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Applying the conservativeness principle to REDD to deal with the uncertainties of the estimates

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Abstract
A common paradigm when the reduction of emissions from deforestations is estimated for the purpose of promoting it as a mitigation option in the context of the United Nations Framework Convention on Climate Change (UNFCCC) is that high uncertainties in input data—i.e., area change and C stock change/area—may seriously undermine the credibility of the estimates and therefore of reduced deforestation as a mitigation option.

In this paper, we show how a series of concepts and methodological tools—already existing in UNFCCC decisions and IPCC guidance documents—may greatly help to deal with the uncertainties of the estimates of reduced emissions from deforestation.

Keywords: uncertainty, accuracy, deforestation, conservative estimates, accounting

1. Introduction

The United Nations Framework Convention on Climate Change (UNFCCC) conference held in Bali, in December 2007, has produced significant steps forward in the process on 'reducing emissions from deforestation and forest degradation in developing countries' (REDD). Among others, the decision on REDD (UNFCCC 2007a) has encouraged the start of 'demonstration activities', which shall follow an agreed indicative guidance. According to this guidance, estimates of reduced emissions should be 'results based, demonstrable, transparent, and verifiable, and estimated consistently over time'. To this aim, parties are encouraged to apply the IPCC's Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC 2003) as a basis for estimating and monitoring emissions.

There is a general understanding that the REDD activities need economic incentives in order to be successful at the appropriate scale. If such incentives are expected from modalities and rules to be negotiated under the UNFCCC and will be used to fulfill parties' commitments, scientifically robust estimates need to be produced. Although at present it is not possible to foresee the exact methodological and reporting requirements of a future REDD mechanism, they will likely need to fulfill the following general UNFCCC principles for estimating and reporting emissions and removals of greenhouse gases (GHGs):

- *Transparency*, i.e. all the assumptions and the methodologies used in the inventory should be clearly explained and appropriately documented, so that anybody could verify its correctness.
- *Consistency*, i.e. an inventory should be internally consistent in all its elements with inventories of other years. An inventory is consistent if the same methodologies and consistent data sets are used along time. Under certain circumstances, estimates using different methodologies for different years can be considered consistent if they have been calculated in a transparent manner.
- *Comparability* i.e. estimates of emissions and removals should be comparable among parties. For this purpose, parties should follow the methodologies and standard

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formats provided by the IPCC and agreed within the UNFCCC for compiling and reporting inventories.

- *Completeness*, i.e. estimates should include—for all the relevant geographical coverage—all the agreed categories, gases and pools.
- *Accuracy*, in the sense that estimates should be systematically neither over nor under the true value, so far as can be judged, and that *uncertainties* are reduced so far as is practicable. Appropriate methodologies should be used, in accordance with the IPCC good practice guidance, to promote accuracy in inventories and to quantify the uncertainties in order to improve future inventories.

Furthermore, it is likely that these principles will guide an independent assessment of the REDD estimates, for example as it is already done for yearly GHG inventories submitted to the UNFCCC.

In this context, it is important to identify which will likely be the main challenges that developing countries may encounter for estimating and reporting REDD estimates.

Although methods to assess tropical deforestation and forest carbon stock changes exist (e.g. IPCC 2006, Achard *et al* 2007, Gibbs *et al* 2007), based on the analysis of scientific literature (e.g. Houghton 2005) and of data submitted to UNFCCC (UNFCCC 2005a) and to the United Nations' Food and Agriculture Organization (FAO 2006), we consider that the principles of *completeness* and *accuracy* will likely represent the major challenges for most developing countries.

In this context, this paper aims to address the following question: is it possible to reconcile the request of robust and credible estimates with the *incompleteness* and *high uncertainty* which will likely characterize the estimates of emissions from deforestation in many tropical countries?

We address this question using as a framework the IPCC methodologies and UNFCCC reporting and review principles, and applying them into the REDD context. Specifically, we analyze the conservativeness principle—already briefly introduced in an earlier paper (Mollicone *et al* 2007b)—and different options for implementing it to REDD. Although the subject of Decision 2/CP.13 (UNFCCC 2007a) is the reduction in emissions coming from both deforestation and forest degradation, as it is not fully clear yet how emissions from forest degradation will be measured the focus of this paper is mainly on emissions from deforestation. However, we believe that most of the considerations expressed hereafter could also be useful in the context of the very uncertain emissions from forest degradation.

2. The principle of conservativeness

To address the potential incompleteness and high uncertainties of REDD estimates, and thus to increase their credibility, it has been proposed to use the principle of *conservativeness* (e.g., Grassi 2007, Mollicone *et al* 2007b): when completeness or accuracy of estimates cannot be achieved the reduction of emissions should not be overestimated, or at least the risk of overestimation should be minimized.

Although such a principle may appear new to many, similar formulations have already been used in the context of UNFCCC: for adjustments under Article 5.2 of the Kyoto Protocol and in the modalities for afforestation and reforestation project activities under the Clean Development Mechanism (CDM).

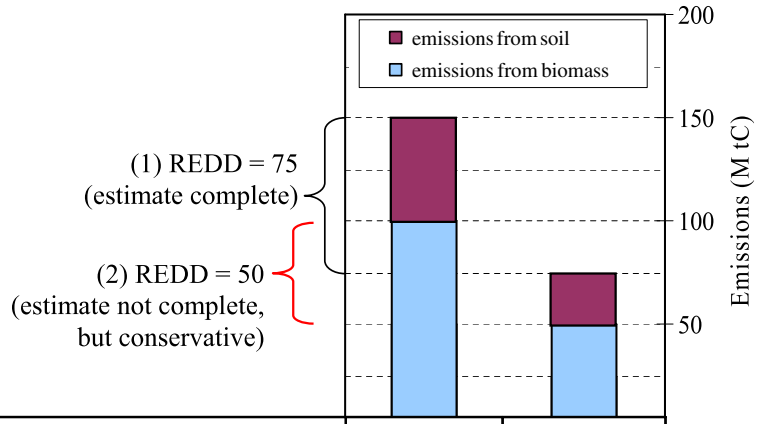
The adjustment procedure works as follows (UNFCCC 2006a): if an Annex I party reports to UNFCCC emissions or removals in a manner that is not consistent with IPCC methodologies and would give benefit for the party, e.g. an overestimation of sinks or underestimation of emissions in a given year of the commitment period, then this would likely trigger an 'adjustment', i.e., a change applied by an expert review team (ERT) to the party's reported estimates. In this procedure, the ERT may first substitute the original estimate with a new one (generally based on a default IPCC estimate, i.e. a tier 1) and then—given the high uncertainty of this new estimate—multiply it by a tabulated category-specific 'conservativeness factor'. Differences in conservativeness factors between categories reflect typical differences in total uncertainties, and thus conservativeness factors have a higher impact for categories or components that are expected to be more uncertain (based on the uncertainty ranges of IPCC default values or on expert judgment). In other words, the conservativeness factor acts to decrease the risk of underestimating emissions or overestimating removals in the commitment period. In the case of the base year, the opposite applies.

The conservativeness principle is also introduced in the CDM afforestation and reforestation modalities (UNFCCC 2006b), where it is prescribed that 'the baseline shall be established in a transparent and conservative manner regarding the choice of approaches, assumptions, methodologies, parameters, data sources, . . . and taking into account uncertainty'.

Furthermore, the conservativeness principle is also implicitly present elsewhere. For example, the Marrakech Accords specify that, under Articles 3.3 and 3.4 of the Kyoto Protocol, Annex I parties 'may choose not to account for a given pool if transparent and verifiable information is provided that the pool is not a source', which means applying conservativeness to an incomplete estimate. Accordingly, chapter 4 of the IPCC-GPG (IPCC 2003) provides some (limited) guidance on how to demonstrate that a pool is not a source. The 85% discount foreseen for the setting of the cap under Article 3.4 for forest management also arises from the conservativeness principle. In addition, the IPCC-GPG indicates the use of the Reliable Minimum Estimate (IPCC 2003, chapter 4.3.3.4.1) as a tool to assess changes in soil carbon, which means applying the conservativeness principle to an uncertain estimate.

Several parties have already included this concept in their submissions of views on REDD (e.g., the European community and the joint submission by 25 Non-Annex I parties state that emission reductions 'should be assessed on a conservative basis', see UNFCCC 2007b), and, similarly, it has been proposed to use 'discount factors' as a pragmatic way to address the uncertainty of REDD estimates (e.g. Greenpeace 2007).

Very recently, this concept also entered into the text of ongoing REDD negotiations (UNFCCC 2008), where among



	Reference period	Assessment period
AD: area deforested (M ha)	1	0.5
EF Biomass (C stock change: tC/ha)	100	100
EF Soil (C stock change: tC/ha)	50	50

Figure 1. Exemplification of how neglecting a carbon pool may produce a conservative REDD estimate. (1) Complete REDD estimate, including the soil pool; (2) incomplete REDD estimate, as the soil pool is not accounted for. The latter estimate is not complete, but is conservative.

the methodological issues identified for further consideration there was included 'means to deal with uncertainties in estimates aiming to ensure that reductions in emissions or increases in removals are not overestimated'. This concept has been further confirmed in the Chair's conclusions of the 'UNFCCC Workshop on Methodological Issues relating to Reducing Emissions from Deforestation and Forest Degradation in Developing Countries' (25–27 June 2008, Tokyo, Japan)

However, although the usefulness of the conservativeness principle seems largely accepted, its application in the REDD context clearly needs some guidance and a statistically robust justification. In other words: how do we implement, in practice, the conservativeness principle to the REDD context? To answer this question, the next two sections illustrate possible applications of this principle as a monitoring perspective—to address incomplete estimates—and in the accounting context—to address uncertain estimates.

3. Conservativeness during monitoring to address incomplete estimates

Achieving the completeness principle will clearly depend on the processes, pools and gases that need to be reported, and on the forest-related definitions that are applied.

For example, it is likely that the most typical and important example of incomplete estimates will arise from the lack of reliable data for a carbon pool. Indeed, evidence from official reports (e.g., UNFCCC 2005a, UNFCCC 2005b, FAO 2006) suggests that only a very small fraction of developing countries currently reports data on soil carbon, even though emissions from soils following deforestation are likely to be significant in many cases. In this case, being conservative in a REDD context does not mean 'not overestimating the emissions', but rather 'not overestimating the reduction of emissions'. In practice, if soil is not accounted for, the total emissions from deforestation will very likely be underestimated in both periods. However, assuming for the most disaggregated reported level (e.g., a forest type converted to cropland) the same emission factor (EF) in the two periods, and provided that the area deforested is reduced from the reference to the assessment period, the reduced emissions will also be underestimated. In other words, although neglecting soil carbon will cause a REDD estimate which is not complete, this estimate will be conservative (see figure 1). However, this assumption of conservative omission of a pool is not valid anymore if, for a given forest conversion type, the area deforested is increased from the reference to the assessment period.

Therefore, any future methodological guidance for estimating emissions in an REDD context (or addendum to current IPCC guidance) should also include an explicit reference to the fact that an estimate of emissions from deforestation (and forest degradation) can be incomplete (in terms of C pools, gases or area coverage) if it is demonstrated—through transparent and verifiable information—that this omission produces a more conservative REDD estimate. Adequate guidance on how demonstrating this conservative omission should also be provided.

4. Conservativeness during the accounting to address uncertainties

Before illustrating a possible approach to use the conservativeness principle to reduce the risk of overestimating an uncertain

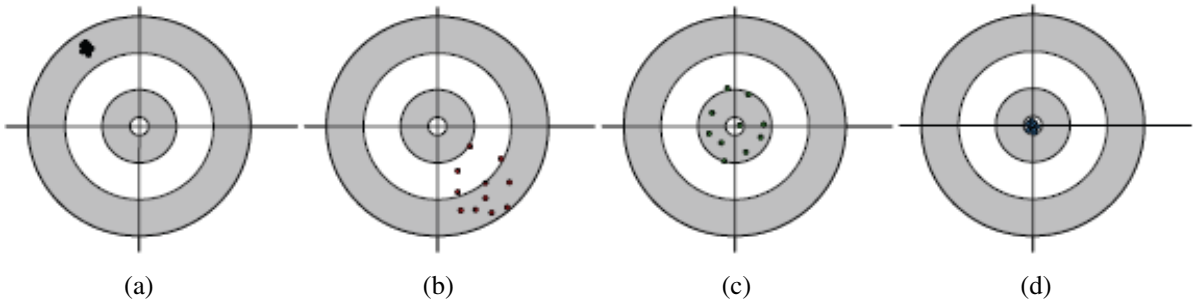


Figure 2. Illustration of accuracy and precision: (a) inaccurate but precise; (b) inaccurate and imprecise; (c) accurate but imprecise; and (d) precise and accurate (from the IPCC 2006 guidelines, chapter 3—Uncertainties).

REDD estimate, an overview of general statistical concepts (section 4.1) and a short analysis of likely uncertainties in the REDD context (section 4.2) are presented.

4.1. Uncertainty, accuracy and precision

The total uncertainty on a variable—i.e. the lack of knowledge of its true value—may be caused by both *random errors*[4], which affect precision, and *systematic errors* (or biases), which affect accuracy. Figure 2 illustrates the concepts of precision and accuracy, which are totally independent.

Random errors typically arise due to a finite sample size of available data. By contrast, systematic errors can occur because of failure to capture all relevant processes involved (e.g., incomplete estimate), because the available data are not representative—in terms of spatial of temporal coverage—of the situation to be assessed, or because of instrument error. Systematic errors are typically more difficult to be quantified even if—as explained later—for some cases it is possible.

Given that emissions from deforestation are calculated as the amount of deforested areas multiplied by the carbon stock changes per unit of those areas—what IPCC calls 'activity data' (AD) and 'emission factor' (EF), respectively—both these two parameters need to be as accurate and precise as possible. Furthermore, as the total uncertainties of the emissions are calculated by combining the uncertainties of both the AD and EF (IPCC 2006), these two parameters should, ideally, be assessed for both random and systematic errors.

Another important concept is the *uncertainty of the trend* (IPCC 2006). Trend refers to the change in emissions or removals. For example, if the emissions in the reference period are 10 Mt C and in the assessment period 15 Mt C, the trend in emissions is 5 Mt C, or 50%. Trend uncertainty reflects the uncertainty in this change, and is often described as percentage points. In example above, if the 95% confidence interval[5] (CI) of trend is from 40 to 60%, we can say that the trend is 50% with an uncertainty of ±10% points.

4.2. Uncertainties of activity data and emission factor

The analysis of available literature relevant for REDD suggests the following situation for the uncertainties of the AD and EF.

For AD estimated with remote sensing, random errors due to sampling[6] (assessable with standard statistical techniques) typically range from few per cent up to 20%, depending on sampling frequency, sample size and deforestation rates (e.g., Stach *et al* 2007, Duveiller *et al* 2008). On the other hand, systematic errors (e.g., due to interpretation of satellite images, assessable through *in situ* observations or by analyzing high-resolution aircraft or satellite data, Achard *et al* (2007)) of 5–20% are achievable for monitoring changes in forest cover with mid-resolution imagery when using only two classes, forest and non-forest (Desclee *et al* 2006, Duveiller *et al* 2008). Furthermore, with respect of systematic errors of the AD, it is useful to distinguish between 'omission' errors (actual deforestation that was not detected) and 'commission' errors (false detection of deforestation). Omission errors are more difficult to quantify because they require the verification analysis of a much larger area (i.e. the whole non-deforested area), while for commission errors only the area detected as deforested should be analyzed.

Assessing uncertainties in the EF is typically more challenging than for the AD, and accomplishing this task at national level inevitably means relying heavily on expert judgments, which are always subjective, at least to some extent. This is particularly true for tropical forests, characterized by a high degree of complexity and generally less intensively studied by the scientific community. Available estimates strongly vary, depending on forest type, on the degree of stratification and on the spatial scale analyzed (from plots to regions). From plot studies, for example, the uncertainty of the aboveground biomass (AGB)—expressed at the 95% confidence interval—is about 40% in central Panama (Chave *et al* 2004), or about 30% for primary forest and 20% for secondary forests in Colombia (Sierra *et al* 2007). However, this picture may differ when a different scale is analyzed. For

[4] Consistently with the IPCC 2006 guidelines, the following definitions were adopted in this paper: *Random error*: random variation above or below a mean value, usually quantified with respect to a mean value (but the mean could be accurate or not). *Systematic error* (or bias): lack of accuracy. *Precision*: agreement among repeated measurements of the same variable. Better precision means less random error. *Accuracy*: agreement between the true value and the average of repeated measured observations or estimates of a variable. An accurate measurement lacks bias.

[5] The *confidence interval* is a range that encloses the true (but unknown) value with a specified confidence (probability). For example, the 95% confidence interval has a 95% probability of enclosing the true value.

[6] If a wall-to-wall approach is used, no random error occurs. However, in this case systematic errors are often higher than the sampling approach due to the interpretation efforts to be spread over the whole territory.

example, Houghton *et al* (2001) compared estimates of forest biomass for the Brazilian Amazon, from seven methods based on spatial interpolations of direct measurements, relationships to climatic variables and remote sensing data. These seven estimates of AGB for Brazil's Amazonian forests vary from a low of 39 Gt C to a high of 93 Gt C, i.e. by more than a factor of two (Houghton *et al* 2001). Similarly, the possible values of AGB reported by IPCC for tropical ecological zones range are, on average, from −60% to +70% of the mean of each zone (IPCC 2006). When comparing these IPCC default values with plot measurements, (Pearson *et al* 2008) found differences up to 30–40%. Furthermore, at least other two important—and often unaccounted—systematic errors may further increase the uncertainty of the EF. The first is related to completeness: although preliminary estimates suggest that 15% and 25–30% of the all carbon losses by deforestation are due to losses from dead organic matter and soil, respectively (Freibauer 2007), these pools are often ignored when calculating the EF (e.g. FAO 2006, UNFCCC 2005a), because few or no data are available. The second potential source of systematic error is related to the representativity of AGB values. AGB values of the forests in the deforested areas may be significantly different than country or ecosystem averaged values. Houghton (2005) considered that accurate estimates of carbon flux require not average values over large regions, but the biomass of the forests actually deforested and logged. For example, it has been considered that the AGB of forests in Brazil's 'arc of deforestation' is lower than the AGB ecosystem average value (Eva *et al* 2003, Nogueira *et al* 2008)

Overall, although synthesizing the current information on total uncertainty of the AD and EF is extremely difficult—and beyond the scope of this paper—from the available literature it seems reasonable to assume that, for estimates of emissions from tropical deforestation at national level, the total uncertainty of the EF is higher than the uncertainty in the AD. This conclusion emerges also from analyses carried out for the LULUCF sector in Annex I countries (e.g., Ramirez *et al* 2006). Furthermore, whereas assessing separately random and systematic errors appears feasible for the AD, it is far more difficult for the EF: indeed, although some estimate in this direction can be derived from research plots (e.g. Chave *et al* 2004, Sierra *et al* 2007), making this distinction at national level risks being a rather subjective exercise.

4.3. Producing conservative estimates based on quantified uncertainties

Assuming that during the 'monitoring phase' the party carries out all the practical efforts to produce accurate and precise REDD estimates (i.e., to reduce uncertainties), as well as to quantify the uncertainties according to the IPCC guidance, here we suggest a simple approach to deal with at least part of the remaining uncertainties in the 'accounting phase', i.e. to reduce the risk of accounting an overestimated REDD value.

If the party has implemented standard statistical techniques to quantify uncertainties (due to both random and—when possible—systematic errors), these uncertainties may be easily expressed through a confidence interval. This interval allows assessing the risk of overestimating the 'true value': indeed, in a normal distribution, if one takes the mean value, there is an equal chance (50%) for overestimation and underestimation of the true value. Similarly to the adjustment procedure under Article 5.2 of the Kyoto Protocol (UNFCCC 2006a), we use the confidence interval as a simple way to be conservative, i.e. to decrease the probability of producing an error in the unwanted direction (i.e. overestimating the emissions in reference period or underestimating the emissions in the assessment period). For example, the selection of the lower bound of the 50% or 95% confidence interval of emissions in the reference period (i.e., correcting downward the original estimate) will limit the probability of overestimating the 'true' value of the emissions during the reference period to 25% or 2.5%, respectively (see figure 3). By contrast, to be conservative in the assessment period, the higher bound of the confidence interval (i.e., correcting upward the original estimate) should be taken.

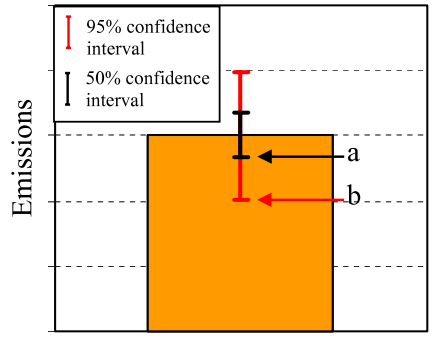


Figure 3. Example of the use of the confidence interval to deal with uncertainties in a conservative manner. By taking the lower bound of the 50% (a) or 95% (b) confidence interval of emissions (i.e., correcting downward the original estimate) means, respectively, having 25% or 2.5% probability of overestimating the 'true' value of the emissions.

In the following paragraphs the possible outcomes of this method are simulated by applying, to a wide range different scenarios, two different approaches to implement the conservativeness concept to quantified uncertainties.

4.3.1. Simulation of conservative estimates: methodology. First, we assumed a standard activity data for the reference period (deforestation rate of 1.0 M ha yr^{-1}, reduced in the assessment period according to the scenarios described below) and a standard emission factor (loss of 100 tC ha^{-1} per unit of deforested area, in both the reference and the assessment period).

Then, we considered all the nine combinations of the following *scenarios*:

- Three *levels of reduction of deforested area* (in the assessment period relative to the reference period): reduction of 10%, 30% and 50%.
- Three *levels of total uncertainty in input parameters* (i.e. due to both random and systematic errors, expressed in % and assessed at the 95% confidence interval): low, medium and high. As reported in table 1, these levels

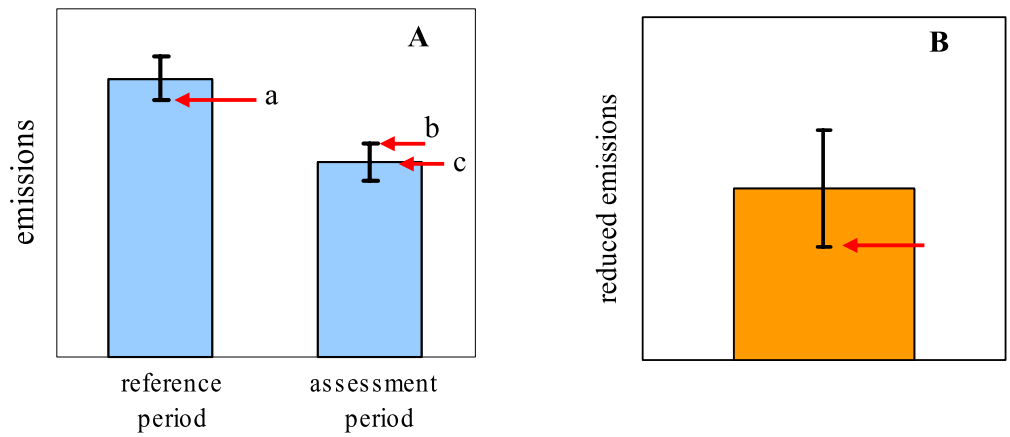


Figure 4. (A) With approach A, the conservative estimate of REDD is calculated based on the uncertainty of the reference period only (approach A1 = a − c) or based on the uncertainties of both the reference and the assessment period (approach A2 = a − b). (B) With approach B, the conservative estimate of REDD is derived from the uncertainty of the difference of emissions between the reference and the assessment period (uncertainty of the trend).

Table 1. Levels of total uncertainty in the input parameters (expressed in % and assessed at the 95% confidence interval) considered in the simulated scenarios.

Input parameter	Low	Medium	High
Activity data (AD)	5	15	30
Emission factor (EF)	10	30	60

range from 5% to 30% for AD and from 10% to 60% for the EF. Although the selection of these levels of uncertainties was done on the basis of the available literature and of expert judgment, these numbers should be regarded as purely exemplificative. Consistently with the conclusions reached in section 4.2, we assumed higher uncertainties for the emission factors than for the activity data at the national level.

Finally, we considered the following two *approaches* for producing conservative estimates of REDD in all the nine combinations of the above scenarios:

- *Approach (A)*: the conservative estimate of REDD is derived from the uncertainty of the reference period only (approach A1) or from the uncertainties of both the reference and the assessment period (approach A2). As illustrated in figure 4(A), approach A1 calculates the difference between the lower bound of the confidence interval (i.e., downward correction) of emissions in the reference period and the mean value of emissions in the assessment period; by contrast, approach A2 calculates the difference between the lower bound of the confidence interval (i.e., downward correction) of emissions in the reference period and the higher bound of the confidence interval (i.e., upward correction) of emissions in the assessment period. The approach A1, already mentioned by other authors for REDD (Ebeling and Yasuee 2008, Olander *et al* 2008), follows the concept of 'conservative baseline' prescribed for CDM projects (UNFCCC 2005b). Approach A2 follows the idea of the Reliable Minimum Estimate (IPCC 2003). Approach A2 seems more consistent over time, but the higher uncertainty of the reference historical period may also support the application of approach A1.
- *Approach (B)*: the conservative estimate of REDD is derived from the uncertainty of the difference of emissions between the reference and the assessment period (*uncertainty of the trend*, IPCC 2006), as illustrated in figure 4(B). From a conceptual point of view, this approach appears more appropriate than approach A for the REDD context, since the emission reduction (and the associated trend uncertainty) is more important that the absolute level of emissions in the reference and assessment period. A peculiarity of the uncertainty in the trend is that it is extremely dependent on whether uncertainties of inputs data (AD and EF) are correlated or not between the reference and the assessment period. For instance, if there is a systematic error in the emission factor, which is used both in the reference and the assessment period, both numbers may be equally overestimated or underestimated. In this case, the systematic error does not have an effect on the difference between reference and assessment periods, i.e. the trend. Therefore, if the uncertainty is correlated between periods it does not affect the percentage uncertainty of the trend. In uncertainty analyses of GHG inventories, no correlation is typically assumed for activity data in different years, whereas a perfect positive correlation between emission factors is assumed in different years. This is the basic assumption given by the IPCC (IPCC 2006), and is applied in the GHG inventory uncertainty analyses presented in the literature (Rypdal and Zhang 2000, Winiwarter and Rypdal 2001, Monni *et al* 2007). Although for the LULUCF sector of Annex I parties the picture may be somewhat more complex, C stock changes are often considered highly or fully correlated (e.g., Baggott *et al* 2005, Monni *et al* 2007).

Overall, we consider the basic IPCC assumption of full correlation of EF uncertainties between periods as broadly

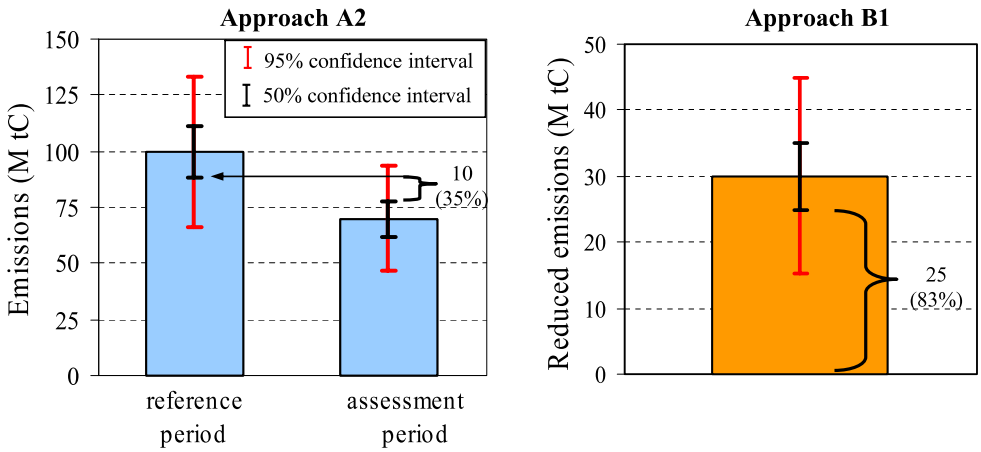


Figure 5. Application of approaches A2 (left panel) and B1 (right panel) to a scenario of 30% reduction of deforestation combined with a medium level of uncertainty in input parameters. Numbers next to curly brackets indicate the conservative REDD estimate assessed at the 50% confidence interval, also expressed as a percentage of the original non-conservative estimate. See the text and figures 3 and 4 for a detailed explanation of the approaches and the scenarios.

valid in the case of emissions from *deforestation*, primarily because, in most cases, no data on C stocks and C stock changes of past deforested areas exist in tropical countries. If some data exist, to be used for REDD they should have been collected consistently with IPCC guidance and with the methodologies applied in assessment period: an unlikely situation for most tropical countries. In other words, for each disaggregated reported level (e.g. tropical rain forest converted to cropland or to forest plantation), it is very likely that the same EF (or at least derived from the same data) will be used both in the reference and in the assessment periods. However, a different situation may occur for *forest degradation*: in this case, the correlation will ultimately depend on how emissions are calculated[7].

Although many different options exist regarding the correlation of input parameters, we explored two cases:

- Approach B1: basic IPCC assumption (*uncertainty of AD not correlated, uncertainty of EF fully correlated*), which we consider largely valid, at least for emissions from deforestation.
- Approach B2: the *uncertainties of AD and EF are both not correlated*

In all the cases illustrated above, the uncertainties were calculated using both methods suggested by the IPCC (2003), (2006): tier 1 (simple propagation of errors) and tier 2 (Monte Carlo simulations).

Furthermore, in all the simulated cases, the conservative estimates were assessed at both the 50% and the 95% confidence intervals. Whereas the latter represents the standard confidence interval suggested by the IPCC when performing the quantitative uncertainty assessment, the former is not used in standard statistical estimations. However, we decided to show also the 50% confidence interval (which means having a 25% probability of overestimating the 'true' REDD value) because it is used when adjustments are applied under Article 5.2 of the Kyoto Protocol. Obviously, the level of the confidence interval greatly affects the results of the simulations. The closer to 100% this level is, the higher is the credibility of the estimates (i.e. the lower is the risk of overestimating REDD), but also the higher is the risk to discourage the implementation of the REDD mechanism by developing countries (i.e. decreasing the amount of positive incentives). Given that determining the best balance of these two tendencies goes beyond the scope of this paper, we deliberately showed only what we consider to be two extremes.

4.3.2. Simulation of conservative estimates: results. Figure 5 illustrates two exemplificative results of the simulations, i.e. the application of the approaches A2 and B1 to a scenario of 30% reduction of deforestation combined with a medium level of uncertainty in input parameters, assessed at the 50% confidence interval.

Figure 6 shows the effect of all the different approaches in decreasing the original (non-conservative) estimate of reduced emission for all the scenario combinations. Expressing such an effect in percentages has the advantage that the results are not affected by the absolute level of input parameters (AD and EF). From these simulations it emerges that:

- By using approach A2, no or very limited reductions of emissions from deforestation could be conservatively demonstrated, unless a large a reduction of deforestation occurred and uncertainties are low (e.g., panel c) or unless the 50% confidence interval is considered (right panels). The situation somehow improves with approach A1.
- Assessing the conservativeness of REDD estimates on the basis of the uncertainty of the trend with approach B1 (uncertainty of EF correlated) determines the lowest reduction of the original non-conservative estimate as compared to all other approaches. In the situation of

[7] Whereas the assumption of full correlation of EF uncertainties may still be valid if the intact versus non-intact approach is used to estimate the degraded areas (Mollicone *et al* 2007a), no full correlation is likely to occur if emissions from degradation are estimated from changes of C stock in the 'forest land remaining forest land' subcategory measured independently in the two periods.

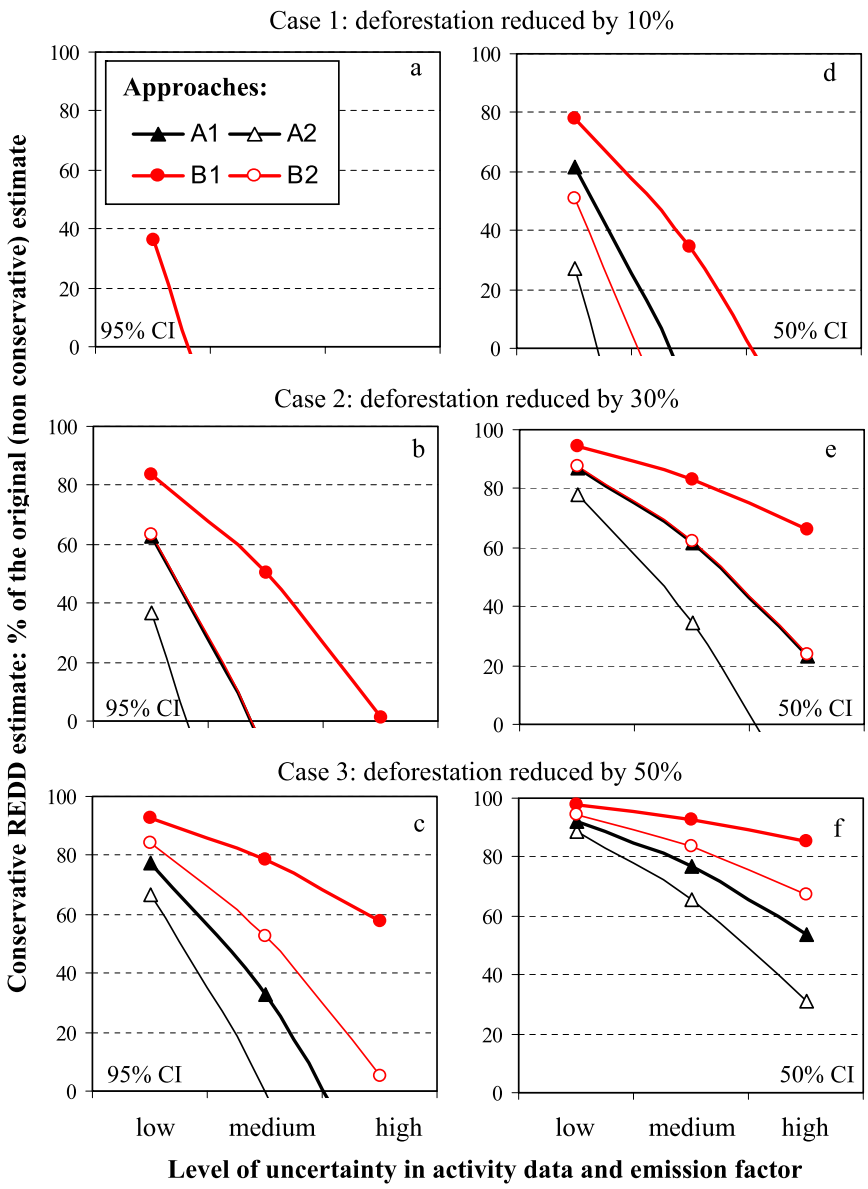


Figure 6. Effect of the different approaches (A1, A2, B1 and B2) on determining a conservative REDD estimate in decreasing the original estimate (100% means that the approach does not decrease the original, non-conservative, estimate of reduced emission). Conservative estimates were assessed at the confidence interval of 95% (left panels, (a)–(c)) and 50% (right panels, (d)–(f)). All the combinations of the following scenarios were considered. Reduction of deforested area: 10% (case 1), 30% (case 2), 50% (case 3); level of uncertainty in input parameters (activity data, AD, and emission factor, EF): low: 5% for AD and 10% for EF; medium: 15% AD and 30% EF; high: 30% AD and 60% EF. See the text and figures 3 and 4 for a detailed explanation of the approaches and of the scenarios.

no correlation (B2), the resulting conservative REDD estimates decrease to a level comparable to approach A1 with a medium level of reduction of deforestation, but remain higher than A1 with a higher reduction of deforestation. In our view, however, approach B2 is more consistent and defensible than approach A1.

The main difference of approach B1 relative to the other approaches is due to the fact that the uncertainty of the EF is irrelevant for the percentage uncertainty of the trend. Thus, this difference increases with increasing uncertainty of the EF, but it is also evident assuming lower uncertainty of the EF, i.e. similar to the uncertainty of the AD (data not shown). However, it should be noted that the fact that the uncertainty of the EF is irrelevant for the percentage uncertainty of the trend does not undermine the importance of using an accurate EF: indeed, the absolute value of the EF will affect the absolute value of the REDD estimates, irrespective of its uncertainty. The correctness of the absolute value of the EF will be analyzed during the review phase, by independent experts.

Using approach B1 (very likely applicable for the emissions from deforestation) has several important consequences: firstly, it allows obtaining REDD values which are robust and politically defensible (i.e., more credible because conservative) even when large uncertainties exist in the EF, which is a likely situation in most tropical countries. Secondly, the uncertainty of AD becomes very important, and reducing it—i.e. through

an intensification of sampling or higher-resolution satellite images—would mean increasing the conservative estimates of reduced emissions, thus allowing a claim for more incentives.

Whereas all the above results were obtained with the tier 1 method for combining uncertainties, the results were checked by using Monte Carlo simulation. The simulation provided qualitatively similar results, which means that the methods were applied in an appropriate manner. However, the larger the uncertainties, the larger the deviation in results of the two methods. Also, in the cases with non-existing correlations, the differences were larger. This is due to the fact that the normality assumption used in the IPCC tier 1 method does not hold for larger uncertainties. This deficiency is noted also in the IPCC guidelines, but the tier 1 method is still largely used.

5. Discussion

This paper does not introduce new methodologies or principles for estimating, reporting and reviewing. Instead, we propose to extend the application of already existing UNFCCC principles (conservativeness) and IPCC methodologies (uncertainty analysis). As the implementation of the conservativeness principles to address incomplete estimates in the monitoring context (section 3) seems rather straightforward, in the discussion below we will mainly focus on the most innovative aspect of our proposal, i.e. on the determination of conservative estimates based on the quantified uncertainties (section 4).

5.1. Widening the scope of uncertainty analysis

An important aspect of our proposal is that it considerably widens the current scope of uncertainty analysis: indeed, from the actual 'information mean' to help prioritize future efforts to improve the inventory (IPCC 2003, 2006), it may become a concrete tool to be potentially applied in the accounting context. Recently, the suggestion to consider explicitly the uncertainty of emission estimates for compliance purposes has been raised by many representatives of the scientific community (e.g., see IIASA 2007, Lieberman *et al* 2007, and references therein). However, those studies which attempted to link the party-specific uncertainty analysis of GHG inventories with a practical political implication (e.g., Gillenwater *et al* 2007) concluded that current quantitative uncertainty analyses at the national level do not yet have the necessary characteristics to be used for accounting and compliance purposes. The main reason for such conclusions stems from the subjectivity of most uncertain analyses, which thus do not meet the requirements of comparability across countries and would be hardly reviewable and verifiable (Gillenwater *et al* 2007). In other words, the uncertainty analysis is often uncertain itself.

Does the REDD context suffer from the same limitations? In other words, which sources of uncertainty are realistically and objectively estimable and reviewable in the REDD context?

Estimating the uncertainty of the EF in REDD is very difficult and, often, at least in part, subjective. In this respect, approach B1 may be more appropriate, because there is no need to estimate the uncertainty of the EF accurately: indeed, the conservativeness of the REDD estimate is assessed only based on the uncertainty of the AD, which is more objectively estimable. As explained in section 4.2, assessing the uncertainty of the AD is straightforward for random error and will be feasible for systematic error at least during the assessment period. Accuracy assessments of land and forest cover change have been demonstrated and, although no uniform methods exist yet, they can be realistically developed by the technical community (Herold and Johns 2007). In this regard, current IPCC guidance could be complemented with some additional guidance, including a standardization of the approaches for assessing accuracy, in order to decrease the level of subjectivity in uncertainty estimates and increase the comparability among parties. For the reference period the feasibility of accuracy assessment depends upon the availability of historical data, and in this regard the period 1990–2000 is more challenging than 2000–2005 as there are more reference data for more recent periods. If no robust reference data are available, a minimum requirement should be to apply a consistency assessment, i.e. the reinterpretation of a sample of the original data in an independent manner by external experts (Achard *et al* 2007). Furthermore, as already pointed out, in the REDD context not all the systematic errors of the AD need to be objectively quantified: indeed, the quantification of omission errors (which are more difficult to quantify, because they require the verification analysis of a much larger area, i.e. the whole non-deforested area) is essential only for the assessment period; by contrast, the estimation of commission errors is essential for the reference period, but it represents less work because only the area detected as deforested should be analyzed.

Thus, we believe that in the REDD context at least *some* of the uncertainties (i.e., those of the AD for calculating emissions from deforestation) can be objectively estimated and used for correcting the REDD estimates conservatively. Using trend uncertainty—and if correlation of EF uncertainties is assumed (a very likely situation for the emissions from deforestation)—the AD uncertainties quantified by the party represent 'the' relevant uncertainties. Although the situation for the emissions from forest degradation may be more difficult (e.g. it is possible that approach B1—assuming correlation of EF uncertainties between periods—cannot be applied), we believe that the principle of conservativeness will also be useful in this context. However, the specific application of this principle to emissions from forest degradation need to be analyzed in detail and this will deserve another paper.

Given the importance of the party's own estimate of uncertainty for the calculation of the conservative REDD estimate, it is clear that such estimates need to be reviewed in depth by independent experts. Provided that sufficient guidance is given, this task appears realistic for those uncertainties quantified consistently with IPCC guidelines.

Furthermore, it should be considered that, in case the party is not able to estimate uncertainties consistently with IPCC guidelines, default uncertainties may also be used. In this regard, the uncertainties already used for the adjustment under Article 5.2 of the Kyoto Protocol—provided by the IPCC

or experts and tabulated for each subcategory, pool and gas (UNFCCC 2005b)—represent a relevant precedent.

Our proposal of conservatively correcting the REDD estimates based on the quantified uncertainties may be applied by the party itself or by the independent expert review team that corrects the estimates based on the estimated (and reviewed) uncertainty estimates or on tabulated default uncertainty values.

In any case, during the review the reported EF and AD are analyzed for the adherence of the methodology used to IPCC guidelines and to the UNFCCC's principles of transparency, completeness, consistency, comparability and accuracy for GHG inventories. At this stage, it should be carefully evaluated if the absolute value of the EF used has been appropriately estimated (irrespective of its uncertainty), and also if the uncertainty analysis (used to calculate the conservative REDD estimate) has been conducted in accordance with IPCC guidelines. If during the review it is seen that the methodology used to estimate the EF or AD is not consistent with recommended guidelines by the IPCC, or is not documented in an adequate and transparent way, and may produce overestimated REDD estimates, the problem could be addressed by applying a default factor multiplied by a conservative factor (see section 2).

5.2. Conservativeness as a win–win option

We believe that our proposal to address potentially incomplete and highly uncertain REDD estimates through the conservativeness principles has the following advantages.

- *It increases the robustness, the environmental integrity and the credibility of any REDD mechanism*. By decreasing the risk that economic incentives are given to undemonstrated reductions of emission, the credibility of any REDD mechanism becomes less constrained by the level of accuracy of the estimates. This should help in convincing policymakers, investors and NGOs in industrialized countries that a robust and credible accounting of REDD estimates is possible.
- *It rewards the quality of the estimates*. Indeed, more accurate/precise estimates of deforestation, or a more complete coverage of the C pool (e.g., including soil), will likely translate into higher REDD estimates, thus allowing claims for more incentives. Thus, if an REDD mechanism starts with conservativeness, precision and accuracy will likely follow.
- *It allows flexible monitoring requirements*: since the quality of the estimates is rewarded, there could be envisaged a system in which—provided that conservativeness is satisfied—parties are allowed to choose themselves what pool to estimate and at which level of accuracy/precision, depending on their own cost–benefit analysis and national circumstances.
- *It stimulates a broader participation*, i.e. allows developing countries to join the REDD mechanism even if they cannot provide accurate/precise estimates for all carbon pools or key categories, and thus decreases the risk of emission displacement from one country to another.
- *It increases the comparability of estimates across countries*—a fundamental UNFCCC reporting principle—and also the fairness of the distribution of eventual positive incentives.

Critical aspects of our proposal include:

- A small and very uncertain reduction of deforestation may receive little or no positive incentives. Although this possibility exists, it largely depends on the confidence interval used (see the end of section 4.3.1), which ultimately is a political decision.
- Although the current uncertainties of the LULUCF sector of Annex I parties are likely to be lower that those of most developing countries, they are still considerable. If a conservative treatment of the uncertainties will be adopted in the REDD context, for consistency reasons it should be applied in a similar manner also to the LULUCF sector of Annex I countries. We think that a generalized application of the conservative treatment of the uncertainties—irrespective of their absolute level—would help to increase the credibility of any reduced emission or increased removal from the land-use sector.

6. Conclusions

This paper shows how the conservativeness principle may be applied in a monitoring context—to address incomplete estimates—and in an accounting context—to address uncertain estimates.

Regarding the potential incompleteness of REDD estimates, an omission of a pool (e.g. soil) should be allowed if adequate documentation is provided that this produces a conservative estimate of REDD (section 3).

Regarding uncertainties, we suggest a series of possible approaches to address the quantified uncertainties in a conservative manner (section 4). To this aim, either uncertainties quantified by the party (if available and estimated consistently with IPCC guidelines) or default uncertainties provided by the IPCC for each subcategory, pool and gas (similarly to those already used for the adjustment under Article 5.2 of the Kyoto Protocol) may be used for a conservative accounting of REDD estimates.

The results of our simulations, with different approaches and scenarios, suggest assessing the conservativeness based on the *uncertainty of the trend*. In any case, our proposal should be regarded not as a punitive correction of uncertain estimates, but rather as an *opportunity to increase the credibility of any REDD mechanism*, despite high uncertainties of input data. In addition, we believe that our proposal may have several other important advantages, including encouraging the improvement of the inventory, allowing flexible monitoring requirements, stimulating a broader participation and increasing the comparability of estimates across countries (see section 5.2).

In conclusion, we believe that an appropriate implementation of the conservativeness principle may help in setting up a practicable, robust and credible REDD mechanism.

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References

Achard F, DeFries R, Eva H, Hansen M, Mayaux P and Stibig H-J 2007 Pan-tropical monitoring of deforestation *Environ. Res. Lett.* **2** 045022

Baggott S L, Brown L, Milne R, Murrells T, Passant N, Thistlethwaite G and Watterson J 2005 UK greenhouse gas inventory 1990 to 2003 *Annual Report for Submission Under the UNFCCC* (Didcot: AEA Technology)

Chave J, Condit R, Aguilar S, Hernandez A, Lao S and Perez R 2004 Error propagation and scaling for tropical forest biomass estimates *Phil. Trans. R. Soc.* B **359** 409–20

Desclèe B, Bogaert P and Defourny P 2006 Forest change detection by statistical object-based method *Remote Sens. Environ.* **102** 1–11

Duveiller G, Defourny P, Desclèe B and Mayaux P 2008 Deforestation in central Africa: estimates at regional, national and landscape levels by advanced processing of systematically-distributed Landsat extracts *Remote Sens. Environ.* **112** 1969–81

Ebeling J and Yasueé M 2008 Generating carbon finance through avoided deforestation and its potential to create climatic, conservation and human development benefits *Phil. Trans. R. Soc.* B **363** 1917–24

Eva H D, Achard F, Stibig H-J and Mayaux P 2003 Response to comment on 'determination of deforestation rates of the world's humid tropical forests' *Science* **299** 1015

FAO 2006 Global forest assessment 2005 *FAO Forestry Paper 147* (Rome: Food and Agriculture Organization of the UN)

Freibauer A 2007 Soil carbon losses by deforestation in the tropics *SBSTA 27 side-event REDD: Steps Towards a Mitigation Mechanism* http://regserver.unfccc.int/seors/file_storage/ky73p7waapir8rj.pdf

Gibbs H *et al* 2007 Monitoring and estimating tropical forest carbon stocks: making REDD a reality *Environ. Res. Lett.* **2** 045023

Gillenwater M, Sussman F and Cohen J 2007 Practical policy applications of uncertainty analysis for national greenhouse gas inventories *Water, Air Soil Pollut.: Focus* **7** 451–74

Grassi G 2007 RED estimates: do we need accuracy or conservativeness? *SBSTA 26 side-event Enhancing participation in REDD (Bonn, Germany)* http://unfccc.meta-fusion.com/kongresse/SB26/templ/ovw_str_sbi_SB26.php?id_kongressmain=26

Greenpeace 2007 *Tropical Deforestation Emission Reduction Mechanism (TDERM): A Discussion Paper* http://www.greenpeace.org.uk/files/pdfs/forests/tderm-funding-mechanism.pdf

Herold M and Johns T 2007 Linking requirements with capabilities for deforestation monitoring in the context of the UNFCCC-REDD process *Environ. Res. Lett.* **2** 045025

Houghton R A 2005 Aboveground forest biomass and the global carbon balance *Glob. Change Biol.* **11** 945–58

Houghton R A *et al* 2001 The spatial distribution of forest biomass in the Brazilian Amazon: a comparison of estimates *Glob. Change Biol.* **7** 731–46

IIASA 2007 Uncertainty in greenhouse gas inventories. Policy brief http://www.iiasa.ac.at/Publications/policy-briefs/pb01-web.pdf

IPCC 2003 Good practice guidance for land use, land-use change and forestry *IPCC National GHG Inventories Programme* ed J Penman *et al* (Japan: IGES)

IPCC 2006 IPCC guidelines for national GHG inventories *IPCC National GHG Inventories Programme* ed H S Eggleston, L Buendia, K Miwa, T Ngara and K Tanabe (Japan: IGES)

Lieberman D, Jonas M, Nahorski Z and Nilsson S (ed) 2007 *Accounting for Climate Change: Uncertainty in Greenhouse Gas Inventories—Verification, Compliance, and Trading* (New York: Springer) p 162 (ISBN: 978-1-4020-5929-2)

Mollicone D, Achard F, Federici S, Eva H, Grassi G, Belward A, Raes F, Seufert G, Matteucci G and Schulze E-D 2007a An incentive accounting mechanism for reducing emissions from conversion of intact and non-intact forests *Clim. Change* **83** 477–93

Mollicone D, Freibauer A, Schulze E-D, Braatz S, Grassi G and Federici S 2007b Elements for the expected mechanisms on reduced emissions from deforestation and degradation (REDD) under UNFCCC *Environ. Res. Lett.* **2** 045024

Monni S, Peltoniemi M, Palosuo T, Lehtonen A, Mäkipää R and Savolainen I 2007 Uncertainty of forest carbon stock changes—implications to the total uncertainty of GHG inventory of Finland *Clim. Change* **81** 391–413

Nogueira E M, Nelson B W, Fearnside P M, Franca M B and Alves de Oliveira A C 2008 Tree height in Brazil's 'arc of deforestation': shorter trees in south and southwest Amazonia imply lower biomass *Forest Ecol. Manag.* **255** 2963–72

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

Pearson T, Harris N, Shoch D, Pandey D and Brown S 2008 *A Sourcebook of Methods and Procedures for Monitoring, Measuring and Reporting GOFC-GOLD* (Alberta, Canada: GOFC-GOLD Project Office) chapter 4 (Estimation of Carbon Stocks) http://www.gofc-gold.uni-jena.de/redd/index.php

Ramirez C A, de Keizer C and van der Sluijs J 2006 Monte Carlo analysis of uncertainties in the Netherlands greenhouse gas emission inventory for 1990–2004 *Report NWS-E-2006-58* (The Netherlands: Copernicus Institute, Utrecht University)

Rypdal K and Zhang L C 2000 Uncertainties in the Norwegian greenhouse gas emission inventory *Report 2000/13, Statistics Norway* (Norway: Oslo-Kongsvinger)

Sierra C A *et al* 2007 Total carbon stocks in a tropical forest landscape of the Porce region, Colômbia *Forest Ecol. Manag.* **243** 299–309

Stach N, Salvado A, Petit M, Ingrassia F, Joubert P and Deshayes M 2007 Monitoring land use and land use changes in French Guiana by optical remote sensing *Forestsat 2007: Forests and Remote Sensing: Methods and Operational Tools (Montpellier, Nov. 2007)* Cemagref-France, Maison de la télédétection

UNFCCC 2005a Sixth compilation and synthesis of initial national communications from Parties not included in Annex I to the Convention *FCCC/SBI/2005/18/Add.2*

UNFCCC 2005b Background documentation on the conservativeness factors for the completion of the technical guidance on adjustments *Working Paper No. 2*

UNFCCC 2006a Good practice guidance and adjustments under Article 5, paragraph 2, of the Kyoto Protocol *FCCC/KP/CMP/2005/8/Add.3 Decision 20/CMP.1*

UNFCCC 2006b Modalities and procedures for afforestation and reforestation project activities under the clean development mechanism in the first commitment period of the Kyoto Protocol *Decision 5/CMP.1*

UNFCCC 2007a Reducing emissions from deforestation in developing countries: approaches to stimulate action *Decision 2/CP.13*

UNFCCC 2007b Views on issues related to further steps under the convention related to reducing emissions from deforestation in developing countries: approaches to stimulate action submissions from parties http://unfccc.int/resource/docs/2007/sbsta/eng/misc14.pdf

UNFCCC 2008 Reducing emissions from deforestation in developing countries: approaches to stimulate action *FCCC/SBSTA/2008/L.12* http://unfccc.int/resource/docs/2008/sbsta/eng/l12.pdf

Winiwarter W and Rypdal K 2001 Assessing the uncertainty associated with a national greenhouse gas emission inventory: a case study for Austria *Atmos. Environ.* **35** 5425–40