A review of methods to measure and monitor historical carbon emissions from forest degradation

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In the absence of historical field data, developing countries can rely on consistent current ground data and remote sensing assessments.

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Disturbances that lead to forest degradation have been estimated to affect roughly 100 million hectares (ha) of forest globally per year (FAO, 2006, in Nabuurs *et al*., 2007). With respect to mitigation of climate change, forest degradation refers to a loss of carbon stock within forests that remain forests (IPCC, 2003a; UNFCCC, 2008). Degradation, therefore, implies that measured forest variables, such as canopy cover, remain above the threshold for the definition of forest. It is distinct from deforestation, which is commonly associated with a land-use change.

In 2005, the eleventh session of the Conference of Parties (COP-11) to the United Nations Framework Convention on Climate Change (UNFCCC) highlighted the role of reducing deforestation and forest degradation as tools to mitigate climate change (Reducing Emissions from Deforestation and Forest Degradation – REDD). The Conference reinforced Article 2 of the Kyoto Protocol regarding the protection and enhancement of sinks and reservoirs of greenhouse gases not controlled by the Montreal Protocol.

Developing country Parties to UNFCCC have been encouraged to take certain guidance into account when engaging in REDD and REDD+ activities (UNFCCC, 2009a), in particular, those related to establishing national forest monitoring systems. These systems need to use an appropriate combination of remote sensing and ground-based approaches to forest carbon inventory to estimate anthropogenic emissions of greenhouse gas by sources, removals by sinks, forest carbon stocks and forest area changes. All estimates should be transparent, consistent and as accurate as possible, and uncertainties should be reduced, as far as national capabilities and capacities permit.

Measuring forest degradation and related forest carbon stock changes is more complicated and more costly than measuring deforestation. Countries can measure current rates of degradation through field data and/or remote sensing data; a combination of the two types of data provides the strongest estimates. However, developing countries frequently lack consistent historical field data. Therefore, in assessing historical degradation, they are forced to rely strongly on remote sensing approaches mixed with current field assessments of carbon stock changes.

This article aims to support developing countries in the implementation of REDD+ activities by providing an overview and review of methods to measure and monitor carbon emissions from forest degradation. It focuses on historical periods in order to provide insight into the historical reference for degradation under REDD+ activities (UNFCCC, 2009b).

ESTIMATING EMISSIONS FROM FOREST DEGRADATION

IPCC Good Practice Guidance

Under the UNFCCC, countries are encouraged to use the Intergovernmental Panel on Climate Change (IPCC) *Good Practice Guidance for Land Use, Land-Use Change and Forestry* (Good Practice Guidance) as a basis for reporting greenhouse gas emissions from deforestation and forest degradation (IPCC,

Carbon pools defined in the Good Practice Guidance

The IPCC (2003b) defines five carbon pools to be measured and monitored: aboveground biomass, belowground biomass, litter, dead wood and soil organic carbon. Key source categories should be assessed and selected. A key source category is "an emission or sink category that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both". Key source categories should be estimated using higher tiers (Box, below), if sufficient resources are available. In the tropics, the most generalized approach is to monitor only aboveground biomass, even though soil carbon stocks in peatlands also require attention because they can contain more carbon stock than aboveground biomass.

2003b; 2006). To estimate the emissions associated with forest degradation, countries should consider:

- Areas of forest that remains forest affected by degradation, considered at the national level, ideally stratified into different disturbance or degradation types. Statistics calculated through forest inventories or through remote sensing can be used to quantify how much forest area is undergoing degradation changes, and where. Such data are referred to as *activity data*.
- Changes in forest carbon stocks that result from degradation processes, per area and time units. The carbon lost from forests and released to the atmosphere through the degradation process is commonly measured through forest field sampling and repeated forest inventories. Changes should be calculated for each of five forest carbon pools (Box, above). Measurements are reported in tonnes of carbon produced per ha per year (Mg C ha^{-1} yr^{-1}). These data are referred to as *emission factors*. (IPCC, 2003b; 2006)

The national emissions from forest degradation result from combining activity data and emission factors for each forest and degradation type, as indicated in the IPCC methodology.

The Good Practice Guidance provides the level of complexity and certainty of different reporting approaches under the UNFCCC, in terms of tiers. The higher the tier, the lower the level of uncertainty associated with the data, and therefore the better the accuracy (Box, below).

Challenges and considerations

There is not one method to monitor forest degradation. The choice of method, or a combination of methods, depends on a number of factors, including the type of degradation, available data, capacities and resources. Additionally, the potential, and limitations, of various approaches to measurement and monitoring should be considered. Challenges associated with the different methods are diverse:

- *Temporal thresholds and spatial scales*. The effect of forest degradation on forest carbon stocks depends on time. Temporal thresholds for each forest type should be established to avoid combining the effects of short-term reductions in carbon stock with the effects of long-term reductions. Sustainable forest management practices, for example, can cause temporary changes to carbon stocks that do not lead to degradation, while unsustainable practices can lead to forest degradation in the long term.
- *Integration of field and satellite data sets*. Monitoring changes in carbon stocks resulting from forest degradation relies heavily on field surveys. However, data benefit from integrating remotely sensed data with site-specific biophysical field attributes. Key issues to consider are which biophysical parameters should be measured and which time thresholds would be appropriate for relating the two approaches.

Good Practice Guidance tiers for estimates of emissions

IPCC (2003b) provides three tiers to categorize methods to estimate emissions. The higher the tier number, the more rigorous the requirements for the data, and the more complex the analysis performed. Hence, the higher the tier number, the more accurate the estimate.

- **Tier 1 uses default values for forest biomass and forest biomass mean annual increment (MAI). They are obtained from the IPCC Emission Factor Data Base (EFDB) and correspond to broad continental forest types (e.g. African tropical rainforest). Tier 1 also uses simplified assumptions to calculate emissions.**
- **Tier 2 uses country-specific data (i.e. data collected within the national boundaries). Forest biomass is resolved at finer scales through the delineation of more detailed strata.**
- **Tier 3 uses actual inventories with repeated measures of permanent plots to measure changes in forest biomass directly. In addition, or instead, well-parameterized models may be used, in combination with plot data.**

A Tier 3 approach requires a long-term commitment of resources, and therefore generally involves establishing a permanent organization to house the monitoring programme.

- *Spatial impact and intensity*. Different activities causing forest degradation are often focused on specific areas within a country. Efforts to measure and monitor must track the most important activities and their impacts to use resources most efficiently (Herold and Skutsch, 2011).
- *Identification of key forest carbon pools affected by degradation*. Methods for calculating changes in carbon stocks vary for each relevant carbon pool (Box, page 17, top), as well as for emissions of non-CO_2 greenhouse gases including methane and nitrous oxide.

Measuring historical forest degradation involves further challenges. Historical degradation is important for quantifying a country's potential reduction in emissions. *Ex ante* estimations of forest degradation may be required to estimate the reference emissions level against which emission reductions will be calculated for a given period. In addition to the general considerations relating to methodology, challenges in assessing historical forest degradation include:

- *Lack of data*. Many countries, in particular those in tropical regions, lack historical data on forest degradation and its impact on forest carbon stocks. Historical data at a national level are often limited to archives of satellite images, while remote sensing, itself, has limitations pertaining to the detection of degradation.
- *Insufficient capacity*. While many developing countries have some level of experience monitoring commercial forestry activities and have maintained some data, human resources and other capacities are often not sufficient to implement a national survey to assess historical deforestation and forest degradation.
- *Temporal considerations*. There is currently no agreement regarding a temporal threshold associated with long-term carbon stock loss. Cumulative, long-term and gradual carbon stock losses can be measured using direct methods. For carbon losses that happen more rapidly, canopy closures impede field and satellite observations.
- *Integration of different data sources*. It is rare that data sets on historical forest degradation are available. Integrating remotely sensed data with site-specific biophysical field attributes from past assessments and other sources, such as forest management data, is challenging.
- *Inconsistencies when linking historical and present data sets and methodologies*. Different systems used to acquire data through different processes are often incompatible and require harmonization and consistency.

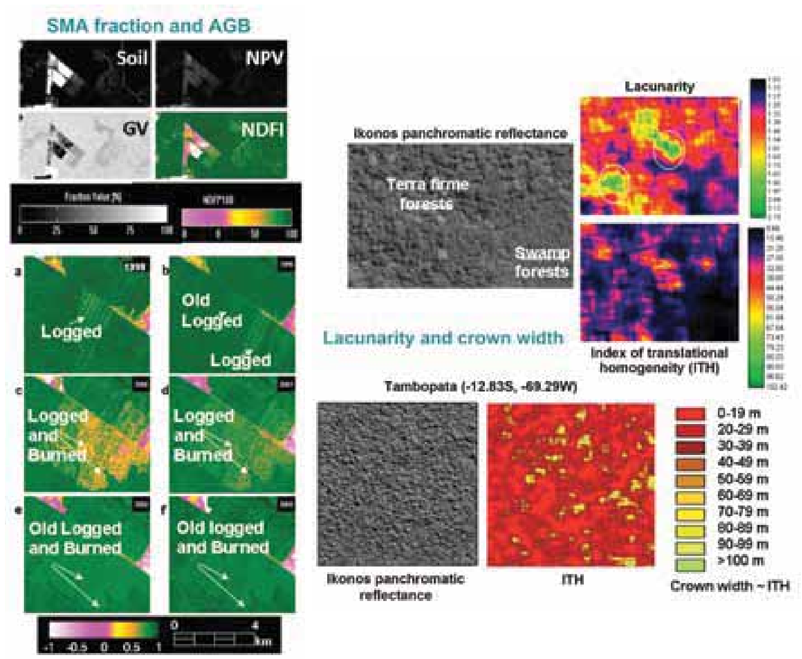
Approaches

Many developing countries have limited, or no, field data. Further, procedures for measuring carbon stock changes on a consistent basis have not been established – but they can be, given the following considerations. Historical emission factors can be derived by analysing present-day data on carbon stock losses that have resulted from similar degradation processes, and by studying and linking their chronosequences with available historical data, such as archived remote sensing images. For certain degradation activities, data might be collected from the records of companies that performed the activities. For example, records of wood volume extracted in selective logging activities could be considered.

In using such approaches to estimate historical emissions, it is important to take into account the uncertainties associated with the resulting estimates. One particular consideration is when country-specific data are used to estimate the change in carbon stocks per area and time units (e.g. through the tier 2 approach; see Box, page 17, bottom).

Selection of studies on methods used to measure forest degradation

Country	Remote sensing	Field data collection	Combination of both	Details on methodology	Source
Brazil			X	Relationship between spectral mixing analysis and aboveground biomass measured through forest transects	FAO (2009a)
Democratic Republic of the Congo	X			Field measuring of forest degradation using permanent plots	FAO (2009b)
Mexico		X		c. 25 000 1 ha plots established, of which 23 000 measured; 20 percent re-measured every year Forest disturbance: intact forest, secondary-tree dominated, secondary-shrub dominated	de Jong *et al.* (2010)
Mexico			X	Relationship between MODIS-derived normalized difference vegetation index values and areal biomass volume derived from the national forest inventory	FAO (2009c)
Nepal	X	X	X	Comparison of methodologies used in Nepal to measure degradation	FAO (2009d)



Sources: Left: Souza, Roberts and Cochrane, 2005. Right: Malhi and Román-Cuesta, 2008.
Note: GV is green vegetation fraction; NPV is nonphotosynthetic vegetation fraction; NDFI is normalized difference fraction index.

1
Examples of direct methods applied to measure forest degradation

Left: spectral mixing analysis (SMA) and estimations of aboveground biomass (AGB) used to follow the degradation dynamics of Amazonian lowland forests

Right: lacunarity analysis and the index of translational homogeneity (ITH) used to estimate crown widths in Amazonian forest landscapes. Further examples are available at claslite.ciw.edu

The estimation of country-specific values for a given parameter relies heavily on field sampling, which is frequently done through national forest inventories. However, the estimation of area affected by degradation might be performed more reliably through national wall-to-wall or sample-based remote sensing approaches (Table). Therefore, the use of remote sensing to support field data collection should be promoted, as should the use of field validation as ground truth for remote sensing.

Selected examples

Direct and indirect methods

There are two approaches to estimating forest degradation area through remote sensing, direct and indirect:

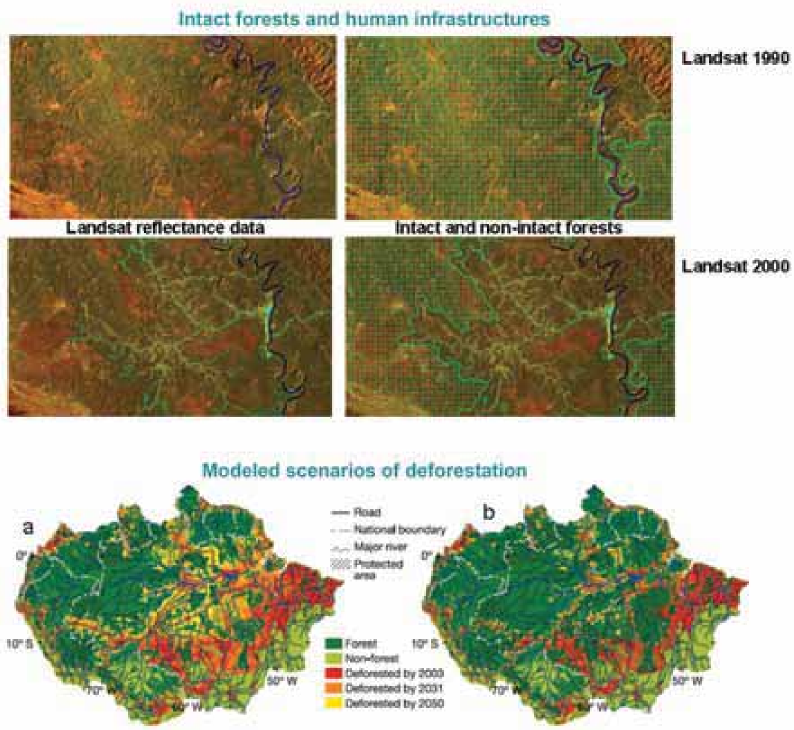
1. Direct detection of degradation processes and related area changes focuses on forest canopy damage. The features enhanced and extracted from the satellite imagery are forest canopy gaps, small clearings and the structural forest changes resulting from disturbance (Asner *et al.*, 2005; Souza, Roberts and Cochrane, 2005; Oliveira *et al.*, 2007).
2. Indirect approaches focus on the spatial distribution and evolution of human infrastructure (e.g. roads and population centres), which are used as proxies for newly degraded areas.

There are limiting factors when mapping forest degradation using direct methods. First, observations must be made frequently, such as annually or biannually, because the spatial signatures of degraded forests change when canopy gaps close. Second, not all degradation processes can be monitored with high certainty using remote sensing data. As a general rule, the more severe the degradation and the canopy damage, the easier it is to map it accurately, directly from satellite observations (Coops, Wulder and White, 2007). However, many local-scale activities that result in degradation, such as collection of fuelwood, affect only the understory and are undetectable through remote sensing analysis. Figure 1 presents two examples of direct methods.

Indirect methods prove useful when the intensity of degradation is low and the area to assess is large, when satellite imagery is not easily accessible or when the direct approach cannot be applied for any other reason. These methods work best to map newly degraded forest areas, but are less effective for repeated degradation.

One effective indirect approach is the "intact forest" approach. In this approach, the presence of human infrastructure is viewed as a proxy for degradation, and its absence is used to identify forest land without anthropogenic disturbance, or intact forest (Mollicone *et al.*, 2007; Potopov *et al.*, 2008). An intact forest is fully stocked, or any forest with tree cover between 10 and 100 percent that is undisturbed, i.e. without timber extraction. A non-intact forest is not fully stocked. Tree cover is higher than 10 percent, so that it qualifies as a forest under the Kyoto Protocol, but it is assumed that the forest has undergone timber exploitation and/or canopy degradation.

Another indirect method, which can be applied to estimate both future and historical forest degradation dynamics, is scenario modelling for forest degradation. Soares-Filho *et al.* (2006) published



Sources: Top: Mollicone *et al*., 2007. Bottom: Soares-Filho *et al*., 2006.

2
Examples of indirect methods applied to measure forest degradation

Top: estimation of intact and non-intact forests based on areas of influence (buffers) from human infrastructures. The example depicts the evolution of a forest landscape where new roads are built, reducing the total area of intact forests (green grid)

Bottom: future deforestation models for the Amazon Basin based on two possible scenarios: (a) business as usual; and (b) effective governance

an example of a "deforestation modelling" approach for the Amazon Basin that produced annual maps of simulated future deforestation under user-defined scenarios. With the right support from field data, a similar modelling approach could be used for (re)constructing historical and future scenarios of forest degradation. Figure 2 offers two examples of indirect methods to evaluate forest degradation.

Aerial photography

Aerial photography has played an important role in forest surveys (Caylor, 2000; Hall, 2003). It was the unique means to monitor canopy condition in detail until the launch, in 1999, of the first satellite to collect publicly available high-resolution imagery – IKONOS. Aerial photographs can provide information on structural changes of forest canopies over time that can be used to assess historical rates of forest degradation. The methods used to detect gaps through multi-temporal digital surface models (DSM) have been applied for long-term studies on canopy dynamics (Nakashizuka, Katsuki and Tanaka, 1995; Tanaka and Nakashizuka, 1997; Itaya, Miura and Yamamoto, 2004; Ticehurst, Phinn and Held, 2007). DSM derived from aerial photographs or light detection and ranging (LIDAR) data can also be used to estimate forest growth.

Collecting data on selective logging

ITTO (2006) estimates that 350 million ha of humid tropical forest are currently involved in timber production. The historical field data needed to assess the carbon impact of selective logging may be available from different sources:

- **data from targeted field surveys, including interviews, and from research and permanent sample plots (often implemented as local studies);**
- **data from commercial forestry, e.g. from logging concessions and harvest estimates, focused on related concession areas; and**
- **proxy data from domestic markets (charcoal, subsistence), such as timber production rates estimated from sawmill, sales and export statistics (Nepstad *et al.*, 1999).**

The use of (direct or indirect) satellite mapping of selective logging for estimating degradation at a national level is currently in an expansive research phase. Research started at the beginning of this century, with results steadily improving over time (Asner *et al.*, 2002; 2004; Souza *et al.*, 2003; Souza, Roberts and Cochrane, 2005). In the past few years, the first large-scale, high-resolution satellite maps of selective logging and degradation have been published for a large portion of the Brazilian Amazon (Asner *et al.*, 2005), throughout Africa (Laporte *et al.*, 2007), for parts of Oceania (Shearman *et al.*, 2008) and for other Amazonian countries (Oliveira *et al.*, 2007). Recently, a first global-scale direct mapping of selective logging in humid tropical forests has shown that logging activities strike deep into forest interiors, often far from deforestation fronts (Asner *et al.*, 2009).

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Road, stream and forest area, Indonesia. Aerial photographs can provide information on structural changes of forest canopies over time

The quality of estimates of historical rates of forest degradation benefits from further analysis of images, in particular assessing carbon stock changes of individual trees. Tree height and crown areas of individual trees can be estimated from aerial photographs or LIDAR data; allometric equations, which provide for extrapolations on the basis of few measurements, can help in the estimation of their carbon stocks. However, individual allometric equations relating tree height, diameter and biomass are frequently not available for the complex structure and species composition of tropical forests.

Two other methodologies to assess individual crown areas from aerial photographs are the valley-following method (Leckie *et al.*, 2003; 2004; Gougeon and Leckie, 2006), which involves following valleys of shade in a grey-level image, and the watershed method (Wang, Gong and Biging, 2004; Hirata, Sakai and Tsuboto, 2009), which views the gradient magnitude of an image as a topographic surface and creates boundaries, or "watershed lines", on the basis of the pixels of the greatest magnitude. The latter method can be useful for the identification of degradation at the canopy level.

Monitoring burning of biomass

Satellite systems have proved useful in detection and monitoring of fires for three primary purposes: identification of active fires, mapping of burned areas, post-fire (fire scars) and characterization of fires (e.g. fire severity, energy released). For the purposes of estimating emissions, the latter two uses are of particular relevance. Two main approaches – indirect and direct – have been identified (GOFC-GOLD, 2010):

1. A "bottom up", or indirect, method (Seiler and Crutzen, 1980):
   L = A × Mb × Cf × Gef,
   where the quantity of emitted gas or particulate L (g) is the product of the area affected by fire A (m^2), the fuel loading per unit area Mb ($g\ m^{-2}$), the combustion factor Cf, which is the proportion of biomass consumed as a result of fire ($g\ g^{-1}$), and the emission factor or emission ratio Gef, which is the amount of gas released for each gaseous species per unit of biomass load consumed by the fire ($g\ g^{-1}$). With this method, there is significant uncertainty associated with the area burned and the combustion factor. In particular, there is uncertainty associated with historical assessment of biomass burning events, where few data sets exist.
2. A direct method that measures the power emitted by actively burning fires and derives total biomass consumption. The radiative component of the energy released by burning vegetation can be remotely sensed at mid-infrared and thermal infrared wavelengths (Ichoku and Kaufman, 2005; Wooster *et al.*, 2005; Smith and Wooster, 2005). This instantaneous measure, the fire radiative power expressed in watts (W), has been shown to be related to the rate of consumption of biomass (g/s). Direct methods, however, have yet to transition from the research domain to operational application.

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Satellite data can be analysed to estimate emissions from burning of biomass

CONCLUSIONS

Measuring forest degradation and related forest carbon stock changes is more complicated and more costly than measuring deforestation. Measurements are based on observing changes in the structure of the forest that do not imply a change in land use – changes that are not necessarily easily detectable through remote sensing.

Measuring all carbon stock changes within a country that are caused by forest degradation, and at consistent levels of detail and accuracy, is not likely to be possible in the near future. Focusing efforts to monitor carbon stock changes on the most important categories of carbon pools and on specific areas within the country in which activities that degrade forests are concentrated can help both to make the monitoring more targeted and efficient and to capture the most important components with priority.

Countries need to assess both carbon stock changes (emission factors) and the total area undergoing degradation (activity data) for their monitoring to be in line with the IPCC Good Practice Guidance. Measurements would ideally be taken for different types of activities resulting in carbon stock changes in forests remaining forests, including fire, logging and fuelwood harvesting.

The assessment of changes in carbon stocks requires consistent ground data. The evaluation of the total area undergoing degradation, particularly for developing countries, is more reliably measured through remote sensing for the major degradation processes of selective logging and fire. Both current and historical assessments of forest degradation will need to collect data on emission factors and activity data consistently to estimate emissions from forest degradation. ◆

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