based on remote sensing data (Zhao *et al.*, 2005, Verstraeten, Veroustraete, and Feyen, 2006). This approach alone is not sufficient for carbon accounting, since only the fluxes of vegetation production can be estimated and not the stocks. However, in combination of the 5-year assessments at higher resolution and with forest inventory data, the low resolution NPP data could be used for permanent monitoring and to identify the areas where analysis with higher spatial detail are necessary. This approach is recently also acknowledged as an emerging technology in the sourcebook on REDD+ (GOFC-GOLD, 2009).

The approach to use remote sensing based carbon fluxes of vegetation to complement the carbon accounting method is justified by the IPCC GPG (2006), which mentions in section 1.6: “*The carbon stock change that is reported in national greenhouse gas inventories for land-use categories is equal to NBP [Net Biome Productivity]*.

This NBP can also be derived from remote sensing sources as shown in Figure 5.

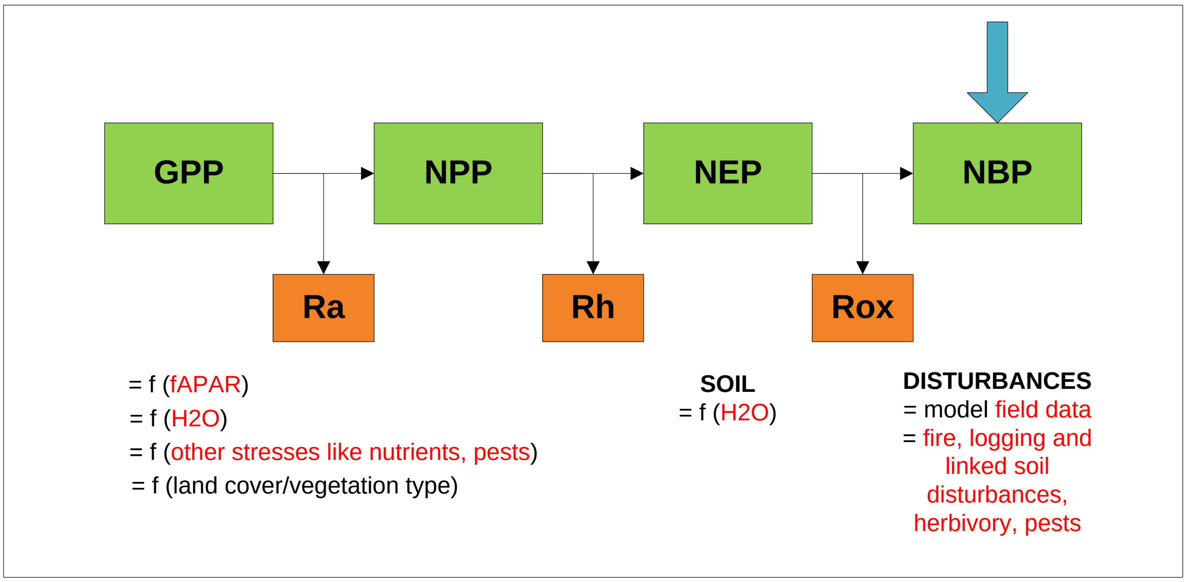

Figure 5. Flowchart from GPP to NBP (carbon balance accounting), with GPP=Gross Primary Productivity, NPP=Net Primary Productivity, NEP=Net Ecosystem Productivity, Ra=autotrophic respiration, Rh=heterotrophic respiration, Rox=disturbances.

To solve this equation and to be of use for the carbon modelling society and forestry services who are studying the carbon balance:

- Accurate GPP and NPP estimates must be derived from remote sensing;
- Heterotrophic respiration is estimated through the incorporation of water limitation data to result in NEP (see for example Verstraeten *et al.*, 2010);
- Data on disturbances preferably per forest type and disturbance type;
- The extent of the forests is known

In the Be-REDDi project, we focused on an evaluation of the estimation of GPP from low resolution, optical remote sensing data, which is just the first component of the chain. The GPP/NPP estimates from optical RS-based models are mostly used for regional to global assessment of carbon fluxes. Application within the context of carbon accounting requires a detailed review of the model parameterisation and a calibration to field-based measurements. Because such a detailed analysis and demonstration was out of the scope of this project, a proposal was submitted to the STEREO II call of Belspo in, 2011. The proposal was unfortunately not honoured. Within the Be-REDDi project, the focus was then put on reviewing one aspect of the NPP-estimation with low resolution Earth observation (EO) data, *i.e.* the efficiency term (see further).

Net Primary Productivity (NPP)

Description

Primary productivity quantifies the conversion of atmospheric CO_2 into plant biomass. It refers to a rate process (a flux), which is the amount of vegetable matter produced per unit time, and is generally expressed in $gC/m^2/day$. NPP is the net result of photosynthetic activity, *i.e.* the increase in biomass (gross primary productivity, GPP) minus autotrophic respiration, the amount of carbon that is returned to the atmosphere as carbon dioxide during plant metabolism. NPP is a fundamental ecological variable, not only because it measures the energy input to the biosphere and terrestrial carbon dioxide assimilation, but also because of its significance in indicating the condition of the land surface area and status of a wide range of ecological processes (Gower *et al.*, 2001). NPP of large land areas is a unique integrator of climatic, ecological, geochemical and human influences (Running *et al.*, 2009).

Several methods exist to derive NPP estimates from vegetation. Roughly, they can be divided into three groups: model-based methods, methods based on earth observation (EO) and the combination of both. The first approach is based on a model that describes physical processes, such as photosynthesis, respiration and evaporation at the leaf or canopy scale, with the goal to extrapolate them to larger regions and longer time scales (*e.g.* CARAIB of Warnant *et al.*, 1994). These models are designed and calibrated for a specific vegetation type, and often need a lot of input data (McMurtrie and Landsberg 1992). It is clear that due to their complexity and high demand of input data, they can only be applied for small areas or specific land cover types. In order to capture also the dynamic behaviour of vegetation (*e.g.* the start of the growing season), these models are often combined with EO data. The EO data then provides information on fAPAR, LAI, albedo or land cover, just like the meteo data are used to characterise the state of the atmosphere. Hazarika *et al.* (2005) integrated LAI into an ecosystem model and evaluated the two approaches for NPP estimation. They found that the NPP from the model enriched with MODIS data was more accurate. Another example of this approach can be found in Prieto-Blanco *et al.* (2009)

The EO approach focuses on the estimation of factors of the Light Use Efficiency (LUE) model, including the fAPAR, *i.e.* the fraction of the incoming Photosynthetically Active Radiation (PAR, 400-700 nm) which is absorbed by green plant elements. This Light Use Efficiency concept for NPP estimation was first formulated by Monteith (1972). He considered biomass accumulation as an ongoing process correlated with the amount of radiation absorbed (absorbed PAR or APAR) or intercepted by green foliage. Plant production is then approximately related to APAR multiplied by a conversion efficiency constant ε_{LUE}, and integrated over the season (NPP=$\int \varepsilon_{LUE}$ *APAR). The ‘energy conversion factor’ ε_{LUE}, expresses the efficiency with which the vegetation performs photosynthesis. These models are also called ‘production efficiency models’ (PEM).

General equations of the EO approach

Monteith (1972) stated that vegetation growth is completely defined by the part of the incoming solar radiance that is used for photosynthesis and which is absorbed by the plants (APAR) and an actual conversion efficiency factor ε_{ACT}.

$$NPP = APAR \cdot \varepsilon_{ACT} \tag{1}$$

The fraction of absorbed photosynthetic radiation (fAPAR) is used in combination with in incident solar radiation from meteo (R) to form APAR in equation (1). fAPAR can be estimated from the reflectance information derived from optical sensors that have at least spectral bands in the red and near infrared part of the solar spectrum (Weiss *et al.*, 2010, Frédéric Baret *et al.*, 2007). In equation (1), the term APAR is replaced by:

$$APAR = R \cdot fAPAR \cdot \varepsilon_P \tag{2}$$

The term ε_P describes the portion of the intercepted solar radiation that is suitable for photosynthesis. In models, this is often a constant fraction, whereas in reality it depends on location and sky conditions (Gower *et al.*, 1999).

The energy conversion factor ε_{ACT} in equation (1) expresses the actual efficiency of converting atmospheric CO_2 into plant tissue. This actual efficiency can be subdivided into a vegetation type specific maximum light-use efficiency terms ε_{LUE} and a number of stress factors. The term ε_{LUE} is then the light-use efficiency in optimal conditions, *i.e.* when there is sufficient water and nutrients, the temperature is optimal for vegetation growth, no pests, diseases, etc. All these limiting factors can be used to downscale ε_{LUE} towards ε_{ACT}.

The equation (1) then becomes

$$NPP = R \cdot fAPAR \cdot \varepsilon_P \cdot \varepsilon_{LUE} \cdot \varepsilon_T \cdot \varepsilon_{H2O} \cdot \varepsilon_{CO2} \cdot \varepsilon_{AR} \cdot \varepsilon_{res} \qquad (3)$$

The different conversion and efficiency terms are explained in Table 1.

Table 1. Definition of the different conversion and efficiency terms in Equation (3).

term	meaning	value	units
ε_P	Fraction of photosynthesis active radiation (PAR) in total shortwave radiation R. This depends on location and on sky conditions (S. T. Gower *et al.*, 1999). In most models only one invariant value is used for ?P.	0.42 – 0.55	J_P/J_T
ε_{LUE}	Maximum light use efficiency, *i.e.* in optimal conditions with no limitations for vegetation growth. It expresses the efficiency with which vegetation performs photosynthesis.	Depending on vegetation type	
ε_T	Efficiency term limiting the vegetation growth for temperature stress. The term is normalized between 0 and 1.	0 – 1	-
ε_{H2O}	Efficiency term limiting the vegetation growth for water stress. The term is normalized between 0 and 1.	0 – 1	-
ε_{CO2}	CO_2 fertilisation effect, normalized between 0 and 1	0 – 1	-
ε_{AR}	Fraction kept after autotrophic respiration	0 – 1	-
ε_{res}	Fraction kept after residual effects (pests, lack of nutritients, etc.)	0 – 1	-

Gross Primary Productivity is obtained when the respiration processes are not taken into account. The equation is as follows:

$$GPP = R \cdot fAPAR \cdot \varepsilon_P \cdot \varepsilon_{LUE} \cdot \varepsilon_T \cdot \varepsilon_{H2O} \cdot \varepsilon_{CO2} \cdot \varepsilon_{res} \qquad (4)$$

The accuracy of GPP estimates depends on the accuracy with which the compounding factors (meteorology, physiological ecology and remote sensing) can be measured or estimated. Much of the uncertainty in estimating GPP is due to variability in estimates of solar radiation conversion to biomass, the light use efficiency factor. This efficiency term is critical for GPP estimation, yet the controls on ε_{LUE} are still poorly understood (Jenkins *et al.*, 2007). Uncertainties are associated with factors such as canopy chemistry and structure, respiration costs for maintenance and growth, canopy temperature, evaporative demand, and soil water availability (Running *et al.*, 2009). Another question on the downregulation of ε_{LUE} is whether it should be downregulated by all stressors or by the most limiting ones. Besides this, the assessment of the maximum ε_{LUE} (*i.e.* in optimal conditions) per land cover type or plant functional type is already a challenge. Some authors even question whether this is necessary (*e.g.* Yuan *et al.*, 2007).

Within this project, we focussed on gaining a better understanding of this ε_{LUE} with the aim to use this information in the future to improve the NPP product that is currently used in and distributed by VITO.

Light Use Efficiency

Estimation

The light use efficiency term ε_{ACT} is a value that represents the actual efficiency of a plant's use of absorbed radiation energy to produce biomass. It is therefore a key physiological parameter at the canopy scale. In order to be used in production-efficiency models, the maximum gross light use efficiency factor ε_{LUE} is needed, and not the actual one. There are a number of ways to assess/estimate ε_{LUE}, either through direct or indirect measurements.

A direct way to assess ε_{LUE} is through chlorophyll fluorescence measurements at the leaf level. In this case, actual light-use efficiency is measured instead of the desired maximum $\varepsilon_{LUE,}$ used for GPP estimation, and this should be upscaled to vegetation types in order to be representative.

Through indirect measurements, ε_{LUE} can be assessed using the eddy covariance (EC) method or the remote measurement of chlorophyll solar-induced fluorescence.

The most common way to estimate ε_{LUE} indirectly is using the eddy covariance (EC) method . The EC method determines carbon fluxes through the covariance between fluctuations in vertical wind profile and the CO_2 mixing ratio in the air above the canopy. The term ε_{LUE} can then be derived indirectly using the Monteith approach, *i.e.* ε_{LUE} = GPP/APAR . This should be done over a certain period of time, from which a general ε_{LUE} can be derived.

Although widely used, this method also suffers from a number of limitations and uncertainties. Firstly, the flux footprint, which is captured in the EC sample area, is restricted to a few 100m² upwind from the tower. Consequently, the size and location of the footprint varies in time, making it less suitable to measure ε_{LUE} at a single canopy or small forest level. In addition, the EC theory assumes steady environmental conditions and surface homogeneity, a condition which is often violated. Secondly, through the EC method, Net Ecosystem Exchange (NEE) is measured, and not the desired GPP to derive ε_{LUE}. But for terrestrial ecosystems, one can assume that inorganic sinks and sources can be neglected (Lovett *et al.*, 2006), meaning that –NEE equals NEP. Then to obtain GPP, the NEP is summed with the daytime ecosystem respiration (R_d). This quantity however, should be measured in the absence of photosynthesis, so night time measurements are used, despite studies demonstrating the problems of extrapolation of night time measurements to daytime (Coops *et al.*, 2010). Thirdly, radiation intercepted by non-photosynthetic plants are not part of NPP (by definition), but dead leaves do absorb PAR. As a result, one can observe an apparent reduction of ε_{LUE} near the end of the growing season by using the Monteith approach to derive ε_{LUE} from EC measurements (Gower *et al.*, 1999). Thus the period from which ε_{LUE} is derived is also important. At last, it is clear that the EC method provides actual light use efficiency terms and not the maximum gross light use efficiency term needed in NPP-models based on remote sensing. However, if the measurement period is sufficiently long, one could derive the gross light use efficiency, by analyzing all limiting factors within the same time span.

Other limitations of the light use efficiency term (derived by the EC method or not) are that ε_{LUE} is often assessed for only for daytime conditions, thereby excluding the night time respiration, which inevitably lowers the ε_{LUE} (Gower *et al.*, 1999). Sometimes it is not clear for which vegetation the ε_{LUE} value were assessed. Excluding *e.g.* understory vegetation from forests in the measurement of ε_{LUE}, results in erroneous estimates in LUE-based GPP/NPP-models. Most estimates of ε_{LUE} are for aboveground components of the overstory layer only. But biomass allocation to belowground GPP/NPP range from 20 to 75% of the total NPP in all terrestrial ecosystems, and should therefore not be omitted.

Another problem is that ε_{LUE} is sometimes expressed and assessed in function of NPP instead of GPP. These published ε_{LUE} values should not be used in GPP-models. But in this way, respiration processes cannot be taken adequately into account (Gower *et al.*, 1999). In addition, ε_{LUE} is sometimes derived using total solar radiation or intercepted solar radiation instead of APAR.

An alternative method to obtain ε_{LUE} is through solar-induced fluorescence (*e.g.* GRACE *et al.*, 2007, Coops *et al.*, 2010, Liu and Cheng, 2010) or the photochemical reflectance index (PRI) (*e.g.* Drolet *et al.*, 2005, Nakaji *et al.*, 2007) . This is a new field of research which looks promising.

Controls of Light Use Efficiency

During the past decade, many researchers have investigated the controls of the light use efficiency term ε_{LUE} (*e.g.* Garbulsky *et al.*, 2010, Turner *et al.*, 2003, Wang *et al.*, 2010). This is important in two aspects: first to derive the maximum gross light efficiency factor ε_{LUE}, and secondly to know which parameters have to be used in order to downregulate ε_{LUE} to ε_{ACT} in GPP-models. So far, the controls on ε_{LUE} are still poorly understood, which is reflected in the multitude of different GPP-models that exist (see next section).

Garbulsky *et al.* (2010) performed an analysis based on 35 EC flux sites, from a wide range of climatic conditions. ε_{LUE} was calculated from EC measurements and MODIS data and inter-annual and intra-annual controls on ε_{LUE} were investigated. They concluded that when vegetation is adapted to its local environment, water availability is more constraining its functioning than temperature. This is in agreement with the results of Yuan *et al.* (2007), who found that ε_{LUE} is predominantly controlled by moisture conditions throughout the growing season and that temperature is only important at the beginning and the end of the growing season.

To explain the spatial variability of ε_{LUE}, Garbulsky *et al.* (2010) found that annual precipitation is more important than vegetation type. Although not the most important factor, they did conclude that vegetation type matters, which is in line with the former results of (Turner, Urbanski, *et al.*, 2003), who support the idea of biome-specific parameterisation of ε_{LUE}. The results of Wang *et al.* (2010) and Ahl *et al.* (2004) suggest that biome-specific ε_{LUE} are even not detailed enough, because of the heterogeneity of these classes. They plead for species-specific ε_{LUE}. In large contrast to these findings are the results of Yuan *et al.* (2007), who claim that their model, using a single biome-independent ε_{LUE} outperforms the MODIS GPP data set using biome-specific ε_{LUE} values, and this based on validation data of 28 EC flux towers at divers locations. Furthermore Garbulsky *et al.* (2010) and Turner, Urbanski, *et al.* (2003) found that ε_{LUE} is highest for annual crops than for any type of forest. In fact, all land cover types with predominantly grass and herbaceous vegetation had higher ε_{LUE} compared to vegetation types including trees in the analysis of Garbulsky *et al.* (2010). This is in contradiction to the MODIS approach (Zhao *et al.*, 2005).

When looking at intra-annual variability of ε_{LUE}, Garbulsky *et al.* (2010) found a larger link with energy-balance parameters (evaporative fraction) and water availability along a climatic gradient, but only a weak influence from vapour pressure deficit and temperature. Although quite a number of models use vapour pressure deficit to describe water stress, Garbulsky *et al.* (2010) concluded that it is better to use evaporative fraction or actual over potential evapotranspiration. Turner, Urbanski, *et al.* (2003) also found a low correlation between ε_{LUE} and vapour pressure deficit or maximum daily temperature.

The main control parameters of the temporal evolution of ε_{LUE} varied across ecosystems. One example is that temperature only played a role in the intra-annual variability of ε_{LUE} at the coldest and energy-limited sites.

For humid and hot ecosystems, Garbulsky *et al.* (2010) concluded that none of the variables analysed are confident surrogates for ε_{ACT}. They suggest that the ratio of direct to diffuse light might play a more important role in the control of ε_{LUE}. Jenkins *et al.* (2007) already concluded from the time series analysis of measurements of one EC flux site that the day-to-day variation in ε_{LUE} is largely explained by changes in the ratio of diffuse to total downwelling radiation. They found no strong correlation with any other measured meteorological variable. Turner, Urbanski, *et al.* (2003) found higher ε_{LUE} values in overcast conditions, and therefore suggest the inclusion of parameters on cloudiness in GPP-models.

Other results from Turner, Urbanski, *et al.* (2003) suggest that the phenological status of the vegetation should be used as a parameter for GPP-estimation, because ε_{LUE} declined toward the end of the growing season for the agricultural site, which was attributed to a decrease in foliar nitrogen concentration.

DeLucia, George, and Hamilton (2002) investigated the effect of elevated CO_2 concentrations on ε_{LUE} for forests plots using a free-air CO_2 enrichment system. They observed a only slight effect on leaf area index and no effect on the patterns of aboveground biomass allocation.

At last (Gower *et al.*, 1999) state that controls on ε_{LUE} should be expressed in function of GPP and not NPP, since the dependence of respiration processes on temperature and other controlling factors is different.

LUE NPP models: examples

At present, a number of NPP models exist that make use of low resolution optical remote sensing data. These models differ in many aspects although they are all based on the general approach defined by Monteith (1972). Most of the current generation of light-use efficiency models have 3 key components (Running *et al.*, 2009):

(1) Satellite derived vegetation properties: land cover, LAI, fAPAR
(2) Daily climatic data including incident radiation, air temperature, humidity and rainfall
(3) A biome-specific parameterization scheme to convert absorbed PAR to NPP (ε_{ACT}).

Here we focus on the difference in the way ε_{LUE} is downregulated to ε_{ACT} using estimators of different stressors. The conversion efficiency term ε_{LUE} is usually expressed in terms of GPP and not NPP, because this allows a better incorporation of respiration processes in the model. Therefore, the models are subdivided in these two classes.

Table 2. Examples of remote sensing driven GPP/NPP-models.

GPP-models	**Stressors**	**ε_{LUE}**	**Reference**
GLO-PEM2	T_s, SM,VPD		(Goetz *et al.*, 2000)
MODIS-PsN	T_s, VPD	Biome defined maximum (11 biomes)	(ZHAO *et al.*, 2005)
3-PGS	Soil, T_s, FD, P, WC	Function of soil nitrogen content	(Coops, Waring, and Landsberg 1998)
VPM	T_s, W, P_L	Fixed value, estimated from EC measurements	(XIAO *et al.*, 2005)
EC-LUE	T_a, EF	Fixed value, estimated from EC measurements	(Yuan *et al.*, 2007)
C-fix	T_s, EF, SM	Biome defined maximum	(Verstraeten *et al.*, 2006)
MARSOP	T_s	Fixed	(Veroustraete *et al.*, 2002)
NPP-model	**Stressors**	**ε_{LUE}**	**Reference**
CASA	T_s, SM		
CASA	T_s, ET, PET		

PARAMETERS: T_s surface temperature; T_a air temperature; SM soil moisture; VPD vapour pressure deficit; P precipitation; WC water holding capacity; EF evaporative fraction; FD frost days; W canopy water content; ET evapotranspiration; PET potential evapotranspiration. WHAT IS PL?

MODELS: GLO-PEM2 global production efficiency model version 2; 3-PGS Physiological Principles Predicting Growth from Satellite; VPM Vegetation Photosynthesis Model; EC-LUE eddy covariance flux light use efficiency model; CASA Carnegie-Ames-Stanford-Approach (different versions of this model exist)

A number of studies compared the performance of different GPP/NPP models with and without input from remote sensing (*e.g.* Coops *et al.* (2009), Ruimy *et al.* (1999), Wu *et al.* (2010), Tao *et al.* (2005), Cramer (1995)). These models can differ in many respects. Firstly, not all models downregulate the ε_{LUE} for the same stressors. The most simple model is only temperature based and only a few models incorporate data on nutrient availability or on frost days. Most recent models include a water balance. Secondly, some stressors are estimated in different ways. The best example is the water limitation. This is realized through water vapour deficit, evaporative fraction, soil moisture content, water holding capacity, evapotranspiration or a combination of a set of parameters. Thirdly, input for the same parameter can be acquired via meteorology or via satellite imagery, *e.g.* temperature, vapour pressure deficit, soil water capacity.

When a comparison is made between two versions of a model, *i.e.* one without remote sensing data and one with (*e.g.* 3-PG versus 3-PGS, Sim-CYCLE versus MOD-Sim-CYCLE), then the version that uses remote sensing data performs best when compared with validation data (Hazarika *et al.*, 2005))

Most models use a different ε_{LUE} for different plant functional types or biomes. However, Yuan *et al.* (2007) developed the GPP-model EC-LUE based on only 4 driving factors, *i.e.* NDVI, PAR, air temperature and evaporative fraction, based on an invariant biome-independent maximum ε_{LUE}. They found that their model results were more accurate than those distributed from MODIS and based on a more complex model approach that needs much more input data. They claim that it is a good candidate for regional to global GPP mapping, since all inputs can be derived from remote sensing, and the model parameters are independent from vegetation types.

An issue which is not related to the efficiency term, but nevertheless important is that GPP-models using SPOT-VGT or MODIS imagery perform better than those based on AVHRR (*e.g.* CHIESI *et al.*, 2005, MASELLI *et al.*, 2006). This is probably due to the fact that the former sensors were specifically designed to monitor vegetation and saturate at higher LAI values.

A workshop was organised in 1995, where 17 different GPP/NPP-models were compared. Most of the models are not based on remote sensing data.

Coops *et al.* (2009) compared the output of 3-PGS, MODIS and C-fix (a former version) for the United States and found that the differences among the models varies up to 50% in areas where topography is and climate are more extreme. For the other areas, the variation was confined to 10%.

Conclusion

Future policy decisions on mitigating climate change, monitoring carbon credits etc. will put a high demand on timely and accurate monitoring and understanding the global carbon cycle (Running et al., 2009). The large number of recent publications demonstrate a renewed interest for this subject, which is undoubtedly related to the present need for accurate monitoring of the carbon cycle. Nevertheless, from the presented literature review, it is clear that uncertainties still exist on the controls of light use efficiency and the usage in GPP-models.

As an example, most GPP-models define a maximum gross light use efficiency factor per biome or plant functional type. This efficiency factor is then downscaled using other limiting factors. This approach implicitly suggests that the efficiency term is predominantly controlled by plant functional type, whereas several authors demonstrated that water availability is a more dominant control.

The largest challenge to set up a GPP-model is to bring together expertise from different domains. In order to improve the GPP-estimation at VITO, contact was made with prof. Ivan Janssens (UA). We will set up a collaboration on GPP validation using data acquired at his lab. In addition, a collaboration was set up with climatologist Brad Evans (University of Murdoch, Australia) to investigate the performance of water limitation in GPP-estimation.

4. Drivers of deforestation and land use change, and policies for REDD+ and global forest transition

Introduction

On global scale, population growth and increases in per capita consumption of commodities produced from the land are expected to continue to lead to a growing pressure on land (Lambin and Meyfroidt, 2011). Over the last decade, commodities produced for global markets, whose production occupy vast amount of lands, and with high income elasticity (*e.g.* soybean, palm oil, beef, coffee, timber), have expanded rapidly. Intensification of land use, made possible by technological progress and better management practices, has the potential to satisfy the bulk of future increases in demand (Godfray *et al.*, 2010). But as long as the rate of increase in demand remains greater than the rate of productivity increase, conversion of land under natural vegetation cover to productive uses will be unavoidable.

Yet, although global rates of tropical deforestation remain alarmingly high, they have decreased over the past decade. Tropical landscapes are dynamic, and many forest areas once cleared or degraded are abandoned a few years or decades later. Restoring natural or seminatural forests on abandoned land can potentially mitigate the environmental impacts of deforestation and forest degradation (Lamb *et al.*, 2005, Chazdon, 2008). A handful of developing, tropical countries have recently been through a forest transition, thus shifting from shrinking to expanding forests (including tree plantations) at a national scale – *e.g.* Vietnam, Costa Rica, China, India (Mather and Needle 1998, Meyfroidt and Lambin, 2011). Forest transitions result from multiple trends—natural regeneration of forests, forest plantation, adoption of agroforestry, continuing deforestation—that combine in various ways through time and space. Forest transition is sometimes presented as a quasi-deterministic process, implying that the long-term development of land change in a country is expected to follow this trajectory of decline and regrowth, which can only be delayed or accelerated by policies. This view has been challenged for its analogy with modernization theory, whereby countries are assumed to move through a standard pattern of development to a modern economy. Some authors argued that a global forest transition might be attainable in the coming decades.

The objectives of this section are, first, to review the current state of global land use and expected trends over the period, 2000-2030, second, to discuss the knowledge on causes and impacts of past and ongoing forest transitions, and third to examine the prospects and policy options for a global forest transition.

Current state and future trends of global land use

Below, we summarize various estimates of global land use for the year, 2000 and the period, 2000-2010 (Table 1, adapted and updated from Lambin and Meyfroidt, 2011), retaining low and high estimates. The most important - and least known - figure for global land use budgeting is the area of potential available cropland (PAC). Estimates of this area have high policy significance, as the debates over risks and benefits of large scale land acquisitions and foreign investments in agriculture, biofuels, afforestation for climate change mitigation and sustainable agricultural standards such as the Roundtables for Responsible Soy and Sustainable Palm Oil all rest on assumptions on the availability of "unused" land. A recent global assessment of agro-ecological zones identified 445 Mha globally that were not yet cultivated, non-forested, non-protected, and populated with less than 25 persons/km^2, and therefore assumed to be available for potential cropland expansion if one attempts to minimize ecological costs of land conversion (World Bank, 2010). A more recent study adopted a spatially-explicit, country-by-country approach to estimate the area of PAC, based on a

Once social, institutional, economic and physical constraints are taken into account, there is less potential available cropland than is generally assumed. Moreover, the social and ecological costs (in terms of carbon and biodiversity) of converting that remaining land would be significant.

limited number of regional or country case studies including the South American Chaco, Cerrado and Amazon arc of deforestation, the Democratic Republic of Congo, Indonesia and Russia (Lambin *et al.*, forthcoming). This study suggests that, once social, institutional, economic and physical constraints are taken into account, there is less PAC than is generally assumed, and that the social and ecological costs of converting that remaining land would be significant, both in terms of carbon and biodiversity (see Table 3). A more realistic estimation of the availability and geographic distribution of the potential available cropland – or land reserve – is a priority for land use planning, policy foresight, and to inform markets and potential investors.

Table 3. Main land uses in, 2000 and, 2010 in million hectares (Mha). Sources: see Supplementary information in Lambin and Meyfroidt (2011), and Lambin and Meyfroidt (2012) for updates and figures for, 2000-2010.

	Area, 2000 (Mha)		Annual change 2000-2010 (Mha)	
	Low	**High**	**Low**	**High**
Cropland	1,510	1518	+0.2	+1.7
Pastures	2,800	3,410	-7.7	-7.2
Natural forests	3,143	3,871	-11.3	-10.1
Gross deforestation			-15.2	-13
Gross natural regrowth			+3.9	+2.9
Planted forests	126	215	+4.9	+4.9
Urban built-up area	60	73	+1.0	+2.7
Potential available cropland	222	445		

Multiple demands for land cumulate to lead to rapid conversion: demands for more cropland to increase food, feedstocks and biofuel production; for industrial forestry to produce timber; for fast growing trees for carbon sequestration; and for urban and recreational spaces to accommodate a growing urban population (Table 2). Moreover, demands for protected areas for nature and biodiversity conservation, and for natural or managed ecosystems to provide a range of regulating and cultural ecosystem services further contribute to potential conflicts between various land uses. Globally, between, 2000 and 2030, feeding a growing population may require an additional 2.7-4.9 Mha of cropland per year on average, depending on future diets, food wastages, and food-to-feed efficiency in animal production. Most of this expansion is likely to occur in Latin America and Africa, while cropland is still expected to decline in developed countries. Meeting the current policy mandates of biofuels use would require an increase by 1.5-3.9 Mha per year of cropland area devoted to feedstock. Projections of pasture expansion range between 0 to 5 Mha per year, depending on intensification of livestock production systems, which become increasingly decoupled from the land. Expansion would occur mainly in Latin America and East Asia, while pasture area would decrease in North America and Europe. Cities cover less than 0.5% of the Earth's land surface but urban area is predicted to more than double by 2030, according to the low scenario. Demand for industrial forestry will grow by 1.9-3.6 Mha per year, mainly in Asia and subtropical regions, to meet an increase in demand for wood products of 2.8-40.3%, depending on income elasticity of demand and on fuelwood substitution (Meyfroidt and Lambin, 2011). Industrial forestry may replace natural forests but will also encroach on agricultural land. Protected areas will continue to expand by 0.9-2.7 Mha per year. Land degradation negatively affects land productivity and makes about 1-2.9 Mha unsuitable for cultivation per year, with a high rehabilitation cost. In summary, the additional land demand for all agricultural, bioenergy, tree plantation, urban and nature conservation uses was estimated to range from 303 to 845 Mha by 2030 compared to the, 2000 baseline (Lambin and Meyfroidt, 2011). The main "friction points" in global land use are expected to be between forests and agriculture; urban land use and intensive agriculture; tree plantations and natural forests; bioenergy, feed crops and food crops; and intensive cropland and extensive agriculture (Lambin and Meyfroidt, 2012). **Based on these global trends, total land demands in the coming decades could exceed the area of productive land that is potentially available, and productive land could become a scarce resource in most developing countries by 2030. Under that scenario, which already includes significant land productivity increases, lands with a lower productivity will be brought into use, and forests will continue to be converted for agriculture.**

Table 4. Projected additional land use for, 2000-2030 (in millions hectares). Source: Lambin and Meyfroidt (2011), and updates in Lambin and Meyfroidt (2012).

	Low	High
Additional cropland	81	147
Additional biofuel crops	44	118
Additional grazing land	0	151
Urban expansion	66	153
Expansion of industrial forestry	56	109
Expansion of protected areas	26	80
Land lost to land degradation	30	87
Total land demand for 2030	***303***	***845***

State of the knowledge on forest transitions

Estimating global rates of natural reforestation is challenging because detecting by remote sensing the signal of the slow regrowth of vegetation is more difficult than for the larger signal of clear-cutting (Meyfroidt and Lambin, 2011). Furthermore, different views exist on defining secondary forests and on whether reforestation should include some or all forms of tree plantations, or only naturally regenerating forests. Modified natural forests might represent ~66% of the global forest cover; natural regeneration of forests amounts to more than 2.2Mha/year in the tropics and at least 2.9 Mha/year globally; and as of, 2010, planted forests covered ~264 Mha or 6.5% of the global forest area. Planted forests expanded by 4.9 Mha/year during the period, 2000 to, 2010. Improving the precision of estimates of reforestation rates requires remote sensing observations at higher spatial and temporal resolutions to separate gross from net deforestation and to isolate gross reforestation, based on a sampling scheme specifically designed for monitoring reforestation and combined with accurate spatial data on plantations to isolate the natural regrowth of forests. Improving the global estimate of the extent of secondary forests requires the use of baseline historical maps to trace the land-use history of forest areas. These monitoring requirements mean that analysis of forest transitions has substantial data uncertainties (Grainger, 2008). **Forest-monitoring systems need to include dedicated sampling designs to measure, map, and characterize reforestation. Locations with the greatest potential for forest regrowth need to be identified.**

Total land demands in the coming decades could exceed the area of productive land that is potentially available, and productive land could become a scarce resource in most developing countries by 2030.

Despite these data uncertainties, it is established that several countries in Europe and the United States experienced a forest transition during the nineteenth and twentieth centuries (Figure 6, Meyfroidt and Lambin, 2011). And more recently, a few small countries in Latin America and some larger countries in Asia experienced such a transition in the late twentieth century. These forest transitions occur through different pathways that are contingent upon the local socioeconomic and ecological contexts. A few generic processes of forest transition were identified (Rudel *et al.*, 2005, Lambin and Meyfroidt, 2010), including agricultural intensification and industrialization driving labour scarcity in the agriculture and concentration of production in the most suitable land, possibly influenced by global markets; scarcity of forest products and services drives tree plantation, forestry intensification and forest protection by private and public actors, possibly influenced by global environmental ideologies and by national political factors external to the forest sector; and smallholder labour intensive tree-based land use intensification. Geographically (Meyfroidt and Lambin, 2011), in Central America and the Caribbean, reforestation occurs more commonly on abandoned land, usually associated with economic changes and globalization. Forest plantations are more common in subtropical and temperate South America, often driven by private actors, and in Asia, through a combination of decentralization and market-driven plantations or larger state-sponsored programs. Afforestation policies may result in large-scale plantations but also in scattered woodlots on smallholders' plots. Land-use policies restricting activities on forestlands and agricultural changes also contributed to forest regrowth in Asia, often at a high cost to local populations. In sub-Saharan Africa, forest plantations and agroforestry expand locally in countries with high population densities and supportive forest policies. Multiple causes, social and environmental contexts, and path dependencies are associated with these forest cover changes. The factors driving deforestation also control reforestation, depending on particular circumstances and small contextual shifts, *e.g.* urbanization, economic development, rural wages, agricultural prices, population density, demand for wood products, land tenure reforms, and trade. Thus, because countries do not necessarily follow a regular pattern of forest cover changes, and the causes and outcomes of forest transitions vary, forest transition is to be seen as a contingent process, and as an empirical regularity rather than one stage in a predictable, universal and deterministic path of land use patterns. Forest transition graphs can play a positive role in public policy discourse as they point to opportunities for a reversal of ‘deforestation’ trends by appropriate policy actions (Meyfroidt *et al.*, 2011). Such actions will, however, require understanding of the driving forces in local context, rather than relying on generic forest transition dynamics as a ‘law of Nature’. **Recovery of tree cover has occurred with many variations of patterns and processes; the forest transition is not a deterministic pathway but an abstraction of reality that is contingent and only occurs under certain conditions. Either linear extrapolation into the future of past rates of deforestation or forest degradation, or the onset of a possible forest recovery in a country, are not automatic and can nowhere be taken for granted.**

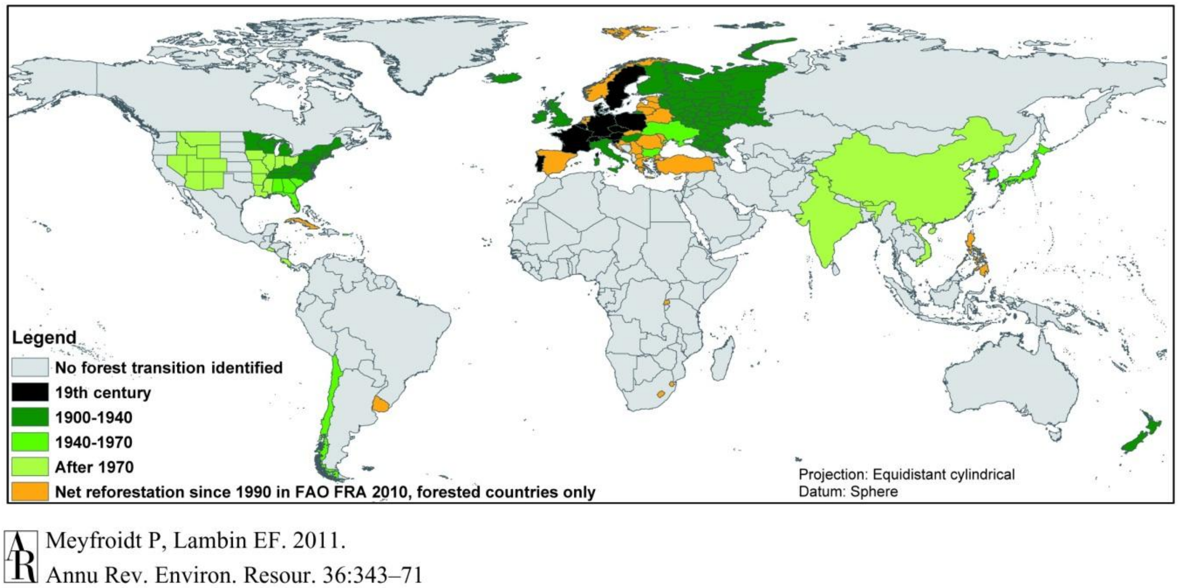

Figure 6. Periods of recent forest transitions. Source and details: Meyfroidt and Lambin (2011).

Restoring forests in one country is generally associated with a significant outsourcing of forest exploitation to neighbouring countries via increased imports of wood and sometimes agricultural products (Meyfroidt *et al.*, 2010). This international displacement of land use through trade facilitates a forest transition in countries that increasingly meet their demand for wood and agricultural products through imports rather than by using their own land. For example, in Vietnam, the policies restricting forest exploitation that contributed to a forest transition, combined with the rapid development of the wood processing industry and the exports of wood products, led to an increase in legal and illegal imports of timber and a displacement of forest extraction to neighboring countries, such as Laos and Cambodia, equivalent to 39% of the regrowth in Vietnam’s forests from 1987 to, 2006 (Meyfroidt and Lambin, 2009). To some extent, international trade could allow allocation of land use to more productive lands, so that increasing deforestation in one place could spare a larger land area elsewhere (Mather and Needle, 1998, Angelsen, 2010). The extent to which land-use displacement or leakage, *i.e.* the form of displacement that occurs as a response to conservation policies that restrict land use in a place, spares land depends among others on the relative yields of the lands from which and where production is displaced. On one hand, wood and food production should be optimized spatially on the basis of the productive potential of forests and

Policies supporting afforestation and reforestation will not lead indiscriminately to environmental gains.

agricultural land, as well as on the environmental and social opportunity costs. On the other hand, negative environmental impacts associated with the long-distance transportation of products and the destruction of ecologically valuable forests should be minimized. **International displacement of land use through trade thus reduces the global benefits of national policies to protect forests and promote reforestation. These policies therefore need to control this displacement and channel it toward areas where the impacts are minimal (or beneficial).**

The ecological effects of this reforestation are very variable, and depend on the residual deforestation of old-growth forests, the proportions of natural regeneration of forests and tree plantations, and the location and spatial patterns of the different types of forests (Meyfroidt and Lambin, 2011). Although generalizations are to be taken with caution, the ecological benefits of secondary forests are generally positive, especially for carbon storage and hydrologic stability, but not necessarily high. The benefits of agroforestry systems vary greatly depending on their type and the land use they replace. Tree plantations often have negative environmental impacts when they replace ecologically diverse swidden areas, natural grasslands, or shrublands. They have mixed effects when they replace permanent agricultural land and mostly positive impacts, especially on soil properties and hydrological flows, when afforestation takes place on severely degraded land. Managing multifunctional mosaics of human-modified landscapes to preserve and restore ecosystem services is an emerging priority in the ecology and conservation literature (Lamb *et al.*, 2005, Gardner *et al.*, 2009). Forest transitions offer some potential in that respect, but much has still to be learned on this issue. Furthermore, net reforestation can conceal a continuing degradation or clearance of partly irreplaceable old-growth natural forests (Meyfroidt and Lambin, 2008, Echeverria *et al.*, 2006). Increase of forest area is thus not a guarantee for a recovery of ecosystem services: the hydrological impacts of fast-growing trees can be mixed, biodiversity recovery slow, and carbon stock increments small. Large scale monocultures of exotic tree species can reduce the provision of ecosystem services. Cases of increase in tree cover associated with a decrease in the potential to restore biodiversity and/or in carbon stocks have been documented. Policies supporting afforestation and reforestation should not assume that it will lead indiscriminately to environmental gains.

Policies for REDD+ and Forest transitions

This section discusses policy options that address the two complementary goals of reducing clearance and degradation of natural forests and encouraging ecologically and socially desirable forms of reforestation (Table 3).

Prospects for a global forest transition

Between 1980 and, 2000, 83% of the agricultural expansion in the tropics came at the expense of intact or disturbed forests (Gibbs *et al.*, 2010), mostly in the Amazon Basin, South-East Asia, and to a lesser extent West and Central Africa. Forested areas are highly affected by the recent wave of large-scale, cross-border land transactions carried out by transnational corporations: about 24% of the land deals are located in forested areas, representing 31% of the total surface of land acquisitions (Anseeuw *et al.*, 2012). Continuing the recent trends, the deforestation from, 2000 to 2030 might represent 152–303 Mha (Lambin and Meyfroidt, 2011). But with more proactive policy interventions, trade-offs between conserving forests and feeding the world's population could be minimized given the low opportunity costs of avoided deforestation and the small contribution of deforested areas to the recent increases in food production (Angelsen, 2010). In the recent decades, only around 10% of the increase in agricultural output came from expansion of agricultural lands over forests, the rest coming from productivity increases. With appropriate policies, most of the future increases in food production might thus be achieved, in theory, without further forest encroachment. But in reality, this will depend on future productivity gains and on how much agriculture and other land uses expand on forest versus nonforested land, as well as on land with marginal versus high potential for agriculture (Meyfroidt and Lambin, 2011). Similarly, one line of thinking argues that forestry intensification could allow satisfying global timber needs from limited areas of high-yielding tree plantations, thus saving the remaining forests from exploitation pressure (Sedjo and Botkin 1997). But in reality, although forest plantations can expand on former agricultural land (Sedjo and Botkin 1997), they often compete for space with natural forests and drive deforestation, as shown in studies in Vietnam, Chile and New Zealand (Meyfroidt and Lambin, 2008, Echeverria *et al.*, 2006, Ewers *et al.*, 2006). Overall, over the coming decades, a decrease in the availability of productive land and competition with other land uses will make a global forest transition difficult to achieve (see Tables 1 and 2).

Globalization and new drivers of land use

Land changes are increasingly caused by global scale factors, with a growing separation between the locations of production and consumption of land-based commodities (Lambin and Meyfroidt, 2011). A large and growing fraction of forest conversion today is associated with commodities produced for global markets. Land use decisions related to these commodities derive from the interactions between factors in distant markets, mostly associated with wealthy urban consumers, and local-scale factors (DeFries *et al.*, 2010, Boucher *et al.*, 2011). The distant factors affecting land use are not restricted to trade patterns, but also include remittances sent by migrants, the specific organization of global commodity value chains, channels of foreign investments in land, the transfer of market or technological information to producers via a diversity of networks (from farmer associations to internet and cell phones), and the development and promotion of niche commodities that target narrow but wealthy market segments with high value commodities produced in limited quantities (Le Polain and Lambin, 2012). Other trends are associated with a globalization of the direct or indirect policy interventions on land use. The final consumers of agricultural and wood commodities, the corporations involved in their transformation and retailing, and civil society show a growing concern for sustainability (Dauvergne and Lister, 2012). These actors are starting to express a preference for goods whose supply chain has been certified as meeting sustainability criteria. Simultaneously, large agri-business corporations increasingly adopt sustainability standards and apply these to their suppliers. In parallel, several countries have pursued more traditional command and control policies, such as land use zoning or harvest regulations, to protect and restore their forests and other valuable ecosystems, and have emphasized greater enforcement of, and compliance with existing regulations.

Policies for a global forest transition

Policies to achieve a forest transition include approaches to improve the supply of land-demanding products, and to control the demand for them (Meyfroidt and Lambin, 2011) (Table 3). On the supply side, innovations and policies should aim at (a) increasing production and productivity from tree plantations, while minimizing their negative social and ecological impacts; (b) expanding the area of natural forests managed sustainably; (c) supporting natural regeneration through land zoning, forest extraction regulations, and plantations on degraded land; (d) promoting nature-friendly farming in areas with biophysical and social conditions unsuitable for large-scale intensive farming; and (e) sparing land for forests through agricultural intensification combined with land zoning in high-potential agricultural areas. On the demand side, ecoconsumerism and a new corporate environmentalism could accelerate a transition in production systems and orient consumption toward less land demanding products.

Contracting or stabilizing global croplands and grazing areas, *e.g.* by concentrating them on the most productive lands, can facilitate reforestation. But the land-sparing benefits of agricultural intensification are partially countervailed by a rebound effect (Lambin and Meyfroidt, 2011): As production efficiency increases, prices of the good decrease, which can increase either the demand for this product if it is elastic to prices or the demand for other goods through substitution of spending. Although the demand for staple crops for human consumption is relatively inelastic, the global demands for biofuels, meat, and luxury goods, such as coffee, are elastic. The growth of the off-farm economy and out-migration from rural areas do not necessarily result in land abandonment, as extensive activities, such as cattle ranching, may replace the labor-intensive, smallholder land uses. At the global scale, urbanization and rising incomes increase the demand for food and wood products, potentially contributing to further forest clearing. Agricultural intensification and out-migration are thus unlikely to reduce the overall demand for agricultural land unless combined with policies to control rebound effects, *e.g.* by land-use zoning and demand-side interventions. Increasing output from plantations can contribute but not be sufficient to relieve pressure on natural forests, and only if negative impacts are controlled (Meyfroidt and Lambin, 2011). To meet the expected demand for high-grade tropical hardwoods, sustainable forest management need to be complemented with specific efforts for hardwood plantations (*e.g.* teak) in the Tropics. Certification schemes need to be tailored for natural forests in tropical / developing countries and for smallholders, *e.g.* group certification in Vietnam (Auer, 2012). Complementary strategies are needed for domestic and intraregional markets (Robiglio *et al.*, 2012). Forest transitions are not sufficient to protect primary forests. Land-use zoning is required for that purpose. Addressing final consumption is needed to control for rebound effects, and future global demand for wood and agricultural products is a critical aspect for any potential global forest transition.

Achieving the desired goals for restoring forests thus requires a combination of state-level command-and-control, regulatory tools with emerging market-based instruments, including eco-certification and other forms of corporate sustainable sourcing strategies, industry roundtables and working groups around specific commodities, moratoria, payments for ecosystem services, NGO campaigns (Table 3). Yet, evidence about the actual effectiveness of these various instruments on land use “on the ground” remains insufficient.

The high local contextual variability in causes of land use changes calls for tailoring these general policy approaches and tools to specific contexts, rather than applying “one-size-fits-all” approaches. For example, in the Central Highlands of Vietnam, policies that may have an impact on deforestation are those that would promote inclusion of the ethnic minorities into the socio-economic, political and agricultural markets spheres, intensify staple crops, strengthen and clarify land use zoning to preserve the remaining forests of value and identify forested land with the lowest tradeoffs between environmental services and agricultural potential (Meyfroidt *et al.*, forthcoming).

In sum, the following factors hold the potential to significantly affect the supply of and demand for wood and agricultural products, and therefore contribute to control deforestation by addressing its drivers: (i) technological innovations and more efficient land-use practices to intensify agricultural and forestry production and reduce its environmental impacts; (ii) sound land management policies a.o. to control for rebound-effects; and (iii) changes in consumption patterns especially reduction of wastes and decreasing demand of the most land-demanding products – e.g. meat. REDD+ could support most of these strategies, and thus should not be considered only as a program of Payments for Environmental Services for agents of deforestation and forest degradation. Case studies highlight the high contextual variability in causes of deforestation and in the appropriate ways to apply the above-described general policy responses.

Table 5. Approaches and Tools for promoting a global forest transition. Source: adapted from Meyfroidt and Lambin, 2011, Table 2.

Approaches	
Increase the supply while decreasing environmental impacts	• Increase productivity & expand intensive production • Promote sustainable forest management / nature-friendly agriculture
➔ BUT: Rebound effect and spatial heterogeneity	
Control expansion over natural ecosystems	• Land use zoning / spatial planning & forest regulations • Off-farm economy
➔ BUT: Displacement and global land scarcity	
Reduce and modify the demand	• Substitution of the most land-demanding and impacting products – *e.g.* change diets • Recycle & re-use • Increase efficiency & reduce wastes • More equitable food distribution
Tools	
Regulation / command-and-control tools	• Forestry & agricultural practices regulations (inc. enforcement) • Land use zoning • Trade policies
Market-based instruments	• Certification / ecolabelling • Payments for Ecosystem Services (inc. carbon offsetting, ecotourism…)
Other tools to promote changes in agricultural and forestry systems	• Extension services • Credits & subsidies • Land tenure reforms • Education & information
Other tools to reduce local reliance on land-based activities	• Development of off-farm economy • Migration policies • Education & family planning

Conclusion

Current international negotiations on REDD+ and other emerging market-based approaches could provide a political momentum for reducing deforestation and promoting desirables forest transitions. But given an increased competition for productive land between different land uses, a global restoration of forests will require major policy and technological innovations as well as modifications in demands for fiber, fuel and food. These changes cannot be taken for granted.

5. The opportunity cost of REDD+

Avoiding dangerous climate change will require significant global emission reductions in a short time frame. Several studies have stated that in order to have a likely chance to keep global warming below 2°C, emissions need to peak well before 2020 and to be reduced with 50 % globally in 2050 compared to 1990 (UNEP, 2010). Such a scenario corresponds with significant emission reductions in developed countries (up to 90% in 2050) and an effective low carbon development in non-annex I countries.

There are many options to reduce the emissions of greenhouse gases, from simple behavioural changes to deploying innovative new technologies. These come with distinctly different costs. One of the best-known studies comparing mitigation potential and costs at a global level is the McKinsey cost-curve. This cost-curve has been used extensively to illustrate that mitigation actions in the LULUCF sector are on the lower end of the cost spectrum. As a cost-efficient mitigation action with potentially multiple co-benefits, reducing emissions from deforestation and forest degradation in developing countries has gained considerable interest at the international negotiations and is now considered an essential building block of a new climate change agreement.

The McKinsey cost-curve has, however, been scrutinized and there are important objections to the methodology and assumptions used to estimate these costs. Most recently a briefing paper of the Rainforest Foundation and a report by Greenpeace criticized the McKinsey cost-curve as misleading, methodologically flawed and unsuitable as policy making tool (Dyer and Counsell, 2010; Greenpeace, 2011). There are nevertheless many other studies that have estimated the costs of REDD+, most of which underscored that a relatively low carbon price could make trees more profitable standing up than cut down. This paper provides a review of the costs associated with REDD+ and lists the constraints to these estimations.

What are the costs of REDD+?

The costs associated with a REDD+ scheme can be divided into four distinct categories.

- Implementation costs. To establish a REDD+ scheme in developing countries there is a need for capacity building, institutional reform, effective forest policies and measures and law enforcement. This will come with a considerable and upfront cost (before any emission reduction is achieved).

- Transaction costs. These are the costs associated with transfer of funds, credits (in case REDD+ is included in a carbon market) and Monitoring, Reporting and Verification (MRV) of emission reductions. Depending on the type of REDD+ funding, transaction costs vary. In case of a fund based scheme, transaction costs are lower than in a market-based approach.

- Stabilization costs. Additional costs to prevent leakage to non-participating countries, in case REDD+ is designed to primarily target countries with historically high deforestation levels.

- Opportunity costs. Reducing deforestation often will imply that certain economic activities will not be possible. Opportunity costs are the foregone benefits that would have been created by the alternative land use.

It is important to note that different studies have used different names and delineations of these different costs. This makes comparison among studies more complex. It also implies that the results of different studies cannot necessarily be added together, because they might overlap (overestimate) or miss out (underestimate) on certain costs.

RED, REDD and REDD+

Since COP11 in Montreal, the discussion on REDD+ has evolved, from avoiding emissions from deforestation only to reducing emissions from deforestation, forest degradation, enhancement of forest carbon and sustainable management of forests. But although the scope of REDD+ activities has increased, cost estimates tend to focus primarily on the costs of avoiding deforestation. This is because most studies have focused on opportunity costs of foregone agricultural activities. It is more difficult to quantify the costs of avoiding forest degradation, as these are not necessarily caused by agricultural expansion or legal activities. Effective forest governance could already reduce degradation with relatively low economic repercussions. Some of the drivers of degradation on the other hand might be difficult to counteract, because they are caused by the rural poor. For them this additional forest income (*e.g.* fuelwood and non-timber forest products) is essential for their livelihoods (Vedeld *et al.*, 2004).

The eye of the beholder – the accounting stance

As Kremen *et al.* (2000) illustrated, the economic REDD+ costs and benefits depend heavily upon the scale. A distinction can be made between costs to individual actors, the local and national economy, governmental agencies or even the global economy (Pagiola and Bosquet, 2009). Most studies have focused on the impacts on land users or countries.

Costs to the country integrate all the costs and benefits within the country as a whole. Such an analysis thus excludes transfers, *e.g.* a tax that a forest owner pays to the government. Costs or benefits that accrue outside the country are neither included in this account. This is important, because the benefits of mitigating greenhouse gas emissions, which will primarily be perceived outside the country, are therefore excluded (see Pagiola and Bosquet, 2009). When looking at it from individual groups or actors perspective all costs must be considered, including taxes and subsidies. Assessing opportunity costs from a farmers perspective is interesting because they point towards the fact that REDD+ needs to provide a valuable alternative for the local actors who are deforesting and degrading forests. Assessing costs for individual actors is, however, difficult and does not necessarily represent the amount of money needed to change behaviour.

Global cost estimates

Comparing global cost estimates needs to be done meticulously and carefully because it depends on the emission reduction pathways that are proposed and also the type of activities that are included (*i.e.* RED, REDD or REDD+). This will have a significant impact on the cost estimates. This explains to some extent the significant differences across studies in global cost estimates. It is not the objective of this paper to review all the cost estimates extensively, but an overview of the most important studies is listed below.

The work of Grieg-Gran (2006) for the Stern report was one of the first global studies, estimating the economic cost of mitigating greenhouse gas emissions in the 8 most important developing countries. Taking into account opportunity and administration costs, halting deforestation in the top-8 deforesting countries (*i.e.* Brazil, Cameroon, DRC, Ghana, Bolivia, PNG, Indonesia and Malaysia) would cost 6.5 billion $ (2005 values). This estimate assumes zero leakage, which seems very unlikely. Based on this result, the Stern report concluded that avoiding deforestation could be a very cost efficient mitigation action. In, 2008, Grieg-Gran (2008) prepared an update, taking into account the significant increases in commodity prices, especially for palm oil, after her first report. Cost had increased to 8.1 billion $ (2007 values) per year.

The work of Strassburg *et al.* (2008) paints the most optimistic picture of the global cost studies. According to their calculations, 29.6 billion $ (2005 values; 20.9 incentives, 1.1 transaction and 7.6 billion forest management and protection costs) would stop deforestation almost completely in 2020. Although they recognize that the way incentives are distributed among countries is crucial to the success of REDD, their estimate does not include leakage as a possible distorting factor.

Following the Stern Report, the Eliasch review (Eliasch, 2008) extended further on REDD. Based on several studies looking into the different costs needed to set-up a REDD scheme, the Eliasch review estimated that 17 – 33 billion $ would be needed to reduce deforestation by 50 % in 2030. In their assessment, REDD would be included in a carbon market and funding would therefore come from carbon trading.

The implementation cost

The first step in any REDD scheme is to install effective REDD+ policies and measures to reduce forestry emissions. For many developing countries this is a difficult step, requiring considerable capacity building, technology transfer and institutional reform. Unlike opportunity costs, implementation costs are not that much related to the emission reductions that will be achieved. Often these are upfront costs with an uncertain impact a priori. In the report prepared by Hoare *et al.* (2008) for the Eliasch Review, readiness costs were estimated. These included costs for *e.g.* the development of a REDD strategy, infrastructure, institutional and land tenure reforms. According to Hoare *et al.* (2008) preparing for REDD would amount to an estimated 13 - 92 million $ for a single country for a 5-year period. At this moment, many developing countries are already preparing themselves for REDD+, with the help from the UN (UN-REDD), World Bank (FCPF), the REDD+ partnership and several others. The proposals and plans submitted to the UN-REDD or the FCPF are interesting references to look for implementation costs. Based on the Readiness Preparation Proposals submitted by developing countries to the FCPF, Simula (2010) reported that budget requirements for establishing a REDD+ strategy, organization and consultation were on average 6.5 million $. However, there were marked differences among countries (from 2.4 to 16 million $, respectively Guyana and neighbouring country Suriname). As was pointed out by Simula (2010), budgetary requirements for some countries were relatively low, because they already had made significant efforts in the past (*e.g.* Guyana's Low Carbon Development strategy).

The objective of REDD+ is to create a paradigm shift, combining economic development with forest conservation. This is difficult because agricultural activities and commodity production have many more opportunities to create economic growth than forest conservation.

It is well established that there are many direct and indirect agents that have an influence on the rate of deforestation (Lambin and Geist, 2002). Agricultural expansion and related deforestation is often considered essential for economic development and for the transition to an industrialized country. The objective of REDD+ therefore should be to create a paradigm shift, combining economic development with forest conservation. This is not easy because agricultural activities and commodity production have many more opportunities to create economic growth than forest conservation (Ghazoul *et al.*, 2010). Effective policies and measures and the institutions and instruments to install and enforce them, have to take this into account. It will be imperative that national or sub-national REDD+ schemes are embedded in comprehensive, cross-sectoral and economy-wide low-carbon development strategies. Embedding REDD+ in national appropriate mitigation actions (NAMAs) offers opportunities to harmonize abatement across sectors with the potential for additional financing (Wertz-Kanounnikoff and Angelsen, 2010).

The transaction costs

There are two important components to the transaction costs. First, participating countries will need an MRV system that is able to report on the verifiable emission reductions that have been achieved. This involves the establishment of a reference level and a monitoring system using both field measurements and remote sensing information.

Hoare *et al.* (2008) estimated that 1–6 million $ would be required for setting reference emissions levels and monitoring systems in each country. This assessment is largely based on the extensive report of Hardcastle *et al.* (2008) who estimated costs for monitoring based on different national circumstances and building on knowledge of existing capacities. On average, the MRV costs amounted to 1 million $ for up-front setup costs and 500.000 $ for annual recurrent costs, depending on the size of the country. Brazil, with the most extensive forest area, would need approximately 7.7 million $ (2009 values) the first year and 2.6 million $ (2009 values) recurring annual costs afterwards. Including degradation did increase the cost, both setup and recurring costs (respectively 9 and 3 million $ (2009 values)), although relatively limited.

Simula (2010) found that setting up a reference level and a monitoring system comprised the largest part of the FCPF budgets. For a reference level costs varied between a mere 85,000 $ for Lao PDR to 6.2 million $ for Indonesia, whereas requirements for a monitoring system were assessed to be between 120,000 $ for Ethiopia to 30.2 million $ for Mexico. With an average monitoring cost of 5.1 million $ for the first three years, these values are higher than the estimates of Hardcastle and Baird (2008). However, high cost estimates of some countries greatly inflated the average cost of the FCPF.

Secondly, there will also be administrative costs for transferring funds or for transactions on a carbon market. Market-based approaches inevitably will come with higher transaction costs than fund based schemes. But in both cases transaction costs are expected to be low, although estimates are still limited. In her analysis for the Stern review, Grieg-Gran (2006) used information from payments for ecosystem services schemes in Latin America to estimate administration costs. These amounted to 4 $/ha to 15 $/ha, but there may be some overlap with monitoring and implementation costs. Antinori and Sathaye (2007) estimated the average transaction costs of 11 forestry offset projects at 0.38 $/ton CO_2. Costs were size-dependent, ranging from 0.03 (for large projects) to 1.23 $/ton CO_2 for small projects. It is likely that the lowest estimates will apply most to REDD+, as REDD+ will probably be organized at national and/or sub-national level.

Stabilization costs

To prevent leakage, it is imperative that not only countries with high deforestation rates are given an incentive. If not, deforestation could to a large extent simply displace to countries with low historic deforestation rates. There are two policy options to prevent this leakage of greenhouse gas emissions: (i) either a mechanism is installed specifically for low deforestation countries or (ii) the reference level against which the effort of countries is compared, allows corrections for low deforestation rates. Although there are differences in approach, in both cases the cost for a REDD+ mechanism will increase because the mechanism will not only reward countries reducing deforestation but also countries for not increasing their deforestation rate. One study estimated that stabilization will cost about 630 million $ per year for the 10 most important stabilization countries, and 1.8 billion $ per year for the 11 most important countries (da Fonseca *et al.*, 2007).

Opportunity costs

Opportunity costs are expected to be the most important part of the costs associated with REDD+ (Pagiola and Bosquet, 2008). Therefore many studies only included opportunity costs in their assessments, implicitly suggesting that other costs are relatively small compared to the size (and uncertainty) of the opportunity cost.

Opportunity cost estimates depend heavily on certain assumptions. One is the alternative land use that would occur without forest conservation. It is important to note that the most valuable alternative land use is not necessarily the most likely to occur. When calculating the opportunity cost, avoided deforestation should be compared to what would have occurred with deforestation. Of course, the business-as-usual scenario is difficult to predict, yet with quantitative spatially explicit land use models, predictions can be made on the most likely land-use change (cfr. for Brazil, Nepstad *et al.*, 2007). Alternatively, historic information on land-use changes is often used as an easy proxy for future agricultural expansion. McKinsey used the highest value alternative in their cost assessment for Guyana, which gives an unrealistically high national opportunity cost and is one of the points of critique (Dyer and Counsell, 2010). Although this does not necessarily apply to the opportunity costs in terms of avoided emissions, as this also depends on the emissions resulting from the land-use changes.

A factor that is often overlooked is that forests are also used by local communities for several purposes, such as fuelwood or other non-timber forest products. Apart from this, forests provide many other services that are beneficial to the local, national and even global community. REDD+ could have a huge ecological benefit from hydrology and water resources, soil resources, biodiversity, pollination, to the local and regional climate (Stickler *et al.*, 2009). These are difficult to quantify in monetary terms, but nevertheless should not be ignored when assessing the opportunity costs of REDD+. In fact, many forest conservation measures increase the benefits generated from forests, decreasing opportunity costs that even could become negative (*i.e.* forests are the most profitable land use).

Indirect opportunity costs

Preventing the conversion of forest to other land uses can have significant effects on the lives of rural people (White and Minang, 2011). It could mean a change in the traditional way of life, which could bring about psychological, spiritual or emotional impacts, loss of local knowledge, and erosion of social capital if no viable alternative livelihood is accessible (White and Minang, 2011). These costs are difficult to measure in economic terms. Nevertheless they could be an important factor hampering successful implementation of REDD+ in the field (see also below).

Another indirect opportunity cost that is often overlooked are downstream effects that may be caused by changes in supply of timber and agricultural products. Ghazoul *et al.* (2010) already warned against the indirect economic costs and implications associated with choosing either forest conversion or conservation. In Indonesia for instance, the paper and pulp and the palm oil industry are responsible for a significant part of the annual GDP. Pirard (2008) pointed out that forest conservation is especially costly in a country (or for individual actors) with few alternative investment opportunities, because capital cannot be invested in other projects. In a globalized world, this could mean that investors will look abroad for alternatives, increasing the foregone revenue. Also, timber and agricultural expansion create considerably more opportunities for increasing economic development than forest conservation (Ghazoul *et al.*, 2010). Agricultural expansion and related deforestation is often considered essential for economic development and for the transition to an industrialized country.

Brazil showed that a moratorium on deforestation for soy does not have to result in direct economic repercussions. Increases in yield largely compensated for the reduced growth in area under cultivation (although there was some leakage to other habitats and agricultural land and indirect deforestation; Boucher, 2011). Yield improvements have their limitations though, and in the long run may not be able to sustain similar growth in output as in the past.

The demand curve

There are many drivers of deforestation and forest degradation, both direct and indirect (see Geist and Lambin, 2002). In this globalized economy, it is clear that the global demand for forest products and agricultural commodities is driving land-use changes in the tropics. The classic example being palm oil (see Box 1). The increasing human population and changing consumption behaviour (linked to increasing welfare in developing countries) implies that agricultural output will need to continue to expand for the next decades. For 2050, estimates show that 109 ha of land could be converted to agriculture, which will predominantly occur in Latin America and sub-Saharan central Africa (Tilman *et al.*, 2001). Global demand will thus continue to be an important driver of deforestation in the future. A REDD+ scheme could thus have significant effects on commodity prices (and the opportunity costs). How much will depend on how much prices will react to reducing deforestation rates and shrinking supply and how will this affect the global demand. Most of the bottom-up studies on opportunity costs are static and do not take into account that opportunity costs will change as demand and supply conditions for timber and agricultural products change. Information on the price elasticity of demand for frontier agricultural products is scarce, but in the global model OSIRIS a default value of 2 is used (Busch *et al.*, xxx). This means that demand will decrease with 2%, if prices increase with 1%. For staple crops however, prices are inelastic. For such crops, increasing commodity prices will have a relatively small effect on the demand. The demand of other agricultural products, such as coffee, on the other hand are elastic. But also other effects could come in play. Persson and Azar (2010) showed that deforestation for palm oil bio-energy production will remain profitably, even if there are carbon credits for REDD+. The reason is that increasing carbon prices to stop deforestation, will be counteracted by the fact that fossil fuels will be more expensive, increasing demand for and revenue from bio-energy palm oil. In this tug of war between carbon stored in forests and carbon emissions saved from biofuels, palm oil comes on top. At least until carbon prices are sufficiently high so that new technologies for transport (*e.g.* hydrogen fuel cells) become competitive (Persson and Azar, 2010).

The discount rate

Ironically, one of the most important factors determining the opportunity cost is not related to either the expected land use, yields or prices, but is the discount rate. The discount rate determines the emphasis we are putting on future costs and benefits. A high discount rate reduces the viability and attractiveness of long-term investments, and looks for the fast buck. With a low discount rate (often called social discount rate), investments requiring a high up-front cost and benefits that are reaped several years later (such as agroforestry), become more attractive. To value ecosystem services, social discount rates are more justifiable than the higher discount rates used in the private sector (White and Minang, 2011). In most cases a discount rate is used of 5% to 10%, which is appropriate if costs are assessed from the perspective of the country. It is important to stress that for individual actors, high discount rates correspond better with their time preferences. This is especially the case in developing countries where tenure rights are not always clear.

Opportunity cost estimates

To determine opportunity costs different methodologies can be used, bottom-up methods, sectoral models and econometric models (see Pirard, 2008). Boucher (2008) summarized the opportunity costs of 29 regional empirical studies. He found that the opportunity costs were on average 2.5 \$/t CO_2, considerably lower than opportunity cost estimates from the Stern review (5.5 \$/tCO_2) and global models (11.3 \$/t CO_2). The latter is based on Kindermann *et al.* (2009) who combined three independent and global models to give an overview of the estimated opportunity costs of REDD+. The results of this study illustrate that underlying assumptions have a huge effect on the model outcome. For a 10% reduction in 2030, an estimated 0.4 to 1.7 billion \$ per year would be needed. Increasing this target to 50% in 2030 would increase the cost to 17 – 28 billion \$. The global models thus seem to be the most conservative (more costly) estimates with respect to the opportunity cost of REDD.

Increasingly, supply and cost curves are estimated, which reflect changes in prices and costs as the emission reduction effort increases. The cost curves for avoided deforestation typically show that significant reductions can be achieved at low-cost, but that costs rise sharply as abatement increases and total elimination of deforestation is reached. Nepstad *et al.* (2007) performed such an analysis for Brazil. Their analysis showed that the opportunity cost for protecting the entire forest at once, is 257 billion \$ (2007 values, at 5.5 \$/tC). This cost is greatly influenced by 6% of the forest area that has an opportunity cost of 10 \$/tC or more. If these forests are removed from the calculation, the opportunity costs declines to 123 billion \$ (2007 values, at 2.8 \$/tC).

The difference between cost efficient and easy

Even the very sophisticated cost estimates are in many ways too simplistic. Economic models cannot take into account many of the complexities and political constraints that will make REDD+ more costly. Also, the estimated cost will not necessarily determine the effectiveness. This is shown by the criticized McKinsey cost curve where there is still potential to take no-regret measures. This is even the case in countries with emission reductions targets under the Kyoto Protocol. Measures that are economically sound to implement (because they are in the long run cheaper), remain untapped because of market inefficiencies, consumer and producer behaviour and various other barriers. In the case of REDD, they have to do with ill-defined property rights, strong vested interests and poor enforcement capacity. For instance, most studies find that the opportunity costs for subsistence farmers are lowest. This group however, depends for their livelihood on clearing land and pure forest conservation is no valid alternative. Ill-advised subsidies, for example for biofuels or agricultural products, can also drive a wedge between the theoretical cost and actual cost of avoided deforestation. It is not possible to put a monetary value on these distortions, but it is clear that they can push up the implementation cost and reduce the impact of REDD+. According to one estimate, constraints to policy effectiveness could mean that only 40% of the economic REDD potential is delivered (xxx).

Estimating the true cost of REDD is a daunting and difficult exercise. The literature shows that the cost of REDD differs substantially across model approaches and studies (CIFOR, xxx). Gregersen *et al.* (2010) therefore categorized opportunity costs as inappropriate (*e.g.* in case of illegal activities), inadequate (*e.g.* if land use rights are not well defined) and inaccurate (*e.g.* when there is not a well-functioning market). Their paper provides us with a good warning that any estimate of the cost of REDD+ has its limitations and that results thus should be treated and interpreted carefully. Nevertheless, assessing opportunity costs provides us with a good picture on the drivers of deforestation, the economic value they represent and gives policy makers an idea on the potential economic impact of REDD+. It could also be used to quantify fair compensation for those who change their land-use practices, taking into account the limitations of opportunity cost estimates.

Conclusion

As our knowledge on the costs associated with REDD+ increases, so does the cost in itself. The picture that was painted at the onset of REDD+ as a cheap silver bullet to reduce emissions significantly, appears not to hold true entirely. It is clear, however, that forests provide ecosystem services to local, national, regional and even the global community that cannot be replaced. As tropical forests are cleared further, we are reaching tipping points that, in combination with climate change, could induce further significant decreases in forest area (Vergara et al., 2010). The ecologic and economic costs this would induce, will outweigh the cost to protect our forests. In, 2010, the world's military expenditure was an estimated 1600 billion $, 50% more than in, 2001. Even with the highest global cost estimates (of around 33 billion $ per year), it would only take a fraction of this to protect our forests. With better co-benefits.

References

Achard, F., DeFries, R., Eva, H., Mayaux, P., Stibig, H.-J., 2007. Pan-tropical monitoring of deforestation. Environmental Research Letters, 2: 045022.

Achard, F., Eva, H., Stibig, H.-J., Gallego, J., Richards, T., Malingreau, J.P., 2002. Determination of deforestation rates of the world's humid tropical forests. Science, 297:999-1002.

Ahl, D.E., Gower, S.T., Mackau, D.S., Burrows, S.N., Norman, J.M., Diak, G.R., 2004. Heterogeneity of light use efficiency in a northern Wisconsin forest: implications for modelling net primary production with remote sensing. Remote Sensing of Environment, 93:168-178.

Aldy, J.E., Robert S.N. (2008) Designing the Post-Kyoto climate regime: lessons from the Harvard project on international climate agreements. An interim progress report for the 14th Conference of the Parties, Framework Convention on Climate Change, Poznan, Poland, December 2008. Cambridge, MA.: Harvard Project on International Climate Agreements, November 24, 2008.

Alvarado, L.X.R., Wertz-Kanounnikoff, S., 2007, Why are we seeing REDD? An analysis of the international debate on reducing emissions from deforestation and degradation in developing countries, Analysis Nr. 2/2007. Institut du developpement durable et des relations internationales (IDDRI), Paris.

Angelsen A (2010). Policies for reduced deforestation and their impact on agricultural production. Proceedings of the National Academy of Sciences USA, 107: 19639–19644.

Angelsen, A. (Ed.), 2008. Moving Ahead with REDD: issues, options and implications. Center for International Forestry Research (CIFOR), Bogor, Indonesia.

Angelsen, A., Brockhaus, M., Kanninen, M., Sills, E., Sunderlin, W.D., Wertz-Kanounnikoff, S. (Eds.), 2009a. Realising REDD+: National strategy and policy options. Center for International Forestry Research (CIFOR), Bogor, Indonesia.

Angelsen, A., Brown, S., Loisel, C., Peskett, L., Streck, C., Zarin, D., 2009b. Reducing Emissions from Deforestation and Forest Degradation (REDD): An Option Assessment Report. Prepared for the Government of Norway, by the Meridian Institute. Available at: http://www.REDD_OAR.org.

Anseeuw W, Boche M, Breu T, Giger M, Lay J, Messerli P, Nolte K (2012). Transnational Land Deals for Agriculture in the Global South. Analytical Report based on the Land Matrix Database. CDE/CIRAD/GIGA, Bern/Montpellier/Hamburg.

Ashton, R., Basri, C., Boer, R., Cosier, P., deFries, R., El-Ashry, M., Flannery, T., Lovejoy, T., Marcovitch, J., Nepstad, D., Nobre, C., Possingham, H., Schlamadinger, B., Soesastro, H., Stiglitz, J., Strassburg, B., 2008. How to include terrestrial carbon in developing nations in the overall climate change solution. The Terrestrial Carbon Group.

Ashton, R., 2008, How to include terrestrial carbon in developing nations in the overall climate change solution. The Terrestrial Carbon Group

Auer, M.R., 2012. Group Forest Certification for Smallholders in Vietnam: An Early Test and Future Prospects. Human Ecology, 40:5-14.

Baccini, A., Laporte, N., Goetz, S.J., Sun, M., Dong, H., 2008. A first map of tropical Africa's above-ground biomass derived from satellite imagery. Environmental Research Letters, 3:045011.

Baker, D.J., Richards, G., Grainger, A., Gonzalez, P., Brown, S., DeFries, R., Held, A., Kellndorfer, J., Ndunda, P., Ojima, D., Skrovseth, P.-E., Souza Jr, C., Stolle, F., 2010. Achieving forest carbon information with higher certainty: A five-part plan. Environmental Science Policy 13, 249-260.

Baret, F., Hagolle, O., Geiger, B., Bicheron, P., Miras, B., Huc, M., Berthelot, B., Nino, F., Weiss, M., Samain, O., Roujean, J.-L., Leroy, M., 2007. LAI , fAPAR and fCover CYCLOPES global products derived from VEGETATION Part 1: Principles of the algorithm. Remote Sensing of Environment, 110: 275 - 286.

Bird, D.N., Pena, N., Schwaiger, H., Zanchi, G., 2010. Review of existing methods for carbon accounting. Center for International Forestry Research (CIFOR), Bogor, Indonesia.

Blackard, J., Finco, M.V., Helmer, E.H., Holden, G.R., Hoppus, M.L., Jacobs, D.M., Lister, A.J., Moisen, G.G., Nelson, M.D., Riemann, R., *et al.* 2008. Mapping U.S. forest biomass using nationwide forest inventory data and moderate resolution information. Remote Sensing of Environment, 112:1658-1677.

Bottcher,H., Eisbrenner, K., Fritz, S., Kindermann, G., Kraxner, F., McCallum, I., Obersteiner, M., 2009. An assessment of monitoring requirements and costs of 'Reduced Emissions from Deforestation and Degradation'. Carbon Balance and Management 4.

Boucher, D., Elias, P., Lininger, K., May-Tobin, C., Roquemore, S., Saxon, E., 2011. The root of the problem: what's driving tropical deforestation today? Union of Concerned Scientists, Cambridge, MA.

Buchner, B., Ellerman, E.D., 2007. The European Union Emissions Trading Scheme: origins, allocation, and early results. Review of Environmental Economics and Policy 1, 66–87.

Bucki, M., Cuypers, D., Mayaux, P., Achard, F., Estreguil, C., Grassi, G., 2012. Assessing REDD+ performance of countries with low monitoring capacities: the matrix approach. Environmental Research Letters, 7: 014031

Busch, J., Strassburg, B., Cattaneo, A., Lubowski, R., Bruner, A., Rice, R., Creed, A., Ashton, R., Boltz, F., 2009. Comparing climate and cost impacts of reference levels for reducing emissions from deforestation. Environmental Research Letters, 044006

Butler, R.A., Koh, L.P., Ghazoul, J., 2009. REDD in the red: palm oil could undermine carbon payment schemes. Conservation Letters, 2:67-73.

Calmel, M., Martinet, A., Grondard, N., Dufour, T., Rageade, M., Ferte-Devin, A., 2010, REDD+ at project scale: Evaluation and development guide. ONF International.

Cattaneo, A., Lubowski, R., Busch, J., Creed, A., Strassburg, B., Boltz, F., Ashton, R., 2010. On international equity in reducing emissions from deforestation. Environmental Science Policy 13, 742-753.

Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Fölster, H., Fromard, F., Higuchi, N., Kira, T, Lescure, J.P., Nelson, B.W., Ogawa, H., Puig H., Riéra, B., Yamakura, T., 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia, 145: 87-99.

Chazdon, R.L., 2008. Beyond deforestation: restoring forests and ecosystem services on degraded lands. Science, 320: 1458–1460.

Chiesi, M., Maselli, F., Bindi, M., Fibbi, L., Cherubini, P., Arlotta, E., Tirone, G., Matteucci, G., Seufert, G., 2005. Modelling carbon budget of Mediterranean forests using ground and remote sensing measurements. Agricultural and Forest Meteorology, 135:22-34.

CIFOR, 2010. Carbofor: Integrating Redd into The Global Climate Protection Regime: Proposals and Implications. http://www.cifor.cgiar.org/carbofor/projects/globalredd/. (11 May, 2010).

Colson, F., Bogaert, J., Filho, A.C., Nelson, B., Pinage, E.R., Ceulemans, R., 2009. The influence of forest definition on landscape fragmentation assessment in Rondonia, Brazil. Ecological Indicators, 9: 1163–1168.

Combes-Motel, P., Pirard, R., Combes, J.L., 2009. A methodology to estimate impacts of domestic policies on deforestation: Compensated Successful Efforts for "avoided deforestation" (REDD). Ecological Economics, 68: 680-691.

Coops, N., Waring, R., Landsberg, J.J., 1998. Assessing forest productivity in Australia and New Zealand using a physiologically-based model driven with averaged monthly weather data and satellite-derived estimates of canopy photosynthetic capacity. Forest Ecology and Management, 104: 113-127.

Coops, N.C., Ferster, C.J., Waring, R.H., Nightingale, J., 2009. Comparison of three models for predicting gross primary production across and within forested ecoregions in the contiguous United States. Remote Sensing of Environment, 113: 680-690.

Coops, N.C., Hilker, T., Hall, F.G., Nichol, C.J., Drolet, G.G., 2010. Estimation of Light-use Efficiency of Terrestrial Ecosystems from Space: A Status Report. BioScience, 60: 788-797.

Corbera, E., Estrada, M., Brown, K., 2010. Reducing greenhouse gas emissions from deforestation and forest degradation in developing countries: revisiting the assumptions. Climatic Change, 100: 355-388.

Cortez, R., Saines, R., Griscom, B., Martin, M., De Deo, D., Fishbein, G., Kerkering, J., Marsh, D., 2010, A Nested Approach to REDD+. Structuring effective and transparant incentive mechanisms for REDD+ implementation at multiple scales. The Nature Conservancy, Arlington, VA.

Costenbader, J., 2010. Legal frameworks for REDD. Design and implementation at the National level. IUCN Environmental Policy and Law Paper No 77.

Cramer, W., 1995. Net primary productivity model intercoparison activity (NPP). IGBP/GAIM report series, Report #5.

da Fonseca, G.A.B., Rodriguez, C.M., Midgley, G., Busch, J., Hannah, L., Mittermeier, R.A., 2007. No Forest Left Behind. PLoS Biology 5:216.

Dauvergne, P., Lister, J., 2012. Big brand sustainability: Governance prospects and environmental limits. Global Environmental Change, 22: 36-45.

Daviet, F., 2009. Beyond carbon financing: the role of sustainable development policies and measures in REDD. WRI.

Daviet, F., McMahon, H., Bradley, R., 2007, REDD Flags: What We Need to Know About the Options. WRI, Washington, DC.

DeFries, R., Achard, F., Brown, S., Herold, M., Murdiyarso, D., Schlamadinger, B. De Souza, C. Jr., 2007. Reducing greenhouse gas emissions from deforestation in developing countries: Considerations for monitoring and measuring, Environmental Science and Policy, 10: 385-394.

DeFries RS, Rudel TK, Uriarte M, Hansen M (2010) Deforestation driven by urban population growth and agricultural trade in the twenty-first century. Nature Geosciences, 3: 178–181.

DeLucia, E.H., George, K., Hamilton, J.G., 2002. Radiation-use efficiency of a forest exposed to elevated concentrations of atmospheric carbon dioxide. Tree Physiology, 22:1003-10.

den Elzen, M.G.J., Hof, A.F., Roelfsema, M., in press. The emissions gap between the Copenhagen pledges and the 2 °C climate goal: Options for closing and risks that could widen the gap. Global Environmental Change.

Dickson, B., Dunning, E., Killen, S., Miles, L., Pettorelli, N., 2009, Carbon markets and forest conservation: A review of the environmental benefits of REDD mechanisms. UNEP World Conservation Monitoring Centre.

Dickson, B., Osti, M., 2010, What are the ecosystem-derived benefits of REDD+ and why do they matter?, Multiple Benefits Series 1. Prepared on behalf of the UN-REDD Programme. UNEP World Conservation Monitoring Centre, Cambridge.

Drolet, G., Huemmrich, K.F., Hall, F.G., Middleton, E.M., Black, T.A., Barr, A.G., Margolis, H.A., 2005. A MODIS-derived photochemical reflectance index to detect inter-annual variations in the photosynthetic light-use efficiency of a boreal deciduous forest. Remote Sensing of Environment, 98:212-224.

Dyer, N., Counsell, S., 2010 McREDD: How McKinsey 'cost-curves' are distorting REDD. The Rainforest Foundation Climate and Forests Policy Brief.

Echeverria, C., Coomes, D., Salas, J., Rey-Benayas, J.M., Lara, A., Newton, A., 2006. Rapid deforestation and fragmentation of Chilean temperate forests. Biological Conservation, 130: 481–494.

Eliasch, J., 2008, Climate change: financing global forests. The Eliasch review. Office of Climate Change, London.

EU, 2008. The 2°C Target Information Reference Document. Background on impacts, emission pathways, mitigation options and costs.

EU, 2009. Council Conclusions on EU position for the Copenhagen Climate Conference (7-18 December, 2009). 2968th ENVIRONMENT Council meeting.

European Commission, 2008. Commission staff working paper, SEC(2008) 2619/2, accompanying COM(2008) 645 final, Addressing the challenges of deforestation and forest degradation to tackle climate change and biodiversity loss. Impact assessment.

Eva, H.D., Achard, F., Beuchele, R., de Miranda, E., Carboni, S., Seliger, R., Vollmar, M., Holler, W.A, Oshiro, O.T., Arroyo, V.B., Gallego, J., 2012. Forest Cover Changes in Tropical South and Central America from 1990 to 2005 and Related Carbon Emissions and Removals. Remote Sensing, 4: 1369-1391.

Evidente, M., Logan-Hines, E., Goers, L., 2009. REDD Policy Options: Including Forests in an International Climate Change Agreement, In: M.L. Tyrrell, Ashton, M.S., Spalding, D., Gentry, B. (Eds.), Forests and Carbon: A Synthesis of Science, Management, and Policy for Carbon Sequestration in Forests. Yale School of Forestry & Environmental Studies, Yale.

Ewers, R.M., Kliskey, A.D., Walker, S., Rutledge, D., Harding, J.S., Didham, R.K., 2006. Past and future trajectories of forest loss in New Zealand. Biological Conservation, 133: 312–325.

FAO, 2009. The 2010 Global Forest Resources Assessment Remote Sensing Survey: an outline of the objectives, data, methods and approach Forest Res., Rome: Published by FAO with FRA RSS partners.

Fee, E., Johansson, D.J.A., Lowe, J., Marbaix, P., Matthews, B., Meinshausen, M., 2010, Scientific Perspectives after Copenhagen. Information Reference Document. EU.

Fee, E., Johansson, D.J.A., Lowe, J., Marbaix, P., Matthews, B., Meinshausen, M., 2010. Scientific perspectives after Copenhagen.

Fry, I., 2008. Reducing Emissions from Deforestation and Forest Degradation: Opportunities and Pitfalls in Developing a New Legal Regime. Review of European Community & International Environmental Law 17, 166-182.

Garbulsky, M.F., Peñuelas, J., Papale, D., Ardö, J., Goulden, M.L., Kiely, G., Richradson, A.D., Rotenberg, E., Veenendaal, E.M., Filella, I., 2010. Patterns and controls of the variability of radiation use efficiency and primary productivity across terrestrial ecosystems. Global Ecology and Biogeography, 19: 253-267.

Gardner, T.A., Barlow, J., Chazdon, R., Ewers, R.M., Harvey, C.A., Peres, C.A., Sodhi, N.S., 2009. Prospects for tropical forest biodiversity in a human-modified world. Ecology Letters, 12: 561–582.

Geist, H.J., Lambin, E.F., 2002. Proximate causes and underlying driving forces of tropical deforestation. BioScience, 52: 143-150.

Ghazoul, J., Butler, R.A., Mateo-Vega, J., Koh, L.P., 2010. REDD: a reckoning of environment and development implications. Trends in Ecology and Evolution 25: 396-402.

Gibbs, H.K., Ruesch, A.S., Achard, F., Clayton, M.K., Holmgren, P., Ramankutty, N., Foley, J.A., 2010. Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. Proceedings of the National Academy of Sciences USA, 107: 16732–16737.

Gibbs, H.K., Brown, S., Niles, J.O., Foley, J.A., 2007. Monitoring and estimating tropical forest carbon stocks: making REDD a reality. Environmental Research Letters, 2:045023.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: The challenge of feeding 9 billion people. Science, 327: 812–818.

Goetz, S.J., Prince, S.D., Small, J., Gleason, A.C.R., 2000. Interannual variability of global terrestrial primary production: Results of a model driven with satellite observations. Journal of Geophysical Research, 105:20077-20091.

Goetz, S.J., Baccini, A., Laporte, N.L., Johns, T., Walker, W., Kellndorfer, J., Houghton, R.A., Sun, M., 2009. Mapping and monitoring carbon stocks with satellite observations: a comparison of methods. Carbon Balance and Management, 4:2.

GOFC-GOLD, 2009. A sourcebook of methods and procedures for monitoring and reporting anthropogenic greenhouse gas emissions and removals caused by deforestation, gains and losses of carbon stocks in forests remaining forests, and forestation,

Gonzalez, P., Hassan, R., Lakyda, P., McCallum, I., Nilsson, S., Pulhin, J., Scholes, R., 2005. Forest and Woodland Systems, In: Millenium Ecosystem Assessment. (Ed.), Ecosystems and Human Well-being: Current State and Trends, Volume 1. Island Press, Washinton DC, pp. 587-621.

Gower, S.T., Krankina, O., Olson, R.J., Apps, M., Linder, S., Wang, C., 2001. Net primary production and carbon allocation patterns of boreal forest ecosystems. Ecological Applications, 11: 1395-1411.

Gower, S.T., Kucharik, C.J., Norman, J.M., 1999. Direct and indirect estimation of leaf area index, f (APAR), and net primary production of terrestrial ecosystems. Remote Sensing of Environment, 70: 29–51.

Grace, J. Nichol, C., Disney, M., Lewis, P., Quaife, T., Bowyer, P., 2007. Can we measure terrestrial photosynthesis from space directly, using spectral reflectance and fluorescence? Global Change Biology, 13:1484-1497.

Grainger, A., 2008. Uncertainty in the construction of global knowledge on tropical forests. Progress in Physical Geography, 34: 811–844.

Grieg-Gran, M., 2006. The Cost of Avoiding Deforestation. Anonymous. Anonymous. International Institute for Environment and Development.

Griscom, B., Shoch, D., Stanley, B., Cortez, R., Virgilio, N., 2009. Sensitivity of amounts and distribution of tropical forest carbon credits depending on baseline rules. Environmental Science Policy 12, 897-911.

Gullison, R.E., Frumhoff, P.C., Canadell, J.G., Field, C.B., Nepstad, D.C., Hayhoe, K., Avissar, R., Curran, L.M., Friedlingstein, P., Jones, C.D., Nobre, C., 2007. Tropical forests and climate policy. Science 316, 985-986.

Hardcastle, P.D., Baird, D., 2008. Capability and cost assessment of the major forest nations to measure and monitor their forest carbon.

Hare, B., Macey, K., 2007, Tropical Deforestation Emission Reduction System (TDERM): A discussion paper. Greenpeace.

Hassan, R., Scholes, R., Ash, N., 2005. Ecosystems and Human Well-being: Current States and Trends. The Millenium Ecosystem Assessment Series. Island Press, Washington DC.

Havemann, T., 2009. Measuring and Monitoring Terrestrial Carbon: The State of the Science and Implications for Policy Makers. The Terrestrial Carbon Group.

Hazarika, M.K., Yasuoka, Y., Ito, A., Dye, D., 2005. Estimation of net primary productivity by integrating remote sensing data with an ecosystem model. Remote Sensing of Environment, 94: 298-310.

Herold, M., 2009. An assessment of national forest monitoring capabilities in tropical non-Annex I countries: Recommendations for capacity building. Report prepared for the Prince's Rainforest Project and The Government of Norway, pp.62.

Herold, M., Skutsch, M., 2011. Monitoring, reporting and verification for national REDD+ programmes: two proposals. Environmental Research Letters, 6:11.

Hoare, A., Legge, T., Nussbaum, R., Saunders, J., 2008. Estimating the cost of building capacity in rainforest nations to allow them to participate in a global REDD mechanism.

Holloway, V., Giandomenico, E., 2009, The history of REDD policy, Carbon Planet White Paper. Carbon Planet, Adelaide, Australia.

Houghton, R.A., Butman, D., Bunn, A.G., Krankina, O.N., Schlesinger, P., Stone, T.A., 2007. Mapping Russian forest biomass with data from satellites and forest inventories. Environmental Research Letters, 2:045032.

Huettner, M., Leemans, R., Kok, K., Ebeling, J., 2009. A comparison of baseline methodologies for `Reducing Emissions from Deforestation and Degradation'. Carbon Balance and Management, 4:4.

IPCC, 2003. IPCC Good Practice Guidance on Land Use, Land Use Cange and Forestry. IPCC National Greenhouse Gas Inventories Programme. IGES, Japan.

IPCC, 2006. Agriculture, Forestry and Other Land Use (AFULO), In: S Eggelston, Buendia, L, Miwa, K, Ngara, T, Tanabe, K. (Eds.), 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IGES, Japan.

IPCC, 2007. Summary for Policymakers, In: S. Solomon, Qin, D. , Manning, M. , Chen, Z. , Marquis, M. , Averyt, K.B. , Tignor, M., Miller, H.L. (Eds.), Climate Change, 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Irawan, S., Tacconi, L., 2009. Reducing Emissions from Deforestation and Forest Degradation (REDD) and Decentralized Forest Management. International Forestry Review 11, 427-438.

Jenkins, J., Richardson, A.D., Braswell, B.H., Ollinger, S.S., Holliger, D.Y., Smith, M.-L., 2007. Refining light-use efficiency calculations for a deciduous forest canopy using simultaneous tower-based carbon flux and radiometric measurements. Agricultural and Forest Meteorology, 143:64-79.

Karsenty, A., 2009. What the (carbon) market cannot do... Perspective Nr. 1, CIRAD, Paris, France.

Karsenty, A., 2008. The architecture of proposed REDD schemes after Bali: facing critical choices. International Forestry Review; 10:443-457.

Kindermann, G., Obersteiner, M., Sohngen, B., Sathaye, J., Andrasko, K., Rametsteiner, E., Schlamadinger, B., Wunder, S., Beach, R., 2008. Global cost estimates of reducing carbon emissions through avoided deforestation. Proceedings of the National Academy of Sciences USA, 105.

Kindermann, G.E., McCallum, I., Fritz, S., Obersteiner, M., 2008. A Global Forest Growing Stock , Biomass and Carbon Map Based on FAO Statistics. Silva Fennica, 42:387-396.

Kremen, C., Niles, J.O., Dalton, M.G., Daily, G.C., Ehrlich, P.R., Fay, J.P., Grewal, D., Guillery, R.P., 2000. Economic Incentives for Rain Forest Conservation Across Scales. Science 288.

Krishnaswamy, A., Hanson, A., 1999. Our forests, our future. World Commission on Forests and Sustainable Development.

Lamb, D., Erskine, P.D., Parrotta, J.A. 2005. Restoration of degraded tropical forest landscapes. Science, 310: 1628–1632.

Lambin, E.F., Gibbs, H., Ferraira, L., Grau, R., Mayaux, P., Meyfroidt, P., Morton, D., Rudel, T.K., Gasparri, I., Munger, J., forthcoming. Estimating the world's potentially available cropland using a bottom-up approach.

Lambin, E.F., Meyfroidt, P., 2010. Land use transitions: socio-ecological feedback versus socio-economic change. Land Use Policy, 27: 108–118.

Lambin, E.F., Meyfroidt, P., 2011. Global land use change, economic globalization, and the looming land scarcity. Proceedings of the National Academy of Sciences USA, 108: 3465–3472.

Lambin, E.F., Meyfroidt, P., 2012. Global land use competition. Unpublished manuscript prepared for the Strüngmann Forum: Rethinking Global Land Use in an Urban Era.

Lanchberry, J., 2010. A REDD revolution in Copenhagen?, RRI Dialogue on Forests, Governance & Climate Change, Chatham House, London.

Lawlor, K., Jenkins, A., Olander, L., Murray, B., 2009, Expanding the Scope of International Terrestrial Carbon Options: Implications of REDD+ and Beyond, Nicholas Institute for Environmental Policy Solutions. Duke Institute, Durham, NC.

Le Polain, Y., Lambin, E.F., in press. Niche commodities and rural poverty alleviation: Contextualizing the contribution of argan oil to rural livelihoods in Morocco. Annals of the Association of American Geographers.

Liu, L., Cheng, Z., 2010. Detection of Vegetation Light-Use Efficiency Based on Solar-Induced Chlorophyll Fluorescence Separated From Canopy Radiance Spectrum. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 3:306-312.

Lovett, G.M., Cole, J.J., Pace, M.L., 2006. Is Net Ecosystem Production Equal to Ecosystem Carbon Accumulation? Ecosystems, 9: 152-155.

Lund, H.G., 2005. Definitions of Forest, Deforestation, Afforestation, and Reforestation. Published online. Forest Information Service, Gainesville, VA, url:http://home.comcast.net/gyde/DEFpaper.htm.

Maniatis, D., Mollicone, D., 2010. Options for sampling and stratification for national forest inventories to implement REDD+ under the UNFCCC. Carbon Balance and Management 5, 9.

Maselli, F., Barbati, A., Chiesi, M., Chirici, G., Corona, P., 2006. Use of remotely sensed and ancillary data for estimating forest gross primary productivity in Italy. Remote Sensing of Environment, 100: 563-575.

Mather, A.S., Needle, C.L., 1998. The forest transition: A theoretical basis. Area, 30: 117–124.

McMurtrie, R., Landsberg, 1992. Using a simulation model to evaluate the effects of water and nutrients on the growth and carbon partitioning of *Pinus radiata*. Forest Ecology and Management, 52: 243-260.

Meyfroidt, P., Lambin, E.F., 2008. Forest transition in Vietnam and its environmental impacts. Global Change Biology, 14: 1319–1336.

Meyfroidt, P., Lambin, E.F., 2009. Forest transition in Vietnam and displacement of deforestation abroad. Proceedings of the National Academy of Sciences USA, 106: 16139–16144.

Meyfroidt, P., Lambin, E.F., 2011. Global forest transition: Prospects for an end to deforestation. Annual Review of Environment and Resources, 36: 343–371.

Meyfroidt, P., Phuong, V.T., Anh, H.V., forthcoming. Trajectories of deforestation, coffee expansion and displacement of shifting cultivation in the Central Highlands of Vietnam.

Meyfroidt, P., Rudel, T.K., Lambin, E.F., 2010. Forest transitions, trade, and the global displacement of land use. Proceedings of the National Academy of Sciences USA, 107: 20917–20922.

Meyfroidt, P, van Noordwijk, M., Minang, P.A., Dewi, S., Lambin, E.F., 2011. Drivers and consequences of tropical forest transitions: options to bypass land degradation? ASB Policy Brief 25. ASB Partnership for the Tropical Forest Margins, Nairobi, Kenya.

Miles, L., Dunning, E., Doswald, N., 2010, Safeguarding and enhancing the ecosystem-derived benefits of REDD+. Multiple Benefits Series 2. Prepared on behalf of the UN-REDD Programme. UNEP World Conservation Monitoring Centre, Cambridge, UK.

Mollicone, D., Achard, F., Federici, S., Eva, H.D., Grassi, G., Belward, A., Raes, F., Seufert, G., Stibig, H.J., Matteucci, G., Schulze, E.D., 2007. An incentive mechanism for reducing emissions from conversion of intact and non-intact forests. Climatic Change 83, 477-493.

Monteith, J., 1972. Solar radiation and productivity in tropical ecosystems. Journal of Applied Ecology, pp.747–766. Available at: http://www.jstor.org/stable/2401901 [Accessed December 22, 2010].

Murray, B., 2008. Leakage from an Avoided Deforestation Compensation Policy: Concepts, Empirical Evidence, and Corrective Policy Options Nicholas Institute for Environmental Policy Solutions, Duke University, Durham, NC, pp.34.

Myers, E.C., 2008, Policies to Reduce Emissions from Deforestation and Degradation (redd) in Developing Countries. Resources for the Future, Washington, DC.

Nakaji, T., Ide, R., Oguma, H., Saigusa, N., Fujnuma, Y., 2007. Utility of spectral vegetation index for estimation of gross CO_2 flux under varied sky conditions. Remote Sensing of Environment, 109: 274-284.

Nepstad, D.C., Soares-Filho, B.S., Merry, F., Moutinho, P., Rodrigues, H.O., Bowman, M., Schwartzman, S., Almeida, O., Rivero, S., 2007. The costs and benefits of reducing carbon emissions from deforestation and forest degradation in the Brazilian Amazon. The Woods Hole Research Center.

Ogonowski, M., Helme, N., Movius, D., Schmidt, J., 2007, Reducing Emissions from Deforestation and Degradation: The Dual Markets Approach, Future Actions Dialogue Working Papers. Center for Clean Air Policy (CCAP).

Olander, L.P., Gibbs, H.K., Steininger, M., Swenson, J.J., Murray, B.C., 2008. Reference scenarios for deforestation and forest degradation in support of REDD: a review of data and methods. Environmental Research Letters, 3:025011.

Pagiola, S., Bosquet, B., 2009. Estimating the Costs of REDD at the Country Level. World Bank.

Parker, C., 2011, Policy Brief. The outcome for forests emerging from Cancun. Global Canopy Programme.

Parker, C., Mitchell, A., Trivedi, M., Mardas, N., Sosis, K., 2009. The Little REDD+ Book, Third ed. Global Canopy Programme, Oxford, UK.

Pedroni, L., Dutschke, M., Streck, C., Porrua, M.E., 2009. Creating incentives for avoiding further deforestation: the nested approach. Climate Policy 9, 207-220.

Persson, U.M., Azar, C., 2010. Preserving the World's Tropical Forests - A price on carbon my not do. Environmental Science and Technology 44, 210-215.

Peskett, L., Huberman, D., Bowen-Jones, E., Edwards, G., Brown, J., 2008. Making REDD work for the poor. Prepared on behalf of the Poverty Environment Partnership.

Pirard, R., 2008. Estimating opportunity costs of Avoided Deforestation (REDD): application of a flexible stepwise approach to the Indonesian pulp sector. International Forest Reviews 10.

Plantinga, A.J., Richards, K.R., 2008, International Forest Carbon Sequestration in a Post-Kyoto Agreement, The Harvard Project on International Climate Agreements. Harvard Kennedy School, Cambridge, MA.

Prieto-Blanco, A., North, P.R.J., Barnsley, M.J., Fox, N., 2009. Satellite-driven modelling of Net Primary Productivity (NPP): Theoretical analysis. Remote Sensing of Environment, 113: 137-147.

Prior, S., O'Sullivan, R., Streck, C., 2007. A Carbon Stock Approach to Creating a Positive Incentive to Reduce Emissions from Deforestation and Forest Degradation. Centre for International Sustainable Development Law (CISDL) and Global Public Policy Institute (GPPI), pp. 24.

Reuters, 2010. California pilots REDD with Brazil, Mexico states. http://www.reuters.com/article/2010/11/16/california-carbon-idUSN1528014320101116. (2 March, 2011).

Reuters, 2011. Greek police trace EU carbon rights thieves. http://af.reuters.com/article/energyOilNews/idAFLDE70S0IY20110129 (3 march, 2011).

Robiglio, V., Lescuyer, G., Cerutti, P.O., in press. From Farmers to Loggers: The Role of Shifting Cultivation Landscapes in Timber Production in Cameroon. Smallscale Forestry.

Rogelj, J., Nabel, J., Chen, C., Hare, W., Markmann, K., Meinshausen, M., Schaeffer, M., Macey, K., Hohne, N., 2010. Copenhagen Accord pledges are paltry. Nature 464: 1126-1128.

Rudel, T.K., Coomes, O.T., Moran, E., Achard, F., Angelsen, A., Xu, J., Lambin, E., 2005. Forest transitions: towards a global understanding o land use change. Global Environmental Change, 15 : 23–31.

Ruimy, A., Kergoat, L., Bondeau, A., 1999. Comparing global models of terrestrial net primary productivity (NPP): analysis of differences in light absorption and light-use efficiency. Global Change Biology, 5: 56-64.

Running, S., Nemani, R.R., Townshend, J.R.G., Baldocchi, D.D., 2009. Next-Generation Terrestrial Carbon Monitoring. Geophysical Monograph Series, 183: 49-69.

Santilli, M., Moutinho, P., Schwartzman, S., Nepstad, D., Curran, L., Nobre, C., 2005. Tropical deforestation and the Kyoto Protocol. Climatic Change 71: 267-276.

Sasaki, N., Putz, F.E., 2009. Critical need for new definitions of "forest" and "forest degradation" in global climate change agreements. Conservation Letters, 2:226-232.

Schlamadinger, B., Bird, N., Johns, T., Brown, S., Canadell, J., Ciccarese, L., Dutschke, M., Fiedler, J., Fischlin, A., Fearnside, P., Forner, C., Freibauer, A., Frumhoff, P., Hoehne, N., Kirschbaum, M.U.F., Labat, A., Marland, G., Michaelowa, A., Montanarella, L., Moutinho, P., Murdiyarso, D., Pena, N., Pingoud, K., Rakonczay, Z., Rametsteiner, E., Rock, J., Sanz, M.J., Schneider, U.A., Shvidenko, A., Skutsch, M., Smith, P., Somogyi, Z., Trines, E., Ward, M., Yamagata, Y., 2007. A synopsis of land use, land-use change and forestry (LULUCF) under the Kyoto Protocol and Marrakech Accords. Environmental Science & Policy 10, 271-282.

Sedjo, R.A., Botkin, D., 1997. Using forest plantations to spare natural forests. Environment, 39:15–20.

Simula, M., 2009. Towards defining forest degradation: Comparative analysis of existing definitions. FAO, Forest Resources Assessment. Working Paper 154.

Skutsch, M.M., McCall, M.K., 2010. Reassessing REDD: governance, markets and the hype cycle. Climatic Change, 100: 395-402.

Sohngen, B., Beach, R.H., Andrasko, K., 2008. Avoided deforestation as a greenhouse gas mitigation tool: economic issues. Journal of Environmental Quality, 37: 1368-1375.

Stern, N., 2006. Stern review: the economics of climate change. HM Treasury UK Government, Cambridge University Press, Cambridge.

Stickler, C.M., Nepstad, D.C., Coe, M.T., McGrath, D.G., Rodrigues, H.O., Walker, W.S., Soares, B.S., Davidson, E.A., 2009. The potential ecological costs and cobenefits of REDD: a critical review and case study from the Amazon region. Global Change Biology 15, 2803-2824.

Stickler, C.M., Nepstad, D.C., Coe, M.T., McGrath, D.G., Rodrigues, H.O., Walker, W.S., Soares, B.S., Davidson, E.A., 2009. The potential ecological costs and co-benefits of REDD: a critical review and case study from the Amazon region. Global Change Biology 15, 2803.

Strassburg, B., Turner, R.K., Fisher, B., Schaeffer, R., Lovett, A., 2009. Reducing emissions from deforestation-The "combined incentives" mechanism and empirical simulations. Global Environmental Change-Human and Policy Dimensions, 19: 265-278.

Tacconi, L., 2009. Compensated successful efforts for avoided deforestation vs. compensated reductions. Ecological Economics, 68: 2469-2472.

Tao, F., Yokozawa, M., Zhang, Z., Xu, Y., Hayashi, Y., 2005. Remote sensing of crop production in China by production efficiency models: models comparisons, estimates and uncertainties. Ecological Modelling, 183: 385-396.

Turner, D.P., Ritts, W.D., Cohen, W.B., Gower, S.T., Zhao, M.S., Running, S.W., Wofsy, S.C., Urbanski, S., Dunn, A.L., Munger, J.W.; 2003. Scaling Gross Primary Production (GPP) over boreal and deciduous forest landscapes in support of MODIS GPP product validation. Remote Sensing of Environment, 88: 256-270.

Turner, D.P., Urbanski, S., Bremer, D., Wofsy, S.C., Meyers, T., Gower, S.T., Gregory, M., 2003. A cross-biome comparison of daily light use efficiency for gross primary production. Global Change Biology, 9: 383-395.

UN, 2009, State of the world's indigenous peoples. United Nations - Department of Economic and Social Affairs, New York.

UNEP (2010) The emission gap report.

UNEP, 2010, The Emissions Gap Report: Are the Copenhagen Accord Pledges Sufficient to Limit Global Warming to 2.8C or 1.5 °C? United Nations Environment Programme (UNEP). http://www.unep.org/publications/ebooks/emissionsgapreport

UNFCCC, 2001. Report of the Conference of the Parties on its seventh session. Held in Marrakesh from 29 October - 10 November, 2001. Addendum Part Two: Actions taken by the Conference of the Parties. Volume I United Nations Framework Convention on Climate Change Secretariat. FCCC/CP/2001/13/Add.1.

UNFCCC, 2005. Reducing emissions from deforestation in developing countries: approaches to stimulate action. . COP Misc. for 11th session. Document FCCC/CP/2005/MISC.1. Montreal.

UNFCCC, 2007. Report of the Conference of the Parties on its thirteenth session, held in Bali from 3 to 15 December, 2007. Decision1/CP.13: Bali Action Plan. Document FCCC/CP/2007/6/Add.1. Bali, Indonesia. http://unfccc.int/resource/docs/2007/cop13/eng/06a01.pdf.

UNFCCC, 2009. Methodological guidance for activities relating to reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries. Decision 4/CP.15. FCCC/CP/2009/11/Add.1. Copenhagen, Denmark. http://unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf#page=11.

van der Werf, G.R., Morton, D.C., DeFries, R.S., Olivier, J.G.J., Kasibhatla, P.S., Jackson, R.B., Collatz, G.J., Randerson, J.T., 2009. CO_2 emissions from forest loss. Nature Geoscience 2, 737-738.

Van Noordwijk, M., Minang, P.A., Dewi, S., Hall, J., Rantala, S., 2009, Reducing Emissions from All Land Uses (REALU): The Case for a whole landscape approach., ASB PolicyBrief 13. ASB Partnership for the Tropical Forest Margins, Nairobi, Kenia.

Vedeld, P., Angelsen, A., Bojö, J., Sjaastad, E., Berg, G.K., 2004. Forest environmental incomes and the rural poor. Forest Policy and Economics 9, 869-879

Verchot, L.V., Petkova, E., 2009, The state of REDD negotiaions. Consensus points, options for moving forward and research needs to support the process. Center for International Forestry Research (CIFOR), Bogor, Indonesia.

Veroustraete, F., Sabbe, H., Eerens, H., 2002. Estimation of carbon mass fluxes over Europe using the C-Fix model and Euroflux data. Remote Sensing of Environment, 83: 376 - 399.

Verstraeten, W.W., Veroustraete, F., Feyen, J., 2006. On temperature and water limitation of net ecosystem productivity: Implementation in the C-Fix model. Ecological Modelling, 199: 4-22.

Viana, V., 2009, Financing REDD: meshing markets with government funds, briefing. iied, London.

Virgilio, N., Marshall, S., Zerbock, O., Holmes, C., 2010, Reducing Emissions from Deforestation and Degradation (REDD): A Casebook of On-the-Ground-Expirience. The Nature Conservancy, Conservation International and Wildlife Conservation Society, Arlington, Virginia.

Wang, H., Jia; G., Fu, C., Feng, J., Zhao, T., Ma, Z., 2010. Deriving maximal light use efficiency from coordinated flux measurements and satellite data for regional gross primary production modelling. Remote Sensing of Environment, 114:2248-2258.

Warnant, P., Francois, L., Strivay, D., Gérard, J.-C., 1994. CARAIB: a global model of terrestrial biological productivity. Global Biogeochemical Cycles, 8: 255–270.

Weiss, M., Baret, F., Eerens, H., Swinnen, E., 2010. FAPAR over Europe for the past 29 years: A temporally consistent product derived from AVHRR and VEGETATION Sensors. In Proc. 3rd International symposium “Recent Advances in Quantitative Remote Sensing.”Valencia, Spain, pp. 1-6.

Wertz-Kanounnikkof, S, Angelsen, A., 2009. Global and national REDD+ architecture Linking institutions and actions. In: Realising REDD+. National strategy and policy options. Ed. Angelsen, A. CIFOR, Bogor, Indonesia.

Wertz-Kanounnikoff, S., Tubiana, L., 2007. Bringing “REDD” into a new deal for the global climate. IDDRI synthèses 05/2007.

White, D., Minang, P., 2011. Estimating the opportunity costs of REDD+. A training manual. World Bank.

World Bank (2010). Rising global interest in farmland: Can it yield sustainable and equitable benefits?

WorldBank, 2008. Forests for Poverty Reduction, In: The World Bank (Ed.), Forest Sourcebook. Practical Guidance for Sustaining Forests in Development Cooperation. The World Bank, Washington DC, p. 402.

Wu, C., Munger, J.W., Niu, Z., Kuang, D., 2010. Comparison of multiple models for estimating gross primary production using MODIS and eddy covariance data in Harvard Forest. Remote Sensing of Environment, 114: 2925-2939.

Xiao, X., Zhang, Q., Saleska, S., Hutyra, L., De Camargo, P., Wofsy, S., Frolking, S., Boles, S., Keller, M., Moore III, B., 2005. Satellite-based modeling of gross primary production in a seasonally moist tropical evergreen forest. Remote Sensing of Environment, 94:105-122.

Yuan, W., Lio, S., Zhou, G., Zhou, G., Tieszen, L.L., Baldocchi, D., Bernhofer, C., Gholz, H., Goldstein, A.H., *et al.*, 2007. Deriving a light use efficiency model from eddy covariance flux data for predicting daily gross primary production across biomes. Agricultural and Forest Meteorology, 143:189-207.

Zhao, M., Heinsch, F.A., Nemani, R.R., Running, S.W., 2005. Improvements of the MODIS terrestrial gross and net primary production global data set. Remote Sensing of Environment, 95:164-176.

Annex

Dissemination

The cluster project had specific objectives with respect to the dissemination of research on REDD+. This output included both peer-reviewed papers and working papers, policy briefs and the organisation of a conference. The most important output can be found in subsequent annexes to the report.

Working papers

- Cuypers D, Dauwe T, Vangoidsenhoven M, 2011. REDD+ in the Cancun Agreement: An analysis from the front line. Be-REDDi working paper 1.

- Vangoidsenhoven M, Dauwe T, Samson R, 2011. Seeing the wood for the trees. A review of the design options for a forestry-based mitigation mechanism in developing countries. Be-REDDi working paper 2.

- Dauwe T, 2012. The cost of REDD+. Be-REDDi working paper 3.

Policy Briefs

- Verbist B, Muys B (2010) Dryland areas, forgotten by REDD? KLIMOS Policy brief 2, KLIMOS, Leuven.
- Meyfroidt P, van Noordwijk M, Minang PA, Dewi S, Lambin EF (2011). Drivers and consequences of tropical forest transitions: options to bypass land degradation? *ASB Policy Brief 25.* ASB Partnership for the Tropical Forest Margins, Nairobi, Kenya.
- Minang PA, van Noordwijk M, Meyfroidt P, Agus F, Dewi S (2010) Emissions Embedded in Trade (EET) and Land use in Tropical Forest Margins. *ASB Policy Brief 17.* ASB Partnership for the Tropical Forest Margins, Nairobi, Kenya.

Research papers

Peer reviewed

- Meyfroidt P, Phuong VT, Anh HV. Trajectories of deforestation, coffee expansion and displacement of shifting cultivation in the Central Highlands of Vietnam, under review.
- Meyfroidt P. Environmental cognitions, land change and social-ecological feedbacks: local case studies of the forest transition in Vietnam, under review.
- Meyfroidt P. (2012) Environmental cognitions, land change, and social-ecological feedbacks: an overview. Journal of Land Use Science, in press.
- Bucki M, Cuypers D, Mayaux P, Achard F, Estreguil C, Grassi G, (2012) Assessing REDD+ performance of countries with low monitoring capacities: the matrix approach. Environmental Research Letters, 7: 014031
- Meyfroidt P, Lambin EF. (2011) Global forest transition: Prospects for an end to deforestation. Annual Review of Environment and Resources, 36: 343–371.
- Lambin EF, Meyfroidt P (2011) Global land use change, economic globalization, and the

looming land scarcity. Proceedings of the National Academy of Sciences, 108: 3465–3472.

- Meyfroidt P, Rudel TK, Lambin EF (2010) Forest transitions, trade and the global displacement of land use. Proceedings of the National Academy of Sciences, 107: 20917–20922.
- Lambin EF, Meyfroidt P (2010) Land use transitions : Socio-ecological feedback versus socio-economic change. Land Use Policy, 27: 108–118.
- de Mûelenaere S, Frankl A, Mitiku H, Poesen J, Deckers J, Nyssen J, 2012. Historical landscape photographs for calibration of landsat land use/cover in the northern Ethiopian highlands. Land Degradation & Development, in press.

Other (newsletters):

- Meyfroidt P, Lambin EF, Rudel TK (2011). Deforestation, international trade and conservation of forests. Newsletter of the Global Land Project, 7: 27–29.
- Lambin EF, Meyfroidt P (2011). Economic globalization as a dominant cause of land change. Newsletter of the Global Land Project, 7: 25–26.
- Meyfroidt P, Lambin EF, Rudel TK (2011). Deforestation, international trade and conservation of forests. Newsletter of the Commonwealth Forestry Association, 52: 1–2.

Conferences attended

- *CNCD workshop "Le climat et les ressources naturelles: quels enjeux pour 2010?"*, Brussels, 15 June 2010. Presentation: Meyfroidt P, "Les forêts tropicales: entre déforestation et préservation internationale."
- *Global Land Project Open Science Meeting 2010*, Tempe (AZ), 17-19 October 2010. Presentations : Meyfroidt P, Rudel TK, Lambin EF "Forest transitions, trade and the global displacement of land use."; Meyfroidt P "Local environmental perceptions and social-ecological feedbacks in the forest transition in Vietnam."
- *Fourth Belgian Geography Days,* Leuven, 22-23 October 2010. de Mûelenaere S, Frankl A, Mitiku H, Nyssen J, "Land use/cover change in the north Ethiopian highlands: integration of satellite imagery and terrestrial photography".
- *Fourth Belgian Geographers Days*, Katholiek Universiteit Leuven, 22-23 October 2010. Meyfroidt P, Rudel TK, Lambin EF "Forest transitions, trade and the global displacement of land use."
- *"Les forêts : entre enjeu climatique mondial et source de services locaux"*, broad audience conference co-organized by P. Meyfroidt and C. Farcy, Louvain-La-Neuve, 15 November 2010. Participants : profs. Q Ponette (UCLouvain), E. Lambin (UCLouvain & Stanford), T. Dedeurwaerdere (UCLouvain).
- *Planet Under Pressure Conference*, London, 26-29 March 2012. Meyfroidt P, Lambin EF, "Prospects and options for an end to deforestation and global restoration of forests".
- *8th International Association of Landscape Ecology (IALE) World Congress*, Beijing, 18-23 August 2011. Meyfroidt P, Robiglio V, Bolognesi M, Assoumou Mezui R "Analyzing the drivers of changes in landscape structure in the tropical forest margins of Cameroon."
- *UNFCCC COP17,* Durban, December 2011. Vangoidsenhoven M, Dauwe T, Cuypers D, Roeland S (2012) "A framework to assess the sustainability of different REDD+ design options".

Conference organised

Forest and climate change: scientific insights and social leverages – 9 November, 2011, Brussels

Almost 20 years after the Rio summit on sustainable development, forests are back on the international policy agenda. A multilateral agreement could not be reached in Rio to reduce the anthropogenic pressure on the remaining forests. It is the hope of many NGOs, scientists and policy makers however that in the context of a new international climate agreement, also provisions will be made to reduce deforestation and the emissions it causes. This mechanism, called REDD+ (Reduced Emissions from Deforestation and forest Degradation in developing countries), should give the incentives developing countries need to preserve their remaining forests as much as possible. To subscribe the importance of forests, ARGUS, the Vereniging voor Bos in Vlaanderen, Groenhart, WWF-Belgium and VITO organised a scientific conference on 9 November, 2011, the UN international year of forests.

At this one-day conference, several scientist presented their research relevant to REDD+ (reducing emissions from deforestation and forest degradation). Topics such as earth observation of forest, the carbon balance and cycle, drivers of deforestation and degradation, sustainability of a REDD+ mechanism and international forest and climate policies were covered. Also, NGO's presented their international REDD+ projects on the ground and a poster session was organised.

Programme:

9:00	Registration	
9:30	Welcome and introduction	Tom Dauwe (VITO)
9:40	Tropical forests on the international policy agenda	Tom Dauwe (VITO)
10:00	Global forest transition in the globalization era	Eric Lambin and Patrick Meyfroidt (UCL)
10:30	A spatio-temporal analysis of woody vegetation cover in the northern Ethiopian highlands since the late 19th century	Jan Nyssen (UGent)
11:00	Coffee and poster session	
11:30	REDD+, Cancun, Durban and us	Dieter Cuypers (VITO)
12:00	Project on the ground:	
	Groenhart and Vereniging voor Bos in Vlaanderen restore more than 500 ha of natural forest in Ecuador supported by Telenet	Debbie Eraly (Groenhart)
	Small scale reforestation in eastern DRC: its potential for A/R CDM and REDD+.	Mone Van Geit (WWF-Be)
12:30	Lunch and poster session	
14:00	Reconciliating mitigation and adaptation by linking environmental and development policies.	Bruno Verbist (KUL)
14:30	Is Congo ready for REDD+	Theofore Trefon (RMCA)
15:00	The COBIMFO project: integrated carbon and biodiversity monitoring in the Yangambi Man and Biosphere Reserve, DR Congo	Pascal Boeckx and Hans Verbeeck (UGent)
15:15	Monitoring forest transitions in mountain areas	Anton Van Rompaey (KUL)
15:30	Coffee and poster session	

16:00	VEGECLIM	Carlos de Wasseige (UCL)
16:30	Forest carbon allocation as a determinant of net primary productivity	Ivan Janssens (UA)
17:00	Closing statement	

In total +60 participants from universities, NGOs, policy makers, ... attended the conference.

Additional funding

- Belspo, STEREO II, call 2011. Contribution of medium resolution remote sensing time series to REDD+ accounting systems Partners: VITO, ICRAF-SEA. Not selected.
- Belspo, SSD, call 2011. Global and local impacts on biodiversity and hydrogeomorphology in the Albertine Rift (GLOCALBERTINE). Partners: UGent. Not selected.
- NUFFIC. STRONGBOW (Sustainable TouRism based On Natural resource management with Gender Balance tOwards Women). Partners: UGent, KUL. Selected.