Executive Summary

Forests, and in particular tropical forests, play an important role in the global carbon budget because they can be either sources or sinks of atmospheric carbon. Annual emissions from land-use change (mainly through deforestation and degradation in tropical developing countries) account for approximately 20-25% of the total anthropogenic emissions of greenhouse gases, but estimates of the magnitude of these emissions are uncertain due to several reasons such as a lack of resources, lack of standard methods, lack of capacity at national levels, and lack of data.

There has been much progress in recent years in the acquisition of data and the developments of methods and tools for estimating and monitoring carbon emissions from tropical deforestation and degradation. Data and analytical methods for monitoring change in land cover/land use using remote sensing at a variety of scales and coverage – from wall-to-wall using coarse scale imagery to sampling "hot spots" of change using fine scale – is practically close to being operational on a routine basis. However, standard protocols need to be developed for using the remote sensing data, tools, and analytical methods that suit the variety of national conditions but yet meet acceptable levels of accuracy.

Well established methods and tools are also available for estimating carbon stocks of forests. However, these methods and tools require high investment for broad-scale national inventories. In particular, the carbon stocks of land cover around the world are poorly known and this aspect lags behind the remote sensing of forest and non-forest vegetation cover.

In general, deforestation and degradation are driven by interactions of many different causal factors that vary by region. Dominant underlying causes include economic factors and institutional policies that drive proximate causes of agricultural expansion, wood extraction and infrastructural extension.

The pertinent definitions based on UNFCCC decisions and on the IPCC reports are:

Forest = minimum crown cover (mCC) 10-30%
minimum tree height (mTH) 2-5m
minimum area (mA) 0.05-1ha
Deforestation = a measurable sustained decrease in crown cover from greater than the mCC to less than the mCC
Degradation = a measurable sustained decrease in crown cover with crown cover remaining greater than mCC

Several different satellites capture images at a range of spatial and temporal resolutions that can be used to detect changes in forest and vegetation cover. New technology such as radar and lidar sensors also offer promise in regions where optical sensors are problematic due to frequent cloud cover.

Currently, there are no widely accepted standard practices for measuring forest carbon stocks remotely at regional or national scales; carbon stocks are measured instead using traditional forest inventories or country-specific default data from the Food and Agriculture Organization of the United Nations (FAO). Dedication and investment are required to expand inventories of carbon stocks so that reliable carbon estimates can be applied to areas sensed as deforested or degraded in remote sensing imagery.

Accuracy assessment in remote sensing imagery analysis is achieved through ground-truth measurements, and accuracies up to 95% are achievable when using high resolution imagery. The accuracy and precision of ground-based carbon stock measurements depend, to a large degree, on the methods employed and the frequency of data collection. Measuring changes in carbon stocks involves a compromise between precision and investment; to assess variations in stored carbon, many samples are desired to increase precision, but this also increases the cost of the inventory.

Any programme to monitor the impact of deforestation and degradation on the global carbon balance depends upon accurate and precise estimates of emissions resulting from such land-use changes and how the emissions change over time. There are three principal aspects to this estimation:

1. Change in forest and vegetation cover;
2. Change in carbon stocks;
3. Estimation of emissions.

Combining the two aspects of estimation – measurements of changes in forest area and estimates of changes in carbon stocks – enables total estimation of emissions from deforestation and degradation over large regions. Both remote sensing and ground measurements play key roles in determining the loss of forest cover and changes in carbon stocks.

For most countries the only practicable approach for monitoring changes in forest and vegetation cover at the national scale is through the interpretation of remotely sensed imagery. Ideally a wall-to-wall coverage is conducted with high resolution, however, the costs of such analysis is likely to be very high, especially for countries with large areas of forests. Coarse scale imagery, population and land use databases and/or expert opinion can be used instead to site high resolution imagery analysis at the locations of deforestation/degradation.

Deforestation and degradation affect all land use carbon pools. To estimate these impacts, the aboveground living biomass should be monitored accurately and precisely and, where possible, other pools could be included through measurement, default values, or correlations with aboveground biomass. Consideration is needed as to the form of the land cover change and whether burning, decomposition and/or wood products will result. Local default parameters could be created to account for these factors.

Methods for estimation of emissions from areas with measurable deforestation and degradation are available in the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 1996) and the IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC 2003). Reliable and transparent results from application of these methods are often hampered by lack of data on both change in forest cover and, more critically, by change in carbon stocks.

I. Introduction

A. Mandate

1. The SBSTA, at its twenty-fourth session, decided that the workshop on reducing emissions from deforestation in developing countries should provide an opportunity for Parties to share experiences and consider relevant aspects relating to reducing emissions from deforestation in developing countries. The specific topics to be discussed in the workshop will include:

(a) Scientific, socio-economic, technical, and methodological issues, including the role of forests, in particular tropical forests, in the global carbon cycle; definitional issues, including those relating to links between deforestation and degradation; data availability and quality; scale; rates and drivers of deforestation; estimation of changes in carbon stocks and forest cover; and related uncertainties;

(b) Policy approaches and positive incentives to reduce emissions from deforestation in developing countries, including causes; short- and long-term effectiveness with respect to emission reductions; the displacement of emissions; bilateral and multilateral cooperation; activities of other relevant international bodies; enhancing sustainable forest management; capacity-building; and financial mechanisms and other alternatives – basing discussions on experiences and lessons learned;

(c) Identification of possible links between relevant scientific, socio-economic, technical and methodological issues and policy approaches and positive incentives that may arise from the consideration of the topics in subparagraphs (a) and (b) above.[1]

2. The SBSTA also requested the secretariat to prepare for the workshop a background paper on the items contained in 1 (a) and (b) above.[2] This background paper focuses on the scientific, socio-economic, technical and methodological issues related to deforestation in developing countries, including the topics in paragraph 1 (a) above.

B. Scope of the paper

3. This paper summarizes scientific, technical, methodological, and socio-economic issues related to greenhouse gas (GHG) emissions from deforestation and degradation in developing countries. Although the scope of this report focuses on deforestation, degradation processes are also included as these changes in land cover also emit GHGs to the atmosphere, and in some countries these changes in vegetation cover are as (or more) important than deforestation.

4. The report draws largely upon information summarized in the IPCC Special Report on Land Use, Land Use Change and Forestry (2000), IPCC Third Assessment Report WG-1 (2001), the IPCC Guidelines for National Greenhouse Gas Inventories (1996), Sections 3 and 4 of the IPCC Good Practice Guidance (2003), the 2005 FAO Forest Resources Assessment, Moutinho and Schwartzman (2005), and the recent report by Herold et al. (2006) of a workshop on monitoring tropical deforestation held under the auspices of Global Terrestrial Observing System's Panel on Global Observations of Forest and Land Cover Dynamics (GOFC-GOLD).

5. In section II, scientific, socio-economic, technical and methodological information is reviewed regarding the role of tropical forests in the global carbon cycle, the current definitions of forest, deforestation and degradation, and the availability and quality of currently available data. Rates, drivers, and estimates of carbon emissions from deforestation and degradation in the tropics, along with associated uncertainties, are also reviewed.

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[1] FCCC/SBSTA/2006/5, paragraphs 52 (a) to (c).

[2] FCCC/SBSTA/2006/5, para. 54.

6. Section III focuses on methodological aspects for estimating changes in carbon stocks and forest cover using a variety of data sources.

II. Scientific, socio-economic, technical and methodological issues

A. The role of forests in the global carbon cycle

7. In the global carbon cycle, carbon dioxide (CO_2) is exchanged between the atmosphere and terrestrial ecosystems through processes of photosynthesis, respiration, decomposition and changes in the use and cover of the land (Figure 1). The sources and magnitudes of the major drivers of the global carbon cycle have changed since the beginning of the last century, when the concentration of CO_2 in the atmosphere started to rise due to human-induced emissions from fossil fuel use and large-scale land use change (Schimel 1995). Changes in the function of either the terrestrial biosphere or the ocean could have significant effects on the fraction of CO_2 emissions that stays in the atmosphere.

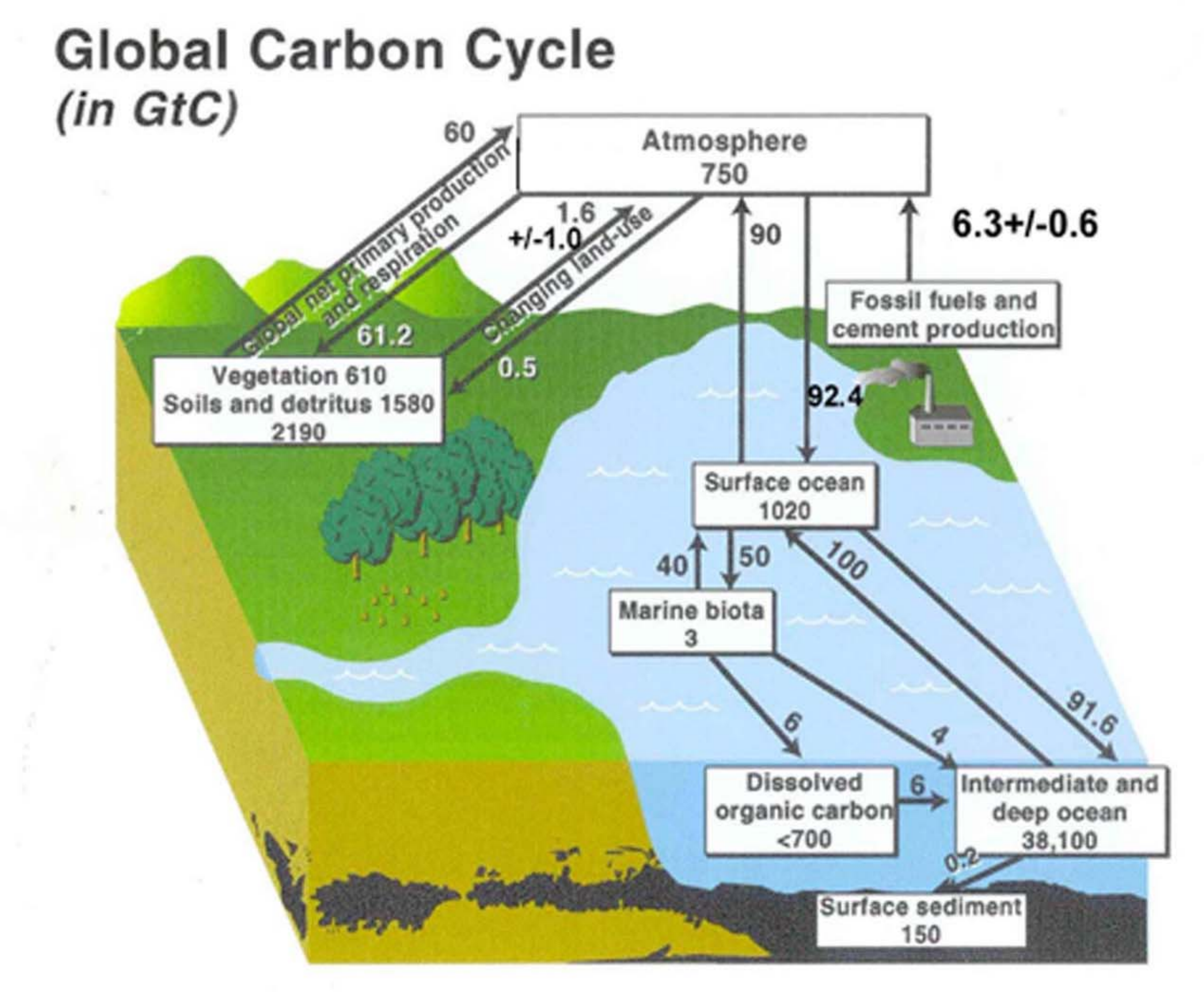

Figure 1. Magnitude of the main global fluxes of carbon (billion metric tons or gigatons [Gt] of carbon as CO_2) to and from the atmosphere in the 1990s (modified from Strategic Plan for the Climate Change Science Program, 2003 (see http://www.climatescience.gov/Library/stratplan2003/final/ccspstratplan2003-chap7.htm).

8. Forests account for almost half of the global terrestrial carbon pool, and if vegetation is considered alone (excluding soils), they hold about 75% of the living carbon. The total carbon content of forest ecosystems in 2005 was estimated at 638 Gt (FAO Forest Resources Assessment 2005). Changes in forest area and forest carbon density are intrinsically linked to carbon emissions and removals; the

landscape patterns seen today reflect long-term sources and sinks of carbon through changes in forest cover, regrowth, and soil organic matter accumulation.

1. The role of tropical forests in the global carbon cycle

9. Tropical forests play a particularly important role in the global carbon budget (Melillo et al. 1993; Dixon et al. 1994; Field et al. 1998) because they contain about as much carbon in their vegetation and soils as temperate-zone and boreal forests combined. Per unit area, tropical forests store on average about 50% more carbon than forests outside the tropics. These forests affect both inputs and outputs to the global carbon budget because they can be either sinks and remove CO_2 from the atmosphere through net primary productivity, regrowth of secondary forests, and long-term carbon storage, or sources of CO_2 and non-CO_2 GHG emissions to the atmosphere through the processes of deforestation, degradation, devegetation, and biomass burning. For example, forest vegetation of the Amazon region stores about 70 Gt of carbon —amounting to between 10 and 15% of global terrestrial biomass (Houghton et al. 2001) – but deforestation activities in this region also cause carbon to be released to the atmosphere, on the order of 7 Gt C for the period from 1970 to 1998 (Hirsch et al. 2004).

10. The permanent conversion of forested to non-forested areas in developing countries has had a significant impact on the accumulation of GHGs in the atmosphere (Achard et al. 2002; Houghton 2003b; Fearnside and Laurance 2004), as has forest degradation caused by high impact logging, shifting cultivation, wildfires, and forest fragmentation. If the emissions of methane (CH_4), nitrous oxide (N_2O), and other chemically reactive gases that result from subsequent uses of the land are considered in addition to CO_2 emissions, **annual emissions from** land**-use change during the 1990s accounted for about 20-25% of the total anthropogenic emissions of GHGs** (Houghton 2005a).

2. Estimates and uncertainties of carbon emissions from deforestation and degradation

11. Recent and independent assessments of the global carbon budget are in general agreement with respect to the fossil fuel and oceanic emissions and removals, and the increase in the atmosphere (Table 1). However they differ with respect to the magnitude of the land-atmosphere flux (a global sink caused mainly by increased carbon uptake in mid to high latitudes lands mostly from forest regrowth) and with respect to the magnitude of the uncertainty around the exchange due to land use change, caused mainly by deforestation and degradation of tropical forests.

Table 1. Comparison of the global carbon budget for the 1990s (in Gt C yr^{-1})

	IPCC TAR[a]	SR LULUCF[b]	House et al. 2003[c]	Schimel et al. (2001)[d]
Fossil fuel emissions	+6.4 ± 0.4	+6.3 ± 0.1	+6.3	+6.3 ± 0.4
Ocean-atmosphere flux	-1.7 ± 0.5	-2.3 ± 0.5	-2.1	-1.7 ± 0.5
Atmospheric increase	+3.2 ± 0.1	+3.3 ± 0.1	+3.2	+3.2 ± 0.1
Land-use change	NA	+1.6 ± 0.8	+1.4 to +3.0	+1.6 ± 0.8
Land-atmosphere flux	-1.4 ± 0.7	-0.7 ± 0.6	-1.0	-1.4 ± 0.7
Residual terrestrial sink	NA	-2.3 ± 1.3	-1.6 to -4.8	-2 to -4

[a] IPCC Third Assessment Report (TAR) (IPCC, 2001; Prentice et al. 2001 (Chapter 3); NA = not available

[b] IPCC Special Report on Land Use, Land-use Change and Forestry (SR LULUCF) (IPCC 2000; Bolin et al., 2000)

[c] House, JI, Prentice IC, Ramankutty N, Houghton RA, Heimann M (2003) Reconciling apparent inconsistencies in estimates of terrestrial CO_2 sources and sinks. Tellus 55B: 345-363.

[d] Schimel, D.S. et al. (2001). Recent patterns and mechanisms of carbon exchange by terrestrial ecosystems. Nature 414: 169-172.

12. While the release of CO_2 from fossil fuels, currently about 7.3 Gt C/yr (Marland et al. 2006), is one of the best-known values in the contemporary global carbon budget, the net emissions of carbon to the atmosphere from tropical land use change are the most uncertain as illustrated by the range of values in Tables 1 and 2. Both top-down (atmospheric) and bottom-up (forest inventory and land-use change) approaches have been used to calculate the sign and magnitude of a net terrestrial flux. Houghton (2003a) suggests that differences in estimates are not necessarily from uncertainties or errors, but from incomplete accounting inherent in some of the methods used.

13. The three estimates of carbon loss from tropical deforestation of Houghton, Fearnside, and Malhi & Grace differ slightly in their compilation methods and data usage, but total emissions among the three studies are in reasonable agreement despite the fact that the time period considered varies – the decade of the 1980s for Fearnside, the 1980s to early 1990s for Malhi and Grace, and the 1990s for Houghton (Table 2). Even though the total emissions are comparable, their distribution among the three continents differs. Moreover, the accuracy of these numbers rely heavily on the assumption that country-reported values of land use change and carbon stocks are accurate, which may or may not be the case. The two studies based directly on remote sensing imagery (DeFries et al. and Achard et al.) are less than half the estimated emissions of the other three studies.

Table 2. Estimates of carbon loss from tropical forests to the atmosphere attributed to deforestation (Gt of carbon per year)

Region	Fearnside (2000)	Malhi and Grace (2000)	Houghton (2003b)	DeFries et al. (2002)	Achard et al. (2004)
	1981-1990	1980-1995	1990s	1990s	1990s
America	0.94	0.94	0.75	0.43	0.441
Africa	0.42	0.36	0.35	0.12	0.157
Asia	0.66	1.08	1.09	0.35	0.385
Total	2.00	2.40	2.20	0.91	0.983

14. **There are different reasons of why the estimates of carbon emissions to the atmosphere from tropical deforestation in Table 2 differ so much.** All of the studies reported in Table 2 derive their estimates based on a simple “bookkeeping” carbon model that tracks the amount of carbon released

to the atmosphere from clearing and decomposition of plant material, plus the amount of carbon accumulated as the vegetation grows back. The main causes for the differences are related to the data used for rates of deforestation, the carbon stocks of the forests being cleared, and the fate of the carbon after clearing (e.g., how much is oxidized immediately versus decomposes over time). The accuracy of the biomass estimates of forests undergoing conversion is of critical importance because they determine the actual estimate of carbon that reaches the atmosphere and the models are very sensitive to these estimates.

- The estimate by Fearnside (2000) uses country-specific reports on annual rates of land-use change and regional estimates on carbon stocks in biomass and soil from a variety of sources; his study also centered on an updated analysis for Brazilian forest and savanna that was based on a regional evaluation of carbon stocks (mostly from small-scale biomass studies), field studies of forest burning and satellite-derived deforestation rates.
- Houghton (2003b) combined an updated analysis of land-use change in China with the estimates of tropical deforestation and afforestation from the FAO for 2000 and regional estimates of carbon stocks in biomass and soil from a variety of sources.
- Malhi and Grace (2000) combine analyses of Houghton (1999) and Fearnside (2000) for the Americas and Asia, and average their results for Africa.
- Emission estimates by DeFries et al. (2002) and Achard et al. (2004) are based on their analyses of changes in forest area using remote sensing to determine percent tree cover. Both of these remote sensing studies indicate that rates of deforestation may be lower than those reported at the country level but the coarse scale of the imagery used may not detect the small-scale events. Also the biomass carbon estimation procedures they used are highly uncertain, and are derived from large regional estimates of biomass in tropical forests.

15. When estimating carbon emissions from land use change, both the area and extent of land cover change from forest to non-forest and the carbon emissions associated with each land cover type must be estimated. Costs aside, the main methodological uncertainty in estimating carbon loss from tropical forests is quantifying the carbon stocks associated with each cover type rather than quantifying the land cover change. Remote sensing technology has improved over the past two decades, and the process of discriminating between forest and non-forest using high resolution imagery can achieve accuracies of up to 95%. However, the high spatial variability in carbon stocks within different forest types causes uncertainty when extrapolating from one or several point surveys to global estimates. Therefore, differences in carbon emission estimates that arise from study to study (such as in Table 2) depend on the methods employed and, more importantly, the quality and extent of available data (discussed further in section D below).

B. Rates and drivers of deforestation and degradation

1. Rates of deforestation and degradation

16. Forest disturbance is a global phenomenon, but regional and national characteristics vary significantly. Over the last two decades, rates of tropical deforestation have increased in some regions and decreased in others (see Table 3). According to global estimates by the FAO, about **15.4 million hectares** of tropical forests were lost each year during the 1980s (FAO 1993). From 1990 to 2000 the annual loss was estimated at **10.1 million hectares** (FAO 2006), with an additional loss of **10.4 million hectares** per year from 2000-2005 (Table 3), but it is unclear whether this change in forest loss reported in the various FAO reports represents a slowdown in actual forest clearance or the use of different forest definitions and data[3]. For example, the methodology used in the 1993 FAO report on tropical deforestation was based mainly on independent assessments by the FAO using a model they developed that related forest cover to population density—this model was developed to harmonize data from different countries and for

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[3] Further details are given in FAO FRA Working Paper 102–FRA 2000 and FRA 2005: comparing estimates of forest area and forest area change and in Forest Resources Assessment Working Paper – 059 FRA 2000 – Comparison of forest area and forest area change estimates derived from FRA 1990 and FRA 2000.

different time periods. The FAO's 2000 and 2005 FRA reports on deforestation estimates relied on national reports, forest inventories, and expert opinion, benefiting also from more recent national inventories in many developing countries. The FAO's 2005 FRA data show that the highest deforestation currently occurs in tropical America (4.5 million hectares per year), followed by Africa (3.1 million hectares per year). Tropical Asia had the least loss of forests at about 2.9 million ha per year.

17. Rates of deforestation reported from inventories and surveys (FAO 2006) are generally higher than estimates based on remote sensing, but this is not always the case. For example, Hansen and DeFries (2004) used satellite data and reported rates higher than those reported by FAO (2001) in 5 out of 6 countries. These differences are difficult to resolve because the accuracy of ground-based estimates (such as FAO data) is not assessed, and estimates based on remotely sensed data are sensitive to the spatial variability of deforestation - the size of clearings may be too small for a change in tree cover to be recognized in a 30-m resolution Landsat image. Therefore, trends in deforestation rates will continue to be difficult to determine accurately until standard and validated methodologies exist that can be applied at a range of spatial scales.

Table 3. Average annual rates of deforestation (10^6 ha yr^{-1}) in tropical regions*

	1980s DeFries et al. (2002)	**1990s FAO (2006)**	**1990s DeFries et al. (2002)[4]**	**1990s Achard et al. (2004)[5]**	**2000-2005 FAO (2006)**
Tropical America[6]	4.426	4.165	3.982	4.41	4.482
Tropical Africa[7]	1.508	3.362	1.325	2.35	3.058
Tropical Asia[8]	2.158	2.578	2.742	2.84	2.851
Total	8.092	10.105	8.049	9.60	10.391

* The FAO rates are based on forest inventories, national surveys, expert opinion and remote sensing. The estimates of DeFries et al. (2002) and Achard et al. (2004) are based on data from remote sensing.

2. Drivers of deforestation and degradation

18. Tropical deforestation and degradation as causes of global environmental change are well understood, but the factors that drive them remain largely under discussion (NRC 1999). In the past, the dominant discourse was whether deforestation was best explained by single causation or multiple causation models. Today, some consensus has been reached that deforestation usually results from a combination of factors, although the quantification of these factors remains poor. Geist and Lambin (2002) used 152 case studies to show that at the regional scale, tropical deforestation is driven by the interactions of many different causes. From their analysis, they suggest that the most prominent *underlying* causes of deforestation and degradation are economic factors, institutions, national policies, and remote influences that drive *proximate* causes of agricultural expansion, wood extraction, and infrastructure extension. At the global scale, agricultural expansion was, by far, the leading land-use change associated with nearly all deforestation cases studied, whether through forest conversion for permanent cropping, cattle ranching, shifting cultivation or colonization agriculture. However, regional

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[4] Rates from DeFries et al. (2002) refer to gross rates of forest loss (not counting gains in forest area).

[5] Rates from Achard et al. (2004) do not include areas of forest increase.

[6] Tropical America refers to South America, Central America and Caribbean subregions in FAO estimates; to Bolivia and 9 states in the Brazilian Amazon in DeFries et al. (2002) and to humid tropical forest biome of Latin America excluding Mexico and the Atlantic forests of Brazil in Achard et al. (2004).

[7] Tropical Africa refers to Eastern and Southern and Southern and Western subregions in FAO estimates, to parts of the Democratic Republic of Congo in DeFries et al. (2002); and to the humid tropical forest biome of Guineo Congolian zone of Africa and Madagascar in Achard et al. (2004).

[8] Tropical Asia refers to south and southeast Asia subregion in FAO estimates; to 4 Indonesian islands in DeFries et al. (2002); and to the humid tropical forest biome of Southeast Asia and India in Achard et al. (2004), including the dry biome of continental Southeast Asia.

differences were apparent as well, which makes the issue of scale important. For example, in Africa, degradation and deforestation was associated with the over-harvesting of fuel wood by individuals for domestic uses. In mainland and insular Asia commercial timber extraction followed by clearing for agriculture was a common cause. Timber extraction is generally not the direct cause of deforestation because harvesting is selective, but rather the logging operations often open up once inaccessible forests to further clearing, or in the case of Asia is followed by conversion to cash crops such as palm oil plantations. Cases of deforestation driven by shifting cultivation are more common in upland and foothill zones of Asia than elsewhere, but when practiced by colonizing migrant settlers in Latin America, it is limited mainly to lowland areas. Pasture creation for cattle ranching was shown to be a cause of deforestation almost exclusively for humid lowland cases from mainland South America.

19. It is difficult to establish clear links to the underlying causes of deforestation, and it is even more difficult to devise mitigating solutions to them due to the complexities and interconnections that exist among environmental, economic, and social aspects of the problem. However, the underlying factor that shows the least amount of regional variation seems to be related to economic development through a growing cash economy. For example, the proximate cause of agricultural expansion is generally driven by the development and/or continuation of market economies. According to the synthesis of relevant information from national communications to the UNFCCC (addendum 1 of this background paper), Parties listed most frequently the proximate causes of deforestation such as agricultural expansion and wood harvesting, but also mentioned underlying causes such as population pressures and policies and laws that encouraged land use conversion (Table 4).

Table 4. Drivers of deforestation and degradation as presented in the synthesis of relevant information from national communications (see Addendum 1)

Driver	**Number of Parties**
Forest conversion to agricultural uses	33
Harvesting for fuelwood and charcoal	25
Improper forest management, including selective logging and overexploitation	17
Fires and biomass burning	13
Population pressure	13
Development pressure, such as expanding urbanization, settlements and new infrastructure (e.g., electricity lines, roads)	11
Illegal logging	8
Policies and laws that drive land use conversions	7
Exploitation of mineral resources, mining	4

20. With respect to assessing causes of deforestation and offering mitigating activities, the UN Intergovernmental Panel on Forests (1996b) suggested using a diagnostic tool that would enable countries to trace the chains of causation for deforestation in their own country so that they could then identify limiting factors and opportunities for effective intervention. The tool would enable countries to assess the extent and quality of their present forest cover, consider the extent and quality of forest cover desired, and decide, against this background, whether the changes taking place were harmful or beneficial. The country would then analyze the chain of causation (from direct to underlying) that was contributing to harmful changes and decide on the most effective ways of treating them. This framework would allow each country to undertake its own analysis and develop its own national forest policy for sustainable development. To date, this formal framework has not yet been developed or applied.

C. Definitional issues

1. Forest

21. The estimation of forest area is affected by the definitions of ‘forest’ versus ‘non-forest’ area that vary widely in terms of tree size, area, and canopy density. Forest definitions are myriad, as is exemplified by the 240+ definitions listed by Lund (1999). However, common to most definitions are threshold parameters including minimum area, minimum height and minimum level of crown cover (FAO 2006). In its forest resource assessment, the FAO (FAO 2006) uses a minimum cover of 10%, height of 5m and area of 0.5ha. However, the FAO approach of a single worldwide value excludes variability in ecological conditions and differing perceptions of forests.

22. For the purpose of the Kyoto Protocol[9], it was determined that Parties should select a single value of crown area, tree height and area to define forests within their national boundaries. Selection must be from within the following ranges:

Forest area:	0.05 to 1 ha
Tree height:	2 to 5 m
Crown cover:	10 to 30 %

Young stands that have not yet reached the necessary cover or height are included as forest.

23. The specific definition chosen will have implications on what activities count as afforestation or reforestation and where the boundaries between deforestation and degradation exist (see below).

2. Deforestation

24. Most definitions characterize deforestation as the long-term or permanent conversion of land from forested to non-forested (Noble et al. 2000). In the annex to decision 16/CMP.1 deforestation is defined as follows:

> ‘Deforestation is the direct human-induced conversion of forested land to non-forested land’.

25. Effectively this means a reduction in crown cover from above the threshold for forest definition to below this threshold. There are additional requirements for this reduction to be human-induced and long-term. For example, if a country defines a forest as having a crown cover greater than 30%, then deforestation would not be recorded until the crown cover was reduced below this limit. Yet other countries may define a forest as one with a crown cover of 20% or even 10% and thus deforestation would not be recorded until the crown cover was reduced below these limits. Clearly, these different country-wide definitions of forests add additional complications to the monitoring of deforestation, but would need to be considered in any program to monitor deforestation.

3. Degradation

26. Where there are emissions from forests due to a decrease in canopy cover that does not qualify as deforestation, it is termed as degradation. Therefore, estimations of degraded areas will be affected by the definition of a “degraded forest”, which is not standardized.

27. The IPCC special report on ‘Definitions and Methodological Options to Inventory Emissions from Direct Human-Induced Degradation of Forests and Devegetation of Other Vegetation Types’ (2003) suggested the following characterization:

> ‘A direct, human-induced, long-term loss (persisting for X years or more) or at least Y% of **forest** carbon stocks [and forest values] since time T and not qualifying as deforestation’.
> (where X and Y are undefined).

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[9] Annex to decision 16/CMP.1 (see FCCC/KP/CMP/2005/8/Add.3).

28. In terms of changes in carbon stocks, degradation therefore would represent a measurable, sustained, human-induced decrease in canopy cover, with measured cover remaining above the threshold for definition of forest. The question to resolve is what are the values of X and Y.

29. Degradation presents a much broader land cover change than deforestation. Technically, a land cover change would be termed ‘degradation’ if canopy cover dropped from e.g., 100% to 85%, or 50% to 40%, or 90% to 35%. In reality, reported degradation will be limited by the technical capacity to sense and record the change in canopy cover, so that small changes will likely not be apparent unless they produce a systematic pattern in the imagery (see section III.A.3 below).

D. Data availability and quality

1. Changes in forest and vegetation cover

30. Satellite observations offer reliable, transparent, and cost-effective measurements of forest and land cover at various spatial and temporal scales (Table 5) that allow for consistent measurements of forest and land cover change over large geographic areas and repeating time periods. Currently, there are a number of satellites providing a range of resolutions. Optical sensors such as NOAA-AVHRR, MODIS, ENVISAT-MERIS, and SPOT-VEGETATION provide data with high temporal repeatability (1-5 days) but coarse spatial resolution (250 m – 1 km) and at relatively low cost of acquisition and processing. These types of sensors allow for replicable, timely detection of large-scale and rapid land cover change events such as deforestation of areas roughly 20 ha and larger (Herold et al. 2006), caused by, for example, large-scale mechanized agriculture, forest plantations, or urban development. This type of assessment can also identify locations where more in-depth analyses should take place.

31. Higher scale resolution optical sensors, such as Landsat, SPOT-MSS, and TERRA-ASTER, can provide finer detail (10-30 m spatial resolution), but the temporal resolution is often much lower (15-30 days) and the cost of data acquisition and processing is much higher. There is currently a Landsat 7 sensor failure which precludes the use of these images, but NASA and the ESA (European Space Agency) have committed to Landsat-type satellites beyond the year 2011. Landsat and SPOT data are used most commonly for national-level land cover mapping and deforestation analyses. This high-scale resolution imagery can also be used for hot-spot analysis guided by coarser scale detection of deforestation (Lu 2006). High resolution imagery can detect smaller agricultural clearings, but spatially heterogeneous landscapes generally require more complex computer algorithms and direct interpretation through visual analysis, thus greatly increasing processing time and cost. This category of remotely sensed imagery datasets has existed globally since the 1970s and 1980s. By reprocessing these datasets for land and forest cover, a historical perspective of land cover change is possible.

32. Sensors such as IKONOS, QuickBird, and airborne photographs and digital imagery can provide fine spatial resolution data (15 cm-5 m spatial resolution). Data cost and processing of these sensors are substantially higher than other remotely sensed data, so they are used most often in focused locations. This fine-scale imagery allows for detailed analysis of vegetation attributes and has been used to link ground-based measurements with remotely sensed forest attributes (Lévesque and King 2003, Brown et al. 2005b). Data at this scale can be used to detect forest degradation and other small scale changes in land cover.

33. Frequent cloud cover over tropical forested areas often reduces the utility of remotely sensed data from optical sensors. However, radar satellite sensors are not limited by cloud cover and may become available for national monitoring as research continues.

Table 5. Comparison of remote sensing platforms (modified from Herold et al. 2006)

Category	Sensor	Spatial Resolution	Temporal resolution (days)	Costs of Data and Analysis	Applicability to type of forest disturbance	Year first available	Overall Status
Fine spatial resolution	IKONOS, QuickBird, Aerial Photographs, Digital aerial imagery	15 cm - 5 m	per request - 5 days	Highest	Forest degradation, selective logging, small scale clearing	Aerial, late 1800s, IKONOS 1999, Quickbird 2001	Acquired on request
Medium spatial resolution	Landsat 5-TM, Landsat 7-ETM+, IRS-2-Resource-SAT, CBERS-2, Terra-ASTER, SPOT-MSS, ERS, RadarSAT	6 m - 100 m, average 30 m	5 - 30 days	High	Clearings and logging ≥0.05 ha, small-scale agriculture	Landsat 1972, -TM 1982, -ETM 1999, Terra-ASTER 1999, ERS 1991, RadarSAT 1995	Landsat 5 aging but widely available, Landsat 7 sensor failure, others acquired on request
Coarse Resolution	Terra/Aqua-MODIS, TIROS-AVHRR, SPOT-VGT, IRS-AWFS, EnviSAT-MERIS	60 m - 1 km	1 – 5 days	Low	Clearings >20 ha, large scale agriculture	MODIS 1999, SPOT 1986, AVHRR 1979	Highly available

34. Accuracy assessment is particularly important for quantifying uncertainties in satellite and airborne imagery analysis. In the case of remote sensing, a spectral signature is correlated with a specific land use (e.g., areas of forest, non-forest vegetation, degraded forest and farmland), so it becomes necessary to define how closely the interpretation represents the reality. This is done by collecting “ground-truth” measurements (i.e., the percentage of pixels classified as “x” that are actually “x” on the ground). Accuracies can also be assessed using comparisons with very high resolution airborne data or additional satellite data. Accuracies of 80 to 95% are achievable for monitoring with high resolution imagery to discriminate between forest and non-forest. While it is difficult to verify change from one time to another on the ground unless the same location is visited at two different time periods, a time series of very high resolution data can be used to assess accuracy of identifying new deforestation. If sampling has occurred with imagery, then precision should be determined in the same manner as used in carbon stock data: reported as the mean proportion of the area deforested or degraded in a given time period plus or minus a recorded confidence interval.

2. Carbon stocks

35. The availability of data and methods to estimate C stocks for different land cover types varies considerably.[10] Table 6 outlines general methods of estimating carbon stocks that are currently used in national to global analyses, as well as their cost and degree of uncertainty. Currently, there are no widely accepted standard practices using the current suite of optical remote sensing satellites for measuring forest carbon stocks remotely at regional or national scales. Although much effort and progress has made on improving data on rates of land use change, less progress has been made in producing reliable estimates of carbon stocks at national scales.

Table 6. Comparison of data sources/methods to estimate carbon stocks at national to regional scales

Products/scale	**Strengths**	**Weaknesses**	**Degree of uncertainty**	**Cost (1-3; low to high)**
Traditional forest inventories (national or regional)	High confidence in data if updated frequently, statistically well-designed	May be out of date Often focused on forests of commercial value and trees of commercial size and species Need factors to convert volume to biomass stocks	Depends on age of inventory and if updated—low to medium confidence based on date of inventory	3
Forest inventory with additional data on canopy cover/type and related to high resolution remote sensing data; update biomass stocks with new fine resolution remote sensing data interpreted for change in canopy density (models relate canopy density to biomass)	Commercial forest inventory data may already be available	Often focused on forests with commercial value	Medium confidence	Costly initially to get field inventory (3), costs decline with updates (2-1)
FAO data –by country and sub region	Wide availability, low cost	Default data based on forest inventories of varying scales and age or on expert opinion Converted from volume to biomass using general factors	Low to medium confidence depending on age and scale of inventory	1
Compilation of plots measured for academic or other research interests	Data available at little to no cost from the literature	Not sampled from population of interest	Low confidence	1-2

36. A variety of methods have been used to combine field-based measurements with remotely sensed land cover estimates to produce estimates of carbon stocks at large regional scales. Spatial models have also been developed using a combination of remote sensing products, spatial data-bases of key factors that are related to forest biomass (e.g., precipitation, temperature, elevation, growing season length, and the like), and field-based forest inventories to derive maps of estimated forest biomass at large regional scales (e.g. Africa – Gaston et al.1998; Asia – Brown et al., 1993, and Brazilian Amazon – Houghton et al., 2001).

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[10] Estimation of changes in carbon stocks is addressed in more detail in section III.B of this paper.

37. The recently updated FAO Global FRA (FAO 2006) presents country-wide and regional estimates of carbon stocks (Figure 2), which provide rough estimates that can be used as a default starting point. Carbon stocks for most major ecosystem types have also been estimated within scientific studies, allowing for broad estimates to be made for a land cover type (e.g., Brown and Lugo 1982). In many countries, forest inventories have been conducted by governmental bodies, research facilities, and forestry operations for some or all of the major forest types. Depending on the data quality, these datasets can be used directly for carbon estimation (IPCC 1996, IPCC, 2003) or in combination with additional field measurements.

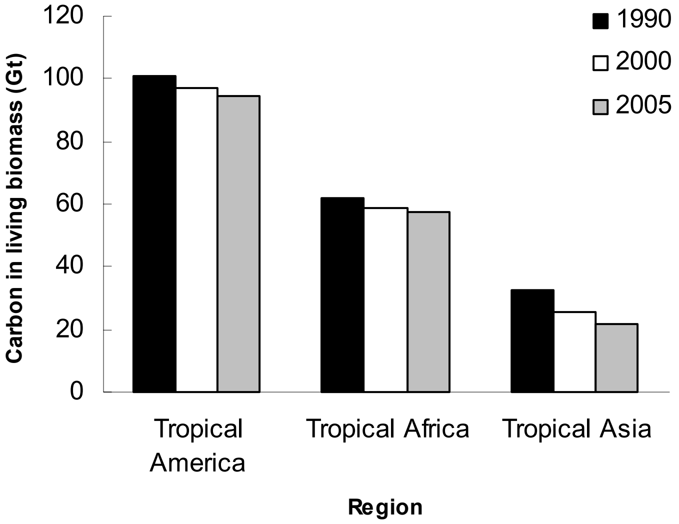

Figure 2. Trends in forest biomass carbon stocks, 1990-2005 (from FAO 2006). Geographic regions as defined in Table 3. The change in stocks is related to both change in forest area as well as changes in carbon density of the forests.

38. For most areas of the tropics, existing datasets may not be sufficient and so collecting additional field measurements using standard forest inventory methods for each ecosystem type will be necessary. Forest inventory data sampled over extensive areas is the only data base to use for estimating forest biomass at the landscape level because it is collected at the scale of the problem (Brown et al. 1989, 1991). The scale of sampling must match the scale of the subject to be measured, in this case the biomass of tropical forests. Data obtained by the direct measurement approach for other research interests, as is commonly used in global estimates of carbon emissions from tropical forests, relies on measurements from forest plots that are too few, too small, not randomly sampled from the population of interest, and are often biased in their selection. For example, even though in Brazil deforestation is monitored using remote sensing data at high resolution, a statistically well-designed recent inventory of carbon stocks in the Brazilian Amazon[11] is not available and it relies mostly on data from research plots non-systematically distributed over the area.

39. The accuracy and precision of ground-based measurements depend on the methods employed and the frequency of collection. If insufficient measurement effort is expended, then the results will most likely be imprecise. For example, the emissions reported by national inventories can be influenced by gaps in knowledge and by the quality and consistency of data available in a country. In addition, estimates can be affected by sampling errors, assessment errors, classification errors in remote sensing imagery, and model errors that propagate through to the final estimation. Nationwide inventories will require detailed documentation, standard operating procedures, and complete transparency in reporting

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[11] In the early 1970s, the forests of the Brazilian Amazon were inventoried under the RADAMBRASIL project but this inventory has not been updated since.

due to the size, complexity, and future updating that will be necessary to track changes in emissions from changes in rates of deforestation and degradation . Without these quality controls and assurances, the error involved in the data analysis would increase and the confidence of estimates would decline. Where accepted IPCC methods are employed and quality assurance and quality control (QA/QC) plans are developed and implemented in line with good practice, the uncertainty of the derived results is expected to be reduced.

40. To illustrate the quality and availability of data used in generating country reports on the situation of their forest cover change and carbon stocks, information from ten country reports submitted to the FAO for the FRA 2005, covering all three tropical regions, are provided as examples in Table 7. Most of these countries (7 out of 10) used some type of remote sensing data to obtain estimates of area change, though the scale varied from high resolution Landsat imagery to coarse scale NOAA AVHRR (see Table 5), however, only two countries used post-2000 data. For carbon stock estimates, all but one country provided an estimate, and the majority were based on forest inventories done in the 1990s and converted to biomass using expansion factor approach of Brown (1997) or factors in the IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC 2003).

Table 7. Sources of data and analyses used to estimate forest cover and carbon stocks by ten tropical countries for the years 1990, 2000, and 2005 and reported to the FAO for the FRA 2005 report

Country	Area Estimation	Date of area data	Biomass Estimation	Date of volume/biomass data
Bolivia	Compare Landsat images of 1993 and 2000	1993-2000, land use map of 2000	Biomass estimation based on volume inventories for humid forest, based on expansion factors and default values for roots and dead wood from IPCC 1996 GHG inventory methods	1999
Brazil	Deforestation rates using Landsat imagery from INPE	Multi-year up through 2004	Mainly from scientific studies with small, non-stratified plots. Amazon: allometric equations developed in Manaus region applied to 31 different sites. Atlantic forest: stock volumes x wood density x BEF	1988-2004
Cameroon	Assume linear change from 1975 to 1999 studies (low confidence)	1975,1999	1990 volume inventory (assumed constant for 2000 and 2005) translated to biomass using density and expansion factors (sources not listed)	1990
Central African Republic	No national inventory, partial only	1994, 1999	Partial inventory only, volume considered constant from 1990-2005 and translated to biomass using average density for Africa and expansion factors from Brown (1997) and FAO (2004) Directives	1996, 1997
Democratic Republic of Congo	NOAA-AVHRR for 1989	1982, 1989, 2000	Volume inventory (constant for all years) translated to biomass using average density for Africa and BEF from Brown (1997)	1999
Indonesia	Remote sensing (Landsat, Radar, aerial photography)	1986-1992, 1999-2000	Volume inventories (year 2000 estimated for various species) translated to biomass using expansion factor from Brown (1997)	1992, 1998, 2000

Country	**Area Estimation**	**Date of area data**	**Biomass Estimation**	**Date of volume/biomass data**
Malaysia	From forest inventories.	Various between 1974-1997, varies by region	Volume inventories for Peninsular Malaysia translated to biomass using GPG (2003), expansion factors from Brown (1997); used average value for PM for Sabah and Sarawak	1993, 2004
Peru	aerial photography and radar images for 1975; Landsat for 1995 and 2000	1975, 1995, 2000	Volume inventories, but biomass not estimated	1995, 2000
Republic of Congo	Base vegetation map for 1993, and satellite imagery for 2003-2004 used for change estimation	1993, 2003-2004	Volumes per ha (all trees with a minimum dbh>40 cm) assumed constant for 1990-2005, translated to biomass using average density for Africa and BEF from IPCC GPG - LULUCF	2004
Tanzania	Forest cover inventories	1984,1995	Volume inventory by vegetation classes, use average density for Africa and expansion factors (sources not listed)	1999

III. Methodological aspects relating to estimating changes in carbon stocks and in forest and non-forest vegetation cover

41. Any program to reduce the impact of deforestation and degradation on the global climate depends upon accurate and precise estimates of emissions resulting from such land use changes and how the emissions change over time. There are three principal aspects to this estimation:

1. Change in forest and vegetation cover;
2. Change in carbon stocks;
3. Estimation of emissions.

42. Combining the two aspects of estimation - measurements of changes in forest area and estimates of changes in carbon stocks - enables total estimation of emissions from deforestation and degradation over large regions. Both remote sensing and ground measurements play key roles in determining the loss of forest cover and changes in carbon stocks.

A. Estimating changes in forest or non-forest vegetation cover

1. Necessity for nationwide monitoring

43. Nationwide monitoring of changes in forest or non-forest vegetation cover is required if accurate national accounting is to be attained. In particular, the full forested area of the country needs to be represented so that reduced emissions through diminishing deforestation and degradation in one area are not fully replaced by displacement into another part of the country. For countries with a small forested/vegetated area, change in cover may be tracked on the ground. However, when forest or non-forest vegetation areas measure into the hundreds of thousands of hectares, then the costs of ground tracking are elevated and accuracy is lowered. For most nations, the only practicable approach for monitoring changes in forest and vegetation cover at the national scale is through the interpretation of remotely sensed imagery (including both airborne and satellite imagery).

44. A variety of remote sensing methods can be applied depending on national capabilities, available resources, deforestation patterns, and forest characteristics, but the key constraints in implementing national systems for monitoring changes in forest cover are cost and access to data at the

appropriate resolution. Where cost is reasonable and/or the area to monitor is small, then **wall-to-wall coverage** with high resolution imagery such as Landsat or even with airborne imagery will provide a high level of certainty to estimates of land use change.

45. Currently available information could enable elaboration of basic steps for creating an effective monitoring system for deforestation and degradation. Key elements of a possible monitoring system include its ability to measure changes throughout all forested area within a country, use consistent methodologies at repeated intervals to obtain accurate results, and verify results with ground-based or very high-resolution observations (Herold et al. 2006).

2. Sampling for estimation of changes in cover

46. The alternative to wall-to-wall coverage is **sampling.** In general, sampling involves examining a subset in order to better understand the whole. Since deforestation and degradation events are not distributed randomly in space, close attention should be paid to the sampling design. With respect to sampling remotely, one approach is to use a 'hierarchical nested approach' using medium to coarse resolution imagery (DeFries et al. 2002, 2006, Morton et al. 2005), whereby coarse resolution imagery is used to identify areas of rapid land use change that then become the focus of further study with higher resolution imagery (see Figure 3 below). Coarse resolution imagery (such as MODIS) can be used cost-effectively at a national scale, but these images can only capture clearings larger than 20 ha. Therefore, high resolution imagery (such as Landsat or SPOT) is required to track small-scale deforestation and degradation events. Under this hierarchical nested approach, the coarse resolution imagery focuses the resources for higher scale, more costly analyses.

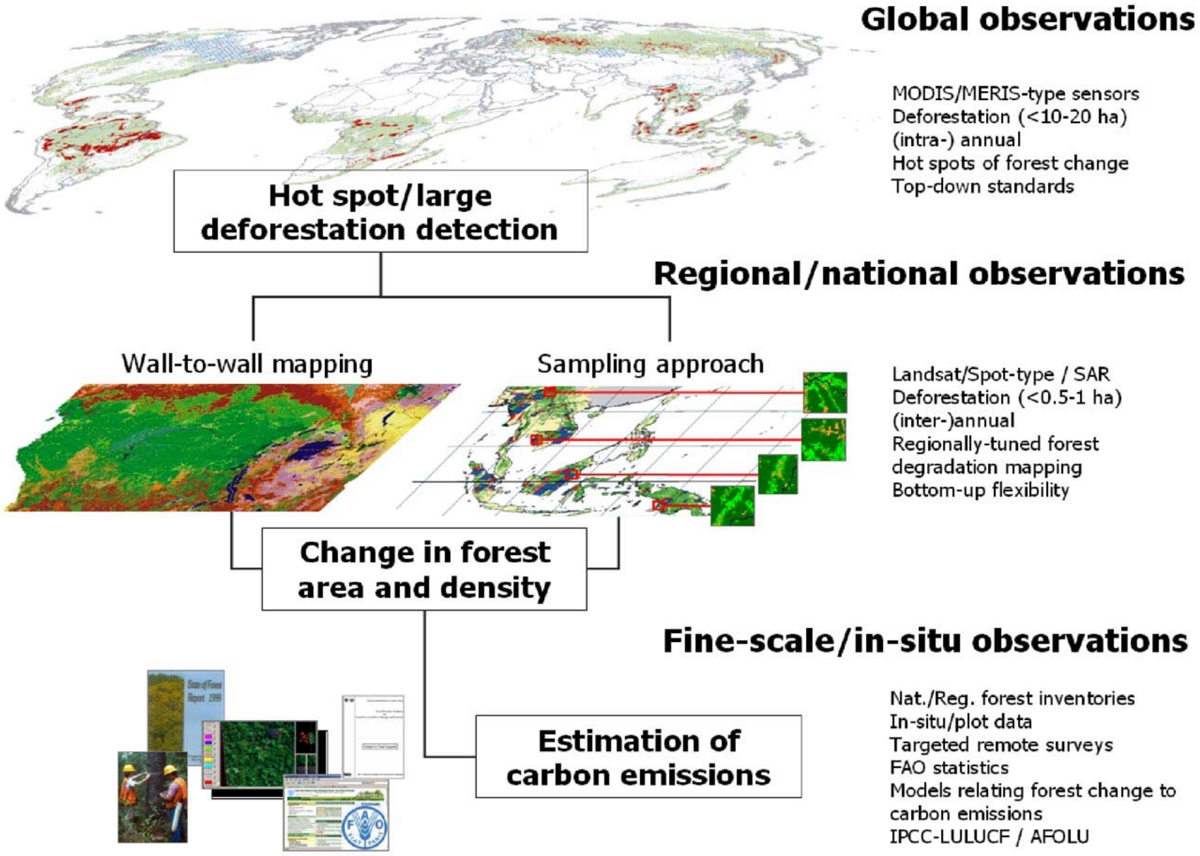

Figure 3. Conceptual framework for hierarchical method of net carbon emissions tracking land use change (from DeFries et al. 2006).

47. Other methods that could be employed to focus resources on areas where deforestation and degradation are occurring include expert opinion and analyses of indicatory databases such as data on

transportation networks, logging concessions, or on population change in rural areas (see section above on drivers).

48. It could be argued that the area of focus for detailed analyses would be the frontier between forest and non-forest. However, the concept of a frontier does not apply to all tropical regions where humans live interspersed across the landscape. In either case and for large regions, it may be preferable to statistically sample. Sampling would involve examining a proportion of the area to obtain estimates of rates of conversion that can be extrapolated across vegetation types or areas with similar population pressures along the entire length. As with carbon stock measurements, the size of the sample would need to be large enough to have confidence in the precision of the derived estimates. Standard methods would need to be developed to produce statistically well-designed sampling protocols for cost effectively analyzing remote sensing imagery.

49. Technical capabilities have advanced since the early 1990s and operational forest monitoring systems at the national level are now a feasible goal for most developing countries, especially since 2000 when MODIS data became routinely available at low cost (Mollicone et al. 2003; DeFries et al. 2005). Brazil (INPE 2005) and India (Forest Survey of India 2004) are examples of large nations with extensive forest cover that have achieved wall-to-wall sampling of changes in forest cover. Each has receiving stations for collecting remote sensing satellite imagery (Landsat or Terra). Brazil uses the results from the previous year to identify focus areas for the current year's analysis.

50. Progress is also occurring in the development of new technologies and approaches to remotely sense changes in canopy cover. Radar and Lidar sensors can be used where cloud cover prevents the analysis of optical satellite data, but they currently do not have the global coverage necessary for widespread use.

3. Challenges in estimating changes in cover

Degraded forests

51. For low level degradation, such as illegal logging or the harvesting of wood fuels, the difference in the reflectance of satellite imagery is often very small between intact forest and degraded forest. However, visual interpretation of high resolution imagery has been successful in detecting even small-scale degradation. For example, Asner et al. (2005) used the spatial pattern of log landings and other infrastructure to identify low level selective logging. Where selective illegal logging of high value timber (such as mahogany) occurs, then sampling should occur near all potential timber extraction points such as roads and rivers.

52. It is possible to assess logging impacts using airborne imagery that can be used to sum areas of logging gaps and lengths of roads and skid trails. Factors calculated on the ground then allow an extrapolation from these measured dimensions to the carbon impact from logging activities directly (e.g. Brown et al. 2005a, Pearson et al. 2006).

Shifting agriculture and seasonal forests

53. Caution must be employed when analyzing areas with shifting agriculture and seasonal forests because each gives the potential to estimate deforestation incorrectly. Shifting cultivation results in a landscape mosaic of clearings and fallow that change in both location and carbon stocks over time. Such clearings, if identified as new deforestation in a monitoring system, would falsely inflate deforestation rates. A longer time series of repeated observations, combined with expert knowledge of the land use patterns in the country, are needed to distinguish new deforestation from clearing dynamics associated with existing practices. However, the monitoring system would need to identify intensification of the shifting cultivation cycle where the fallow period is shortened as this would lead to increases in carbon emissions. Guidelines for monitoring would need to be developed to identify and exclude these areas from the analysis. A key requirement for a monitoring system is initial designation of the forest area under which future clearings are considered new deforestation.

54. For seasonal forests, examining forest cover when leaves are missing at the beginning of the cycle will falsely identify deforestation. However, in the wet season when the leaves have flushed out, the imagery may indicate forest without any degradation.

55. The solution to these pitfalls with shifting agriculture and seasonal forests is to use time-series analyses that indicate the status of the land over several seasons and several years. In addition, expert knowledge can identify areas with seasonal forests or areas that are currently being farmed on a shifting cycle.

B. Estimating changes in carbon stocks

1. Measurement of carbon stocks

56. With current technologies, the most accurate estimations of carbon stocks are based on field measurements. The 2005 FAO Forest Resource Assessment provides country-level data on forest area, rates of conversion, and carbon stocks to facilitate the estimation of changes in carbon stocks in the absence of more detailed national data (see Table 7). However, in most cases these estimates should be used only as a starting point and supplementary data on land cover type and carbon stocks must be compiled or created. In many countries, existing field data can be adapted for use in carbon stock estimation or can be used to supplement additional forest inventory data collection. Some countries, e.g., India (Forest Survey of India 2004, see Box), have had well-established operational forest monitoring systems in place for over a decade. However, for most countries, a forest inventory program based on the IPCC Inventory Guidelines (IPCC 1996), the IPCC Good Practice Guidance for Land Use, Land Use Change and Forestry (IPCC 2003), and FAO would be needed in order to obtain C stock estimates.

Box – Example of national vegetation survey

The Forest Survey of India

The forest survey of India assesses forest cover in India on a two-year cycle. The first assessment was in 1987. In recent assessments, IRS satellite data have been used with a resolution of 23.5 m to create forest cover maps on a 1:50,000 scale. Since 2001, the forest survey has been comprised of an entirely digital assessment. Threshold values for vegetation classes are defined on a 'Normalized Difference Vegetation Index' (NDVI) image and the forest is automatically classified accordingly. Six vegetation classes are used:

Very dense forest:	canopy density over 70%
Moderately dense forest:	canopy density between 40 and 70%
Open forest:	canopy density between 10 and 40 %
Scrub:	canopy density less than 10%
Mangrove	
Non-forest	

The forest survey of India has also conducted forest inventories since 1965. To date, approximately 80% of the country's forests have been inventoried. Under the current scheme, 10% of districts are sampled every two years. The country is stratified into 14 physiographic zones based on tree species composition and other physiographic and ecological factors. Tree measurements are conducted in 0.1 ha plots.

Information from: http://fsiorg.net/

57. Five main carbon pools have been identified and accepted by relevant UNFCCC decisions and include living biomass (above and belowground), dead biomass (dead wood and litter), and soil carbon (soil organic matter). The uptake or emission of CO_2 from each pool is assumed to be equal to the growth or reduction in carbon stocks of each pool. The majority of carbon stocks in most vegetated ecosystems can be found in the living biomass, and this pool can be monitored cost-effectively. Other pools could be measured if resources allow and standard methods are available (Brown and Masera 2003). As an

alternative, default factors can be used or created for their inclusion (IPCC, 2003). If the additional pools are *not* included, then reported stocks will be *underestimated*, which will lead to lower estimates of emissions from deforestation and degradation. If no national inventory of carbon stocks already exists, it is likely to be most cost effective to estimate carbon stocks through forest stock volumes estimated using standard and well established forest inventory methods. Note that all species should be considered and minimum diameters need to be as low as 10 cm (or lower in drier forests with smaller stature trees) to account fully for all carbon.

58. Ground-based field measurements of carbon stocks have a long history of well-recognized and field-tested methods. The IPCC Good Practice Guidance has established field methods for estimating carbon emissions as well as non-CO_2 GHGs at the project scales (Brown and Masera 2003) and improved methods for three levels of detail (tiers 1-3) at the national scale (IPCC, 2003). The recently published Sourcebook for LULUCF Projects (Pearson et al. 2005) presents in-depth, straightforward methodologies for field-based measurements and calculations of carbon stock changes over time that can be used at varying scales. Tree biomass is estimated via forest stock volumes and converting to total tree biomass using wood density and biomass expansion factors, or alternatively via allometric equations based on measured tree diameter and/or height volume (Brown 1997; Brown et al 1989; Gillespie et al 1992). Other pools of carbon are measured directly in the field or through additional relationships.

2. Net changes in carbon stocks

59. Loss in canopy cover is not directly equal to the emission of the equivalent carbon stock. For example, burned carbon can remain fixed as charcoal, or some carbon will remain on the land as dead wood to decompose slowly through time. The Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories discuss three forms of CO_2 emissions with respect to the conversion of forest to pasture or cropland:

1) CO_2 emitted from burning aboveground biomass, either on site or off-site (generally fuelwood);
2) CO_2 released from decomposition of aboveground biomass;
3) CO_2 released from soil.

60. When carbon stocks are burned, there will also be emissions of non-CO_2 gases. The 1996 IPCC Guidelines (Section 5 of Volumes 2 and 3) also provide equations and methodologies for these calculations.

61. For deforestation, the IPCC default assumption is that 50% of the aboveground carbon stock will be burned and 50% will be left to decompose. Of the burned fraction, the 1996 IPCC Guidelines assume default values of 90% oxidized and 10% permanently sequestered as charcoal. Of the decomposing dead wood fraction, the default is to assume complete decomposition over 10 years at a rate of 10% per year. For CO_2 released from soil, the IPCC default is a 20% loss for conversion to shifted cultivation, a 30% loss to unimproved pasture and a 40 to 50% loss for conversion to long-term cultivation.

62. While these defaults are useful for broad national accounting, there is room for improvement and new estimates of country or region of country defaults could be obtained.

3. Future technologies for monitoring of carbon stocks

63. There are currently no standard practices or capabilities for measuring forest biomass through remote sensing at regional and national scales. New aerial technologies have begun to be used for estimating carbon stocks remotely, although these techniques still require ground-based biomass measurements in order to calibrate the aerial measurements taken. Pilot studies using airborne Lidar data and very high resolution optical data have been used in a sampling approach to estimate biomass of different forest types (Drake et al. 2003, Brown et al. 2005b). High resolution digital optical data can be used to obtain key metrics of individual trees in the forest canopy, and new tools are developing for

automatically delineating tree crown areas in complex tropical forests. In addition, new field data for developing allometric models for converting data from such products to estimates of biomass stocks would need to be acquired and relationships between remotely-sensed metrics of tree canopies and biomass would need to be established. These methods are currently costly, though more cost effective than traditional large field-based forest inventories, but not sufficiently developed for widespread operational use. Experimental data from Radar observations reveal potential for biomass mapping.

C. Combining estimations of change in cover and change in stocks for emissions inventories

64. The total carbon stock change that occurs under a specific land use conversion can be calculated as (IPCC 1996):

$$\Delta C_{Conversion} = A_{Conversion} \bullet L_{conversion}$$

where:

$\Delta C_{Conversion}$ = change in carbon stocks as a result of clearing biomass in a land use conversion, tonnes C

$A_{Conversion}$ = area of land converted to cropland/pasture land, ha

$L_{Conversion}$ = carbon stock change per area for that type of conversion when land is converted to cropland/pastureland, tonnes C ha^{-1}

65. Where deforestation occurs for cattle production or for large-scale mechanized agriculture, the carbon stock will decrease from a high carbon level associated with forest to a new low steady state (scenario A below). If this is the prevalent land use change in the country or in a region of the country, then the stock change would be estimated as the area undergoing the change multiplied by the difference between the stock before and after deforestation. If a variety of agricultural or pastoral land uses exist after deforestation, either a conservative value (the highest carbon stock land use), or the carbon stock of the dominant land use could be used.

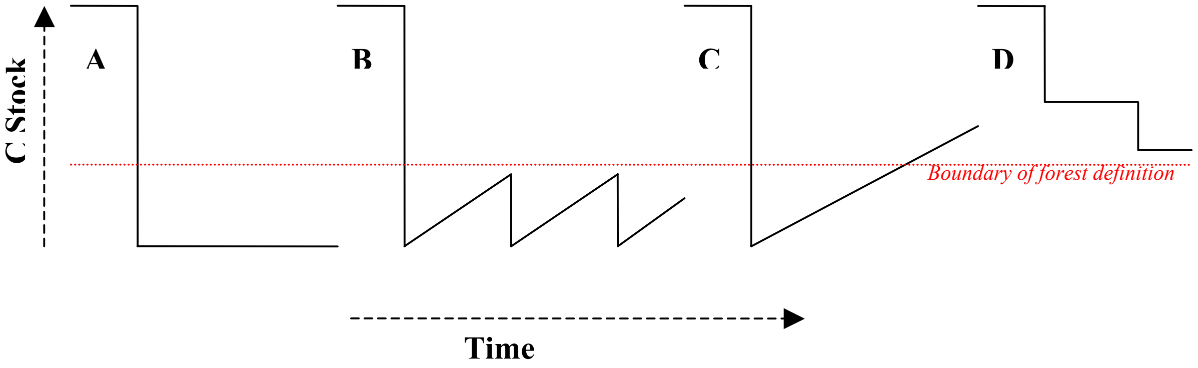

Figure 5. Changes in carbon stocks for four different land-use change scenarios: (A) complete and permanent conversion from forest to non-forest; (B) conversion from forest to a shifting cultivation agricultural system; (C) temporary conversion from forest to an alternative land-use followed by regrowth; (D) degradation from undisturbed forest to marginal forest.

66. Where deforestation results in a shifting agriculture land use (scenario B above), the carbon stock change could be estimated as the difference between forest and either the highest stock over the shifting cultivation cycle or the mean stock over the cycle (calculated by dividing the sum of the stock in each year of the cycle by the number of years in the cycle).

67. Where deforestation is followed, either immediately or shortly after a period under alternative land use, by forest regrowth, the carbon stock reduction is only temporary (scenario C above), and the temporary nature will lead to this land use change not being regarded as deforestation or even degradation

under many definitions. The benefit of avoiding deforestation under this scenario (where regrowth immediately occurs) diminishes through time after the deforestation event. Measurement plots could be used to estimate the rate of forest regrowth.

68. Degradation (scenario D above) will likely cover a wide spectrum of canopy cover values from undisturbed forest (almost 100% cover) to the boundary of the forest definition (10-30% cover). As already discussed, estimation of degradation with remote sensing imagery is beset with complications and difficulties. While it is possible to determine where degradation is occurring, determining the degree of degradation is less likely. Two alternative solutions exist:

(a) Create a local model correlating spectral reflectance received by satellite with canopy cover and canopy cover with carbon stock. This will require substantial work on the ground correlating the satellite image with percent cover and installing carbon measurement plots to correlate percent cover with carbon stock.

(b) A conservative value for the average canopy cover decrease that results from degradation could be selected and correlated with a carbon emission.

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