5.7 VERIFICATION

5.7.1 Introduction

The purpose of verifying national greenhouse gas inventories is to establish their reliability and to check the accuracy of the reported numbers by independent means. Verification can be performed at several levels: project, national and international.

The overall goals of verification are to:

- Provide inputs to improve inventories;
- Build confidence on estimates and trends;
- Help to improve scientific understanding.

These goals can be achieved through internal or external inventory checks. Internal verification is generally performed by inventory agencies, while other bodies (e.g., other government agencies, private companies, research consortiums, independent scientists, non-governmental organisations) will carry out external verification.

The Glossary of IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (*GPG2000*, IPCC 2000) defines verification as shown in Box 5.7.1 (see also Glossary):

BOX 5.7.1
DEFINITION OF VERIFICATION FOR THE INVENTORY

Verification refers to the collection of activities and procedures that can be followed during the planning and development, or after the completion of an inventory, that can help to establish its reliability for the intended application of the inventory.

In general, verification as discussed in Annex 2, Verification, of *GPG2000* is also relevant to the LULUCF sector. There are many approaches to verification, including: comparison of the inventory estimates with independent assessments, procedures and datasets; peer and public review; and direct measurement of emissions and removals of greenhouse gases. Verification approaches can also include examination of specific aspects of the inventory, such as underlying data (collection, transcription, and analysis), emission factors, activity data, assumptions and rules used for the calculations (suitability and application of methods, including models), and upscaling procedures. No matter which verification approaches are used or what aspects of the inventory are verified, it is *good practice* to conduct verification using data and methods that are independent from those used to prepare the inventory.

To some extent specific approaches for verification are needed for LULUCF sector because of the uniqueness of estimation methods. Ideally, verification of LULUCF activities would be based on complete accounting of emissions and removals at the national scale, measured by independent methods at different levels and, possibly, complemented by top-down approaches based on atmospheric measurements. Such verification would be complex and resource intensive, and will be possibly performed by research consortiums and/or programmes. It is more likely that inventory agencies would apply some more limited verification approaches or seek to address their verification needs through already ongoing research activities. The external verification approaches described in this section may help inventory agencies to evaluate their results.

This section presents a range of verification approaches and provides practical guidance on how to apply them to the entire national inventory, or parts of it. Section 5.7.2 describes some of the approaches available for verifying inventory estimates and/or the data on which they are based. Section 5.7.3 provides practical recommendations for verifying LULUCF Inventories. Section 5.7.4 considers some of the verification issues that are specific to the Kyoto Protocol[24]. Section 5.7.5 addresses reporting and documentation issues. QA/QC is closely related to verification, and it is covered in Section 5.5 of this chapter. Finally, some details for verification approaches are given in Section 5.7.6.

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[24] Verifiability is a requirement under Article 3.3 of the Kyoto Protocol and for Articles 3.3 and 3.4 under paragraph 17 of the Annex to the draft LULUCF decision agreed in Marrakesh (see FCCC/CP/2001/13/Add.1, page 61).

5.7.2 Verification Approaches

An inventory agency (or an external group) may decide to verify the entire inventory, a part of it or the underlying data and models from which the inventory estimates have been calculated. This section describes approaches that can be used to verify inventory estimates, including some techniques that allow the verification of the overall inventory, and many that can be used to verify selected elements of an inventory. The criteria for selecting verification approaches include: scale of interest, costs, desired level of accuracy and precision, complexity of design and implementation of the verification approaches, and the required level of expertise needed to verify. For each approach, a technical description is given with reference to its applicability (e.g., for a particular category, types of data). Guidance for the application of the approach is also provided, and Table 5.7.1 contains information to assist in identifying the most suitable approaches for particular categories or inputs. Table 5.7.1 addresses verification approaches for land area classification, major carbon pools and non-CO_2 gases, although it is not exhaustive. The general applicability of the verification approaches for the estimations of emissions and removals from LULUCF sector for the reporting under the Kyoto Protocol is described in Section 5.7.4.

Generally, the most significant emissions and removals related to LULUCF are of carbon dioxide (CO_2). However, the LULUCF sector also includes non-CO_2 greenhouse gases (mainly emissions) from the fertilisation of forests, land clearing, soil preparation for afforestation/reforestation, grasslands and croplands management and other practices. These non-CO_2 greenhouse gases include methane (CH_4), nitrous oxide (N_2O), carbon monoxide (CO), oxides of nitrogen (NO_x), and non-methane volatile organic compounds (NMVOCs). Emissions and removals of CO_2 can be determined and verified directly as changes in carbon stocks in biomass or soils. For non-CO_2 gases, fluxes can be measured to verify annual emission estimates.

There are many approaches that can be used to verify emission and removal estimates for the LULUCF sector. An overall verification exercise may include cross-checking of the results at different geographical scales, from regional to global. Such cross-checking, however, requires considerable time and it is likely to be implemented over multiple years rather than on single year basis. Compared to fossil fuel emissions, LULUCF activities are more difficult to assess over short time periods, because biospheric carbon is often difficult to monitor and slow to equilibrate. The assessment of the net anthropogenic impacts on biospheric carbon would consequently require a long-term perspective (Nilsson *et al.* 2001).

Table 5.7.1 summarises the applicability of a range of verification approaches to different aspects of LULUCF inventory estimation. More detailed descriptions of the approaches are given in the following part in this section.

APPROACH 1: COMPARISON TO OTHER INFORMATION

Comparison of the LULUCF inventory to other independently compiled inventories or data sets can be a useful and efficient means of verification. Two broad types of verification are possible under this approach: comparison with independent inventories (Approach 1a) or comparison with international programmes and datasets (Approach 1b).

Approach 1a: Comparison with independent inventories

In some countries, it may be possible to verify the national LULUCF estimates prepared by the inventory agency with inventories put together by other organisations (i.e., other national, regional/provincial agencies, research organisations, etc.). Such external inventories can be used for verification if the same underlying data have not been used to produce the reported estimates and if the relationships between sectors and categories in the different inventories can be assessed. In this respect, it is *good practice* to ensure that the same dataset has not been already used to calculate/estimate some of the reported LULUCF category. When comparing independent inventories it is also important to take into account the uncertainties in the estimates.

Another effective verification approach is to compare inventory information between countries or groups of countries. Such comparison could be made for overall estimates of particular source/sink categories, default assumptions and/or data used to compile the national inventory. This approach can be quite inexpensive to perform, but care must be taken to ensure that the characteristics of the selected countries are, in fact, comparable (i.e., they should have similar climatic or biome characteristics). Sometimes data based on inventories from other countries can be better related to national circumstances than those calculated with general default emission factors or activity data, and can in turn be used to improve the inventory.

The comparison of inventory data or estimates with other inventories can be an inexpensive and fairly simple verification approach. In general, it does not require skilled technicians or highly trained personnel, particularly when compared to the requirements of approaches like remote sensing or modelling. It can be applied to all elements of an estimate, including land area classification, inventories of various carbon pools, estimates of non-CO_2 gases, and activities like afforestation, reforestation and deforestation. The key determinant in its applicability is the availability of alternative inventories against which to compare. It is *good practice* to use this approach if such inventories are available. If such comparisons identify significant differences, the causes should be investigated, in order to correctly interpret the results and flag possible areas for further inventory checks.

TABLE 5.7.1
APPLICABILITY OF VERIFICATION APPROACHES FOR LAND AREA IDENTIFICATION AND FOR CARBON POOLS AND NON-CO_2 GREENHOUSE GASES

	Approach 1 **Comparison with other inventories and other independent datasets**	**Approach 2** **Applying higher tier methods**	**Approach 3** **Direct measurement**	**Approach 4** **Remote sensing**	**Approach 5** **Modelling**
Land area	Suitable, if data are available	Suitable, if data are available	Not applicable	Suitable	Not applicable
Carbon pools					
Aboveground biomass	Suitable, if data are available	Suitable, if data are available	Suitable (resource-intensive)	Suitable (ground data needed)	Suitable (regression, ecosystem and growth models)
Belowground biomass	Suitable, if data are available	Suitable, if data are available	Suitable (resource-intensive)	Not applicable	Suitable, (regression, ecosystem and growth models)
Dead wood	Suitable, if data are available	Suitable, if data are available	Suitable (resource-intensive)	Not applicable	Applicable (ecosystem and inventory-based models)
Litter	Suitable, if data are available	Suitable, if data are available	Suitable (resource-intensive)	Not applicable	Applicable (ecosystem and inventory-based models)
Soil organic matter	Suitable, if data are available	Suitable, if data are available	Suitable (resource-intensive)	Not applicable	Suitable (ecosystem and inventory-based models)
Non-CO_2 greenhouse gases	Suitable, if data are available	Suitable, if data are available	Suitable (resource-intensive)	Not applicable	Suitable (ecosystem models)
Emission factors	Suitable, if data are available	Suitable, if data are available	Suitable (resource-intensive)	Not applicable	Suitable (ecosystem models)
Activity/land-based report					
Forest, grassland, cropland, other land uses	Suitable, if data are available	Suitable, if data are available	Suitable (resource-intensive)	Suitable, particularly to identify land cover/land use and their changes	Suitable, Data-intensive, Can be an alternative approach when estimates from direct measurements and remote sensing are not available
Afforestation, Reforestation, Deforestation, projects	Suitable, if data are available	Suitable, if data are available	Suitable (resource-intensive)	Suitable, particularly to identify land cover/land use and their changes	Not practical

Approach 1b: Comparisons with International Programmes and Datasets

A number of research and monitoring initiatives are currently under way at the international level, both at regional/continental scale (research projects, monitoring networks, etc.) and at global scale (remote sensing of the biosphere, global data archiving centre, networks of similar research initiatives between regions, etc).

For the LULUCF sector, most of this research is linked to the quantification of the role of terrestrial ecosystems, particularly forests, in the carbon cycle, from ecosystem to global scale. In this respect, many of the results gathered by research and monitoring networks could be relevant for verification of LULUCF reporting, as well as for other cross-cutting issues such as those linked to QA/QC and uncertainties.

The scale and aggregation level (national, regional, etc.) of the data and information that can be gathered from such programmes and datasets may be useful in different phases and levels of the verification process (internal and external auditing, comparison with data collected by other agencies, etc.).

As with Approach 1a, the comparison of inventory data or estimates with independent datasets can be an inexpensive and straightforward verification approach. It can be applied to any element of an inventory for which there is an alternative source of data. Generally, it is most applicable for land area classification, although it can also be used to verify selected elements of estimates of carbon pools, non-CO_2 greenhouse gases, and activities, while data coming from research networks can be used to verify country-specific data (emission factors). As mentioned for the previous approach, when using an international dataset for verification purposes, it is *good practice* to ensure that the same dataset has not been already used to calculate or estimate some elements of the reported LULUCF category. This situation can occur particularly when the internationally available programmes and datasets are compiled from national statistics or include the results of specific studies performed in the territory of the country that is planning to use the data for verification. The analysis of the eventual differences emerging from the comparison with internationally available data-sets and inventories should be devoted particularly to the identification of the possible reasons for such differences, with the final objective of overall inventory improvement. Links to some international programmes and datasets that could be useful for verification purposes can be found in Box 5.7.6, Links and Networks Relevant to LULUCF, in Section 5.7.6. Other useful links to open sources for land-use/land-cover data may be found in Chapter 2, Annex 2.A.2, Examples of International Land Cover Datasets.

APPROACH 2: APPLYING HIGHER TIER METHODS

A country may not have sufficient data or resources to use higher tier methods for its total inventory of emissions and removals from all of the various categories of the LULUCF sector. In some cases, however, the country may have access to more comprehensive datasets for specific areas (e.g., a region or subcategory). In this case, the country could conduct verification of part of its estimate using a higher tier method. As an example, if greenhouse gas emissions and removals in managed forests have been estimated using the Tier 1 methods, an inventory agency may consider performing verification by applying, over a portion of the forested area, country-specific data (Tier 2 or Tier 3). In this case, biomass and growth equations would have to be available or developed in selected areas at least for homogeneous growth conditions (biome, climatic regions), forest age classes and management regimes.

The application of higher tier methods for parts of an inventory can be an effective verification technique if the necessary data, derived from the more detailed method are available. This approach can be applied at a variety of scales, from plot to national level. Costs will vary depending upon the scope of the verification. In general, development of higher tier estimates for verification can be fairly simple and may use the already available inventory expertise. A key issue with this approach is whether to use the partial higher tier estimates as a part of the inventory itself or as a verification approach.

APPROACH 3: DIRECT MEASUREMENTS OF EMISSIONS AND REMOVALS OF GREENHOUSE GASES

Direct measurements are a verification approach for various carbon pools, as well as non-CO_2 greenhouse gas emissions and LULUCF activities. However, this approach is not generally applicable for verifying land area classification. The scale of the approach can vary from plot to national level. At limited scale, direct measurements can provide country-specific default factors and activity data, while larger scale approaches can be used for verification of sectoral estimates and specific activities. Costs can vary substantially, depending upon sample size and the desired accuracy. With a large sample size, accuracy can be quite high. When applying this approach, the most significant challenges are generally designing the sampling strategy and measurement protocols. Once the infrastructure is in place, measurements collections are generally not technically difficult, although they can be labour intensive.

When performing direct measurements of emissions and removals of greenhouse gases in the LULUCF sector, temporal and spatial variability needs to be properly considered, because emissions/removals in a given year are not necessarily indicative of long-term trends. This is due to the fact that most of the emissions and removals in the sector are linked to biological processes and subject to climate variability. The problem can be partly addressed by using average, cumulative measurements or smoothing over several years to get representative results. Furthermore, the effect of inter-annual variability of data tends to decrease as larger areas are considered. Thus, direct measurements over larger areas or with longer measurement intervals are more likely to reflect the effect of management practices (see Chapter 4, Section 4.2.3.7, Interannual Variability). While recognising these issues in using direct measurements as a verification tool, they can still be useful in several ways to verify LULUCF sector estimates and background data, as described below.

Living Biomass (*aboveground and belowground biomass*)

Reported carbon stock changes in biomass can be verified by **direct measurements of stock changes**. Currently available techniques allow reasonably accurate measurement of changes in aboveground biomass at periodic intervals, although, in mature forests, the annual changes in stocks can be small for the size of the pool. Methods for estimating belowground biomass are also available, although the sampling is more difficult than for aboveground biomass. This approach can be used particularly in forests, but it is also suitable for the changes in living biomass in other land-uses which contain woody biomass while not matching the definition for forest land (e.g., agro-forestry systems, revegetated grasslands, etc.).

There is a variety of ways in which direct measurements can be used to verify biomass estimates. For example, a country may decide to collect forest inventory data by direct measurements more frequently than they typically do, e.g., on a 5-10 year interval, for a selected subsample of plots or for a region. An inventory agency may also use direct measurements to derive local allometric relationships including belowground biomass that could be used to verify stock changes for the entire living biomass component. Direct measurements could also be used as a verification tool for young forest stands or lands which are undergoing biomass regrowth, as the available allometric equations and biomass expansion factors are normally not applicable for these pools. Available **ecosystem studies** could be used to derive species-specific biomass expansion factors, which could be compared against the default factors used for reporting and also to check growth rate of specific forest types.

Dead Organic Matter (*dead wood and litter*)

As for aboveground and belowground biomass, stocks of dead organic matter (litter and dead wood) can also be estimated from direct measurements. However, in forests, litter and dead wood pools are highly variable both in space and in time (e.g., seasonal changes in litter, sudden changes due to natural or human disturbances) and a proper sampling scheme would be needed to accurately assess stocks of dead organic matter. It is expected that litter pools are not changing significantly in mature forests and verification should be preferably directed to afforestation/reforestation areas and to forest stands that are undergoing major management operations such as harvesting, site preparation, thinning, etc.

Generally, ecosystem studies are measuring aboveground litter input using netted traps (foliage and twigs) and litter stocks through collection of litter in several plots (also for coarse dead wood). Such studies, if available, could serve to check Tier 1 default factors eventually used for reporting.

Soils (*soil organic matter*)

Verification of emissions and removals from **soils** could also be undertaken. As for aboveground biomass, sensitive methods for estimating soil carbon stocks are available. Repeated soil sampling over a certain area, region or at national scale can be a relevant approach for detecting changes in soil carbon in different land uses (forests, grasslands, croplands). However, for ecosystems that are not undergoing land-use changes or are not subject to significant management operation (e.g., harvesting of a mature forest, improvement of a grassland, ploughing of croplands, etc), changes in soil carbon stocks could be small and difficult to assess accurately over short periods.

Greenhouse gas emissions and removals from soils can be measured at several sampling points in a plot using portable or transportable gas-sampling systems (cuvettes and gas analyser). Measurements at the sampling points would then need to be upscaled to plot/ecosystem levels, taking into account the significant spatial variability typical of soil-related gas emissions and removals. Both CO_2 and other greenhouse gases (N_2O, CH_4) have been measured with this approach (Butterbach-Bahl *et al.*, 2002; Janssens *et al*, 2001). Direct measurements of greenhouse gas fluxes obtained in this way can be useful also in comparing emissions before and after the application of a specific management practice (Steinkamp *et al.*, 2001; Butterbach-Bahl and Papen, 2002). Directly measured values can be used to verify the default emission factors eventually used at lower tiers.

Verification of changes in soil carbon in land that is undergoing transition in use can be performed by comparing measured carbon stocks in the land that has undergone the transition against carbon stocks of lands where the former land use is still present. In such case, care should be taken to ensure paired sites are well matched in terms of factors that may influence soil carbon turnover rates (e.g., soil type, native vegetation, drainage, topography, etc.).

Measurements of Greenhouse Gas Fluxes at Ecosystem Scale

Direct measurements of **ecosystem fluxes of greenhouse gases** can be used to verify, at a local scale, reported changes in carbon stocks. These flux observations are usually conducted by micrometeorological techniques, such as eddy covariance, using canopy towers placed inside forests or other ecosystems, mainly for CO_2 exchanges measurements (Aubinet *et al*., 2000). Generally, they provide data on the Net Ecosystem Exchange (NEE, see footnote 26). This approach is suitable for the comprehensive estimation of carbon emissions and removals at plot/ecosystem scale, providing data that can be compared with activity data/emission factors and default values used in deriving the emissions/removals for a particular LULUCF category. However, there are limitations in the upscaling of these results to regional and national level, as temporal and spatial variability, long-term trends and disturbances needs to be properly considered (Körner, 2003). Direct measurements of ecosystem net fluxes require significant investments in equipment and have limitation for possible locations (depending on topography, vegetation and canopy structure). Once implemented, such measurements can be performed on a continuous basis, providing an estimation of the interannual variability of the balance of CO_2 emissions and removals of a certain ecosystem. Due to its complexity, it is likely that ecosystem fluxes will be measured by research institutes/networks. If such experiments are available within a country, the inventory agency may consider using these results for verification.

APPROACH 4: REMOTE SENSING

Remote sensing is an effective approach for verifying land-cover/land-use attribution, detection of land-cover change and estimations of land areas under conversion and abandonment. In addition, remote sensing can be used to estimate changes in aboveground biomass. Both of these uses of remote sensing for verification are described below. Remote sensing is not applicable to the verification of belowground biomass, litter, dead wood or soil organic matter.

Remote sensing can be employed at scales ranging from plot to continental level. However, extracting accurate and repeatable information from remotely sensed imagery can be a demanding task, and is likely to require considerable technical expertise. The cost will depend upon the scope and scale of the programme. Costs can be relatively low if archived data are available. If frequent measurement and extensive data interpretation are required, however, both costs and the need for skilled expertise can increase substantially. Among other factors, the accuracy of remote sensing will depend upon the scale at which it is used and the source of the images. Generally, it can be quite accurate, but ground truthing is needed to improve result accuracy.

Approach 4a: Remote Sensing to Verify Land Use and Land-use Changes

Remote sensing is the most direct tool that can be used for verification of the area involved in conversion of forests and grassland to other land-use types (cropland, settlements, etc), the abandonment of managed land, and for fire detection (which is one of the main factors causing conversions in the tropics). However, if a country has used remote sensing techniques for the consistent representation of land areas (see Chapter 2, Section 2.4.4.1), or for the attribution of land-use and activities related to specific aspects of the Kyoto Protocol (see Chapter 4, Section 4.2.2), care must be taken to ensure that the remote sensing data used for verification are independent of those used for inventory development. From a technical point of view, remote sensing can be considered a verification ex-post, comparing consecutive surveys taken in different years.

It is also important to bear in mind that although remote sensing will in many cases readily detect changes in *land cover* (e.g., from a vegetation cover to bare ground), it may not always provide adequate and accurate information on changes in *land use* or *vegetation types* (e.g., from Crop A to Crop B)[25]. For example, detecting clear-cuts in forests based on remotely-sensed data alone is relatively easy, but it is more difficult to distinguish whether these are part of on-going forest management or represent deforestation (see also Chapter 4, Section 4.2.6.2.1). Similarly, separation of unmanaged pine forest from managed coniferous plantation forest has been reported to be difficult, with accuracies of only about 50% (Okuda and Nakane, 1988). Distinguishing between different crop types is a further area where remote sensing can have difficulty. The combination of frequent observation by moderate spatial resolution sensors and detailed observation by high-resolution sensors can sometimes solve this problem.

Due to interactions with the atmosphere, clouds in particular, the use of optical remote sensing data may have limits in certain regions of the globe (e.g., boreal and tropical zones) or periods of the year. In this respect, Synthetic Aperture Radar (SAR) sensors are better suited to this purpose, as data acquisition can be performed regardless of sunlight and cloud cover. Even using new sensors such as SAR, it would be challenging to estimate or verify land-use and land-cover changes on a yearly basis. In part, the challenges result from the resources (personnel and funding) that are needed for such efforts. Nonetheless, as the temporal and spatial resolution of

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[25] In some cases land cover might change, but not the land use, and vice versa.

satellite sensors improve, detection of sudden and/or recent changes in land use or cover may become possible on an annual or even more frequent basis.

Approach 4b: Remote sensing to verify changes in living biomass

Satellite remote sensing and its image products may also be appropriate for assessing biomass and biomass changes at the major ecosystem level (e.g., grassland vs. forest). Carbon stocks in forests can be estimated using correlations between spectral image data and biomass, provided that adequate data (not used for inventory estimates) are available to represent the range in forest biomes and management regimes for which estimates are required (Trotter *et al.* 1997). Correlation equations, may be affected by several parameters (canopy and understorey type, season, illumination, satellite-viewing geometry) (Okuda *et al.*, 2003), and must in general be developed for each forest type. In addition, vegetation indices (e.g., the Normalised Difference Vegetation Index, NDVI) have also been used for the estimation of above ground biomass (see Section 5.7.6 for an overview on such indices).

Another approach is to employ Synthetic Aperture Radar (SAR) data that provide structural, rather than spectral, information about the monitored land cover. For some forest types, wood biomass can be estimated with a certain level of accuracy, using the relationships between biomass and radar intensity (amplitude, backscattering) (Rauste *et al.*, 1994; Foody *et al.*, 1997; Luckman *et al.*, 1998; Saatchi *et al.*, 2000; Terhikki Manninen and Ulander, 2001) or indirectly, for instance by linking SAR derived tree heights with *in situ* derived allometric relationships. SAR data are suitable for assessing relative incremental changes in aboveground biomass stocks between two or more points in time, particularly when changes are relevant. Time sequences rather than single-date imagery allows characterisation of change trends and minimisation of errors in the estimations.

Both optical and SAR sensors have limitations in rough topographic terrain and in areas with heterogeneous canopy cover. The accuracy level of remotely sensed data varies with the geometric and radiometric characteristics of the sensors, including change in sensor calibration over time. The imaging data used should be chosen according to the geographical scale of the target area and the desired degree of resolution. Specifications (sensor type, spatial resolution, availability, etc.) of various satellite sensors are listed in Table 5.7.2, in Section 5.7.6.

Other approaches for area and biomass verification using imagery data may include:

- Airborne photography (for the vertical canopy structure of forest, labour-intensive);
- Laser profiler (LIDAR canopy height and structure, accuracy still to be examined, experimental, expensive);
- Comparison with maps/data produced by independent agencies using remote sensing.

APPROACH 5: VERIFICATION USING MODELS

Models can be used to verify estimates of carbon pools, activity data and also the overall inventory. Generally, they are not used in verification of land area classification. For specific land-use categories under the UNFCCC and activities selected under the Kyoto Protocol, models can be an attractive option when direct measurements combined with remote sensing are not feasible. Modelling costs can vary significantly, depending on the specific applications, availability of appropriate tools, and the degree of resolution desired. Starting costs associated with model design and calibration are generally much higher than ongoing running costs. Verification using models is quite complex and requires a high level of technical expertise.

There are two very different types of modelling approaches for verification purposes: bottom-up models and top-down models. Bottom-up models scale up from lower scale processes to higher aggregation levels, whereas top-down models follow the other direction and try to infer smaller scale processes from larger scale measurements. Although in principle both approaches may be used for verification purposes at the national level, the top-down models are more suited for continental scale verification. Bottom-up models can be used from site/plot level scale to regional and national and even continental level, provided the input data are available.

Models that are used for verification purposes, as models used in inventory preparation, need to be well documented and should have undergone peer-review. Input parameters, data, functions and assumptions should have been subjected to scrutiny, which is typically referred to as validation. The term validation is used in the generally accepted meaning of testing adequately the performance of a model, which is not equal to say that the model is the only true representation of reality (Oreskes *et al*, 1994).

As with other approaches, it should be noted that models have their advantages and drawbacks, and so far there is no such thing as a “best model”. For avoiding some of the possible biases associated with model choice, an ensemble of identically calibrated models could be used (Alexandrov *et al.*, 2002). Expert advice is often required to use models as verification tools.

Approach 5a: Bottom-up Modelling

There are several types of bottom-up models that can be used for verification:

Ecosystem and growth models can simulate growth of vegetation and the fate of carbon at sufficiently long time scales, which can be used for verification. They compute biomass growth and fluxes of carbon, water, and nitrogen, and are able to provide estimates of gross primary production (GPP)[26] and net primary production (NPP)[26] of carbon per unit area in forests (Kramer *et al.*, 2002) and other vegetation types. They can be used to verify Tier 1 and Tier 2 component estimates of biomass and fluxes, and also to derive "emission factors" and/or country-specific parameters relevant to Tier 2 calculations (see Table 5.7.1). In the case of forests, there are basically two classes of ecosystem models that can be applied: those that focus on physiology and biogeochemistry of the ecosystem, and those that are based on forest inventories. Well-known examples of these two classes are FOREST-BGC (Waring and Running 1998), Biome-BGC (Running and Coughlan, 1988; Running and Hunt, 1993; Running, 1994) and inventory based models (Kauppi *et al.*, 1992; Nabuurs *et al.*, 1997; Birdsey, 1996; Kurz and Apps, 1999)

Recently, a new generation of terrestrial carbon cycle models have been developed to integrate the effects of changes in climate, atmospheric chemistry, disturbance rates on NPP, NEP[26] and NBP[26] (e.g., Landsberg and Waring, 1997; Chen *et al.*, 2000a; Chen *et al.*, 2000b; McGuire *et al.*, 2001). Using spatial data from remote sensing (e.g., land cover, burnt area, and leaf area index) and georeferenced datasets of climate, atmospheric chemistry and soil inventory, these process-based models can scale up site-level data (e.g., ecosystem flux measurements) to regional and national scales. Without direct dependence on a forest inventory, the data estimated using these models could be used to compare to forest inventory-based carbon accounting. However, the ability of models in which land representation is based on remote sensing to quantify the carbon stock changes resulting from land use changes at small scale (e.g., afforestation, reforestation and deforestation) is limited by the spatial resolution of the remote sensing information.

If models are used to aggregate results and to provide data on biomass changes at national scale, model parameterisation needs to be adequately performed, taking into account the different land use and land cover existing in a country. As an example, to use model results as verification for forest inventory data, the parameterisation should be performed at least for the main tree species.

Regression models have been used to calculate NPP from basic meteorological data (e.g., Chikugo models, Uchijima and Seino, 1985). NPP values derived from regression and process-based models can be used for cross-checking of Tier 1 and Tier 2 data at large scale (see Table 5.7.1).

Modelling approaches using Geographical Information Systems (GIS) that incorporate ground truth data provide more accurate values than remote sensing approaches. GIS based data, such as topography and canopy cover and structural features such as climate can also be used to drive ecosystem and growth models in order to retrieve spatially explicit results. Accordingly, at continental and global scales, GIS modelling can be used to verify national land survey methodologies (Mollicone *et al.*, 2003).

Approach 5b: Top-down Modelling and Large-Scale Approaches

Top-down models could be used for the verification of carbon stocks and stock changes from regional to global scales. These approaches are not easily applicable to country level estimates, but can be used for aggregated countries, large regions or continents. For countries with very large land area or with features that allow to separation of in-country from external air-mass movements (e.g., North America, Boreal Zone-Siberia, Australia, United Kingdom, etc.), regional/continental scale approaches can be useful also at national scale. While top-down modelling can provide overall constraints on regional carbon budgets, they are not suitable for verification of sectoral carbon budgets, because they cannot separate the contribution of emissions and removals from different land-use categories or management activities -as required for the reporting under the UNFCCC and the Kyoto Protocol. Moreover, top-down modelling approaches include emissions and removals from land-use categories that are not subject to reporting under either the UNFCCC or the Kyoto Protocol (e.g., non-managed lands). Nevertheless, at larger scales, atmospheric measurements of greenhouse gas concentrations and isotopic composition should in principle be able to prove if the aggregate actions taken under UNFCCC and the Kyoto Protocol will be effective with respect to the trend in atmospheric greenhouse gas concentrations (Schulze *et al.*, 2002).

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[26] GPP: Gross Primary Production, given by the gross photosynthesis; NPP: Net Primary Production, net photosynthesis or GPP minus autotrophic respiration (from above- and belowground living plant biomass); NEP: Net Ecosystem Production, the net emissions or removals of carbon (CO_2), or NPP minus heterotrophic respiration (soil organic matter and soil organic carbon decomposition, animals), when NEP is measured using flux techniques in correctly defined as NEE, Net Ecosystem Exchange; NBP: Net Biome Production, the net emissions or removals of carbon at large scale (biome), which takes into account also natural and human-induced disturbances (fire, windtrows, harvest, NBP=NEP-disturbances). NBP is the term that finally is reflected in the global carbon budget (i.e., the atmosphere).

Inverse models calculate fluxes from concentration measurements and atmospheric transport models. They can be used to determine overall carbon dynamics at continental to global scales, but have limited ability to separate the contribution of different land-use categories or management activities to the total budget. By measuring the spatial and temporal distribution of CO_2 concentrations, it is possible to detect terrestrial and oceanic carbon fluxes. Inverse models are also used to calculate fluxes of methane and other greenhouse gases.

Incorporating airborne observations and using regional-level transport models in the inverse analysis can improve the estimates, as can the consideration of spatially distributed emissions/removals data. The implementation of inverse modelling approaches is under continuous development, requiring scientific collaboration and a networked system among nations. It is probable that such estimations will be independent from country data and will be valuable for overall verification at regional to continental level (see Gurney *et al.*, 2002 for a comparison of several inverse modelling results at continental scale).

At national level, another large scale approach that can be used for overall verification is the use of tall towers, which are generally available within a country (e.g., TV towers, transmission towers), to measure the CO_2 gradients (Bakwin *et al.*, 1995). This approach can be combined with the use of inverse modelling to derive regional/national balances of emissions and removals. Once in place, the system can be automated and is not very expensive.

5.7.3 Guidance for Verification of LULUCF Inventories

Several components of an inventory can be identified by inventory agencies (or external groups) for verification including emissions/removals estimates, input data, and assumptions. The questions in Box 5.7.2 can be used by an inventory agency as guidance for the development of a verification plan.

BOX 5.7.2

GUIDANCE FOR SELECTING INVENTORY COMPONENTS FOR VERIFICATION AND VERIFICATION APPROACHES

Which criteria can be used to choose the inventory elements for verification?

If any source/sink category is “key”, it should be given priority for verification. However, emissions and removals that are not “key” can also be selected for verification, especially if these are of relevance to mitigation policies or their uncertainty is high. If a pool is expected to change significantly over the inventory reporting period, particular attention should also be devoted to it.

How will the inventory elements be verified?

Selection of the verification approach will depend largely on the suitability/availability of the approach for the inventory agency or the country-specific conditions. Additional criteria are: the type of data to be verified, the spatial scale of the inventory coverage, the quantity and quality of the data to be verified, and the accuracy, precision and cost of the approach itself. The approaches and criteria for choosing them are elaborated in Table 5.7.1 and described in detail in Section 5.7.2.

If a country undertakes internal verification of its inventory, it is *good practice* to ensure that:

- Sufficient independent expertise is available;
- Documentation of the verification is included in the national inventory report;
- Uncertainty estimates and QA/QC documentation is included in the report;
- Other available national verification activities are described;
- Applied verification methods are transparent, rigorous and scientifically sound;
- Verification results are reasonable and well-explained;
- Final calculations can be reasonably linked to underlying data and assumption.

The checklist in the Box 5.7.3 summarises some of the tools that can be used for internal verification of an inventory, with particular emphasis on the LULUCF sector. A specific box is provided also for Kyoto Protocol aspects (see Section 5.7.4, Box 5.7.5).

BOX 5.7.3
VERIFICATION OF INVENTORY OF LULUCF SECTOR IN A NATIONAL INVENTORY

A. Checks:

Does the inventory of the LULUCF sector document the data and assumptions used for estimating emissions and removals for all IPCC source/sink categories?

Have all important carbon pools been included in the inventory?

If some LULUCF emission/removal categories have been omitted, does the report explain why?

Are emissions and removals reported as *positive* and *negative* terms, respectively?

For the total area of the inventory of the LULUCF sector, are the overall changes in land-use for the inventory year equal to zero within the confidence limit?

Are any discontinuities in trends from base year to end year evaluated and explained?

B. Comparisons of emissions and removals from LULUCF:

Compare the inventory of the LULUCF sector with independently prepared national inventories for the **same** country or compare regional sub-sets of the national inventory with independently prepared inventories for those regions. (Table 5.7.1, Approach 1).

Compare the inventory of the LULUCF sector with national inventories for a **different**, but similar country (Table 5.7.1, Approach 1).

Compare activity data and/or emission factors of the inventory of the LULUCF sector with independent international databases and/or other countries. For example, compare Biomass Expansion Factors of similar species with data from countries with similar forest conditions (Table 5.7.1, Approach 1).

Compare the inventory of the LULUCF sector with results calculated using another tier methodology, including defaults (Table 5.7.1, Approach 2).

Compare the inventory of the LULUCF sector with available high-intensity studies and experiments (Table 5.7.1, Approach 1-3).

Compare land areas and biomass stocks used in the inventory with remote sensing (Table 5.7.1, Approach 4).

Compare the inventory of the LULUCF sector with models (Table 5.7.1, Approach 5).

C. Comparisons of uncertainties:

Compare uncertainty estimates with uncertainty reported in the literature.

Compare uncertainty estimates with those from other countries and the IPCC default values.

D. Direct measurements:

Carry out direct measurements (such as local forest inventory, detailed growth measurements and/or ecosystem fluxes of greenhouse gases, Table 5.7.1, Approach 3).

Taking into account resource limitation, the information provided in the national inventory report should be verified as far as possible, particularly for key categories. The verification approaches in Box 5.7.3 can be applied as follows:

- The checks listed under A are essential and, ideally, these should have been conducted as part of QA/QC.
- It is *good practice* to perform verification with at least one of the approaches listed in Box 5.7.3 under B (see Table 5.7.1 and Section 5.7.2 for more information on the applicable approaches).
- If independent estimates on emissions and removals of greenhouse gases by LULUCF are not available, then internal or external verification will most probably be limited to scrutiny of the data and methods (Smith, 2001). Under these circumstances, it is *good practice* for the inventory agency to carry out these checks and to provide sufficient documentation in its national inventory report and other supporting material to facilitate external verification.

- Inventory agencies, taking into account country-specific circumstances and the availability of resources, can assess the proper combination of approaches for verifying their LULUCF inventories. Approaches 1, 2 and 3 are feasible for verifying several components of the inventory. Among those listed, Approaches 1 and 2 can be easily implemented by an inventory agency with low to moderate resources. Remote sensing is the most suitable method for the verification of land areas. Direct measurements (under D in Box 5.7.3) are relevant, although this approach can be resource-intensive and, on a large scale, costs may be a constraint. Models can be used as an alternative when direct measurements combined with remote sensing is not feasible.

5.7.4 Specific Issues Linked to the Kyoto Protocol

In general, the same approaches discussed in Section 5.7.2 can be used for verifying both an inventory submitted under the UNFCCC and reporting under the Kyoto Protocol. Although, the cost of measuring changes in carbon stocks for a given area increases as both desired precision and landscape heterogeneity increase, the same principles of *good practice* apply to projects and national inventories.

An inventory agency can use the questions in Box 5.7.4 to help guide the development of a verification plan for supplementary information reported under Articles 3.3 and 3.4 of the Kyoto Protocol.

BOX 5.7.4
GUIDANCE FOR VERIFYING CARBON POOLS AND ACTIVITIES

Which carbon pools to verify?

It is *good practice* to focus verification on those carbon pools that are expected to be most relevant to the Kyoto Protocol but also on non-CO_2 greenhouse gas emissions. The Marrakesh Accords list the following pools: aboveground and belowground biomass, litter, dead wood and soil organic carbon. As stated in the Marrakesh Accords, a Party may exclude particular pools from reporting, if verifiable information is provided showing that the pool has not been a source of greenhouse gases for activities under Article 3.3 and elected activities under Article 3.4, or for projects. Therefore the information required is different for selected (changes of the pools following advice provided on Chapter 3 and 4) and non-selected pools (additional information demonstrating that they are not a source). As for LULUCF inventories, if a pool is expected to change significantly over the inventory reporting period, particular attention should also be devoted to it.

Which activities to verify?

According to the Marrakesh Accords, a Party has to report activities under Article 3.3 and may choose only certain activities under Article 3.4 of the Kyoto Protocol. For all obligatory or elected activities, elements which are specific to the reporting under Kyoto Protocol inventories include: the identification of the areas in which such activities have taken place, the demonstration that the activities have occurred since 1st January 1990 and are human induced, and the establishment of the “1990” base year (reference year for reforestation activities and base year for net-net accounting).

Specific verification related to estimates developed under Articles 3.3 and 3.4 of the Kyoto Protocol may include:

- For lands introduced into a reporting under Kyoto Protocol, it is *good practice* to verify such lands using geographical and statistical information, such as remote sensing data. Even if georeferencing was not required, this would facilitate verification (Smith, 2001).
- The reporting of greenhouse gas emissions and removals of most Article 3.3 and 3.4 activities require reference to 1990 or pre-1990 data (classification of forest/non forest lands for 1990, net-net accounting for cropland management, grazing land management, revegetation, etc.). In some cases, these data may not be available or their reliability may be limited and estimates may be used, subject to advice in Chapter 4 Section 4.2.8.1. In such cases, it is *good practice* to verify the estimation approach and values, as much as possible.

Emissions and removals from project activities can be reported under Articles 6 and 12 of the Kyoto Protocol, and Chapter 4 of this report lists different types of projects and suggests the type of information that may need to be verified for each. While many of the approaches presented in Section 5.7.2 are useful for project verification, additional rules are being developed under the Kyoto Protocol and the Marrakesh Accords[27]. This factor not withstanding, verification of projects is generally easier than national level verification. For projects, boundaries, carbon pools and lifetimes are all factors that can be well established, and hence verified. Generally, projects with good monitoring and reporting plans are likely to be easier to verify.

As with inventories of LULUCF sector, inventory agencies, taking specific circumstances and the resource availability into account, may choose the proper combination of approaches for verifying supplementary information reported under the Kyoto Protocol. Among these approaches, remote sensing is the most suitable for the verification of land areas. Direct measurements are relevant, although this approach can be resource intensive. Models can be used as an alternative when direct measurements combined with remote sensing is not feasible. Some verification steps, which are unique to the Kyoto Protocol, are presented in Box 5.7.5.

BOX 5.7.5
VERIFICATION OF LULUCF UNDER THE KYOTO PROTOCOL

Checks:

If a Party reports that an activity has occurred on forest land, is the definition of 'forest' provided and consistent with activities and land units reported? Is information on selected crown cover and tree height provided?

Are changes in all carbon pools reported (aboveground and belowground biomass, dead wood, litter, soil organic carbon)? If not, is the reason and documentation for omitting a pool given?

Are geographical boundaries of land areas specified for the activities eligible under Articles 3.3 and 3.4?

Is the total land area reported under Article 3.3 and 3.4 constant or increasing throughout subsequent or contiguous commitment periods?

Is information provided that demonstrates that the elected activities under Article 3.4 occurred since 1990 and are human induced?

For Article 3.3, is information provided to distinguish deforestation from harvesting (clear-cut) or forest disturbance followed by re-establishment of a forest?

The checks listed in Box 5.7.5 are essential and, ideally, should have been conducted as part of QA/QC. In addition to these specific checks, the comprehensive list presented in Box 5.7.3 under items B to D can be used to identify additional useful verification activities.

5.7.5 Reporting and Documentation

When an inventory agency has undertaken verification activities, it is *good practice* to report and document the following items:

- Information that has been verified;
- Criteria that were used for the selection of verification priorities;
- Verification approaches, along with relevant data that were collected;
- Any limitations in the approaches that have been identified;
- Eventual comparisons that have been performed with independent inventories, datasets, scientific literature, etc;
- Any feedback received from external reviewers, with a summary of key comments;
- Main conclusions of the verification;
- Actions taken as a result of the verification process;

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[27] The verification to which the paragraph refers is to be considered in the context of the present chapter (as defined in Section 5.7.1). According to the Marrakesh Accords, projects have to be subjected to specific "verification", as defined in draft decision -/CMP.1 (Article 6), -/CMP.1 (Article 12) and their annexes (FCCC/CP/2001/13/Add.2).

- Any recommendations for inventory improvements or research at national/international level arising from the findings.

Inventory agencies are also encouraged to provide information on the external verification activities by other bodies, to the extent that they are relevant to the inventory and that any such information can be readily collected and summarised.

If modelling has been used for verification, it is *good practice* to fully document the modelling process. Other information to be reported includes: sources of input data, a discussion of model and data assumptions, and description of procedures and analysis. Because of the volume of input data, and the number of variables that are needed for a typical large model, documentation may be dense, technical and lengthy. It is *good practice* to report the above information comprehensively and transparently. The information to be included should allow a third party to fully understand the verification process, and to corroborate the results if needed.

5.7.6 Some Details for Verification Approaches

COMPARISONS WITH INTERNATIONAL PROGRAMS AND DATASETS

For an inventory agency that is willing to compare an inventory or part of it against datasets coming from international monitoring and research programmes, it can be useful to follow the links provided in Box 5.7.6. Obviously, the Box is not exhaustive of all programmes available, but it provides information for some of those that are more relevant to LULUCF.

BOX 5.7.6
PROGRAMMES AND NETWORKS RELEVANT TO LULUCF

FLUXNET (Ameriflux, CarboEuroflux)
Network of ecosystem flux measurements, mostly on forest stands, but also other land use type
Common database, links to ecosystem studies
http://www-eosdis.ornl.gov/FLUXNET/index.html

CarboEurope (funded by the European Commission)
Cluster of projects aimed at understanding the carbon balance of Europe with different approaches (flux measurements, ecosystem studies, regional and continental budgeting, inverse modelling, ecosystem modelling)
http://www.bgc-jena.mpg.de/public/carboeur/

International Geosphere-Biosphere Programme (IGBP)
Net Primary Production data sets, coordination of international research efforts, global change and terrestrial ecosystem, etc
http://www.igbp.kva.se/cgi-bin/php/frameset.php
http://www.gcte.org/

Long Term Ecological Research (forests, grasslands)
Network of ecosystem ecological studies present in different countries
http://www.lternet.edu/

FAO
Database of terrestrial ecosystem research sites (TEM), Global Terrestrial Observing System (GTOS), Global Climate Observing System (GCOS), Forest Resource Assessments (FRA)
http://www.fao.org/

Monitoring networks:
ICP Forests
The common European Union International Cooperative Programme on Forest (EU/ICP Forests) works on two levels with standardised protocols and methods in 35 countries. The systematic grid net has approximately 6000 Level I points where limited number of surveys are carried out, whereas the intensive monitoring grid net has 860 Level II plots in the mayor forest types of the European continent where large number of surveys are carried out.
http://www.icp-forests.org/

ICP/IM and EMEP
The multi-disciplinary ICP Integrated Monitoring programme (ICP/IM) and the Co-operative Programme for Monitoring and Evaluation of the Long-Range Transmissions of Air Pollutants in Europe (EMEP)

BOX 5.7.6 (CONTINUED)
PROGRAMMES AND NETWORKS RELEVANT TO LULUCF

A part of the monitoring strategy and evaluation of the effects under the Long-range Transboundary Air Pollution Convention of the United Nation's Economic Commission for Europe (UNECE). The EMEP programme relies on three main elements: (1) collection of emissions data, (2) measurements of air and precipitation quality and (3) modelling of atmospheric transport and deposition of air pollution.
http://www.vyh.fi/eng/intcoop/projects/icp_im/im.htm
http://www.emep.int/

Global Carbon Project
The Global Carbon Project is a project of the Earth System Science Partnership of the International Geosphere Biosphere Programme (IGBP) World Climate Research Programme (WCRP) and the International Human Dimensions Programme (IHDP). The scientific goal of the Global Carbon Project is to develop a complete picture of the global carbon cycle, including both its biophysical and human dimensions together with the interactions and feedbacks between them.
http://www.globalcarbonproject.org/

The Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC)
A source for biogeochemical and ecological data collected on the ground, from aircraft, by satellite or generated by computer models. The scale of data ranges from site-specific to global, and duration range from days to years. ORNL Environmental Sciences Division (ESD) operates the ORNL-DAAC for Biogeochemical Dynamics as part of the National Aeronautics and Space Administration's (NASA) Earth Science Enterprise (ESE) programme.
http://www-eosdis.ornl.gov/

REMOTE SENSING

Overview of Available Remote Sensing Sensors

Optical satellite data going from coarse to high resolution, are available worldwide from NOAA AVHRR, SPOT Vegetation, ERS/ATSR, MODIS, Envisat MERIS, Landsat TM/ETM and several other sensors. Multi-frequency/polarisation radar, that was only recently made available from NASA AIRSAR missions, is also very useful for vegetation classification. Those sensors, being sensitive to vegetation structural characteristics, provide an excellent complementary data source to optical remote sensing. Such radar data will begin to become more available with Envisat ASAR and the launch of RadarSat 2. The accuracy of remotely sensed data varies with the geometric and radiometric characteristics of the sensors. Specifications (sensor type, spatial resolution, availability, etc.) of various satellite sensors are listed in Table 5.7.2, further information can be found at http://idisk.mac.com/alexandreleroux/Public/agisrs/arsist.html. The imaging data used should be chosen according to the geographical scale of the target area and the desired degree of resolution. The use of different sensors can be a solution to circumvent the limitation of remote sensing in areas of persistent cloud cover (e.g., optical and radar data).

Use of Remote Sensing to Derive Vegetation Parameters

Net Primary Production (NPP) is known to be positively correlated with photosynthetically active radiation (PAR), which also can be estimated from NDVI (Normalised Difference Vegetation Index) and solar radiation.

The functional relationship between optical remote sensing data (including indices like the NDVI) and carbon stocks is that canopy reflectance is related to leaf area index (LAI), and LAI in turn has a strong functional relationship to woody biomass and NPP (Gholz, 1982; Waring, 1983). An alternative interpretation of the relationship is that reflectance is related to the fraction of absorbed photosynthetically active radiation (fAPAR), which over longer time periods is linearly correlated to NPP (e.g., Monteith, 1977; Landsberg and Waring, 1997). The NDVI has been widely used to estimate both LAI and fAPAR from remotely sensed data.

NDVI and solar radiation determined by remote sensing, coupled with meteorological measurements and geographical information system (GIS) data, can be used to make estimates also at larger scales (regional to global). NDVI has also been used to derive growing season duration, a parameter that has been shown to be closely linked to the Net Ecosystem Exchange (NEE, the net carbon sink) measured by ecosystem fluxes, particularly in deciduous forests (Baldocchi *et al.*, 2001). However, when this approach is used, care must be taken in considering that fine-scale differences are difficult to handle and that not all vegetation successional phases are properly covered by NDVI (recovery processes, etc.). Furthermore, most of the ecosystem parameters derived from correlations with NDVI are likely to be species and/or biome specific. Moreover, the NDVI is influenced by factors other than canopy LAI or fAPAR, and the relationships have a tendency to saturate at LAI values above about 3 $m^2 m^{-2}$ (Moreau and Li, 1996; Carlson and Ripley, 1997; Gemmell and McDonald, 2000), although, for conifer canopies, the saturation did not occur for LAI up to 10 $m^2 m^{-2}$ (Chen *et al*., 2002). Because of the saturation, NDVI derived from LANDSAT images was found to be poorly correlated with stand structure variables or total aboveground biomass within forest stands in the tropics. In general, NDVI-based approaches to estimating LAI or fAPAR will be a function of soil reflectance, fractional cover, biome type, and illumination/viewing conditions. These factors result in a wide variation in the equations used for estimating LAI (or fAPAR) from NDVI (Moreau and Li 1996), and users should consider this if selecting or deriving equations. If spectral indices are to be used as the basis for constructing a relationship with LAI or fAPAR, consideration should be given to using an index that is less affected by variations in parameters such as soil reflectance (Kaufman and Tanré, 1992; Huete *et al*., 1997). The Enhanced Vegetation Index (EVI) is perhaps the most promising of these, and is both simple to implement for most sensors and linearly related to fAPAR (Huete *et al*., 1997; Gobron *et al*., 2000). For datasets for which 1-km pixels are sufficient, users may be able to use the MODIS or MERIS fAPAR data and MODIS LAI data. In addition, software is freely available to generate high-quality fAPAR values (Gobron *et al*., 2000) from data acquired by the SeaWIFS, MERIS, VEGETATION, or GLI sensors.

Above ground biomass can be estimated efficiently also by LIDAR airborne sensing that measure the canopy surface and ground elevation height at the same time, by emitting laser pulses with wavelengths that reflect over the canopy surface but pass through trees and reflect off the ground as well. However, because of the small diameter beams of laser, mapping large areas requires extensive flying missions (Dubayah and Drake, 2000). The Laser Vegetation Imaging Sensor (LVIS) by airborne or satellite instruments such as Vegetation Canopy LIDAR with large footprints will possibly solve such problems (Blair *et al*., 1999; Means *et al*, 1999; Dubayah and Drake, 2000). One can also estimate vegetation structure from optical satellite data using the Bi-Directional Reflectance property based on the Sun-Target-Sensor Geometry.

Use of Remote Sensing for Fire Detection and Burnt area

Remote sensing is also frequently applied for forest fire detection.. Examples of forest fire or fire scars detection at different scales range from detection of 1 ha burn scars on a national basis using Landsat TM (e.g., ITALSCAR, 2003: Regional Burned Forest Mapping in Italy, http://www.esa.int/dup) or for European Union’s Member States (http://natural-hazards.jrc.it/fires/) to the use of ERS SAR in Indonesia (Page *et al*., 2002), to global detection of active fires (ATSR World Fire Atlas, 2003: http://earth.esa.int/ionia/FIRE/), burn scars (GLOBSCAR, 2003 Global Burned Forest Mapping, http://earth.esa.int/ionia/FIRE/; GLOBCARBON, 2003: Global Land Products for Carbon Model Assimilation, http://www.esa.int/dup) and burnt areas (Global Brunt Area 2000: http://www.gvm.sai.jrc.it/fire/gba2000_website/index.htm). As an example, a recent study using remote sensing techniques has estimated the total area deforested due to fires in the humid tropics between 1990 and 1997, arriving at a different number to that reported by FAO statistics, that are using deforestation data reported by countries and experts (Achard *et al*., 2002).

TABLE 5.7.2 FEATURES OF SOME OF THE MAIN REMOTE SENSING PLATFORMS

Satellite	Sensor name	Country (Operation)	Spatial Resolution	Swath	Sensor type and scale		Spectral information				Data availability (acquisition period)			
			(m) at nadir	(km)	Type	Scale	VNIR	SWIR	TIR	SAR	1980 - 1990	1990 - 1999	2000 - 2007	2008 - 2012
NOAA (POES)	AVHRR	USA	1100	2700	O	Co-G	M	S	M	-	A	A	A	A
SPOT	Vegetation	EU	1150	2250	O	Co-G	M	S		-		PA	PA	MA
ADEOS-II	GLI	Japan	250, 1000	1600	O	Co-G	M	M	M	-			PA	MA
Terra/Aqua	MODIS	USA	250, 500, 1000	2330	O	Co-G	M	M	M	-			A	PA
Terra	MISR	USA	275, 550, 1000	360	O	Co-G	M			-			PA	
ERS-1/2	ATSR-1/2	Europe	1000	500	O	Co-G	M	M	M			PA	A	MA
Envisat	AATSR	Europe	1000	500	O	Co-G	M	M	M				PA	MA
NPOESS	VIRS	USA	400	3000	O	Co-G	M	M	M	-				A
Envisat	MERIS	Europe	300 (Land)	1150	O	Co-G	M	M		-			PA	MA
Landsat	MSS	USA	80	185	O	R	M			-	A	A		
Landsat	TM	USA	30, 120	185	O	R	M	M	S	-	PA	A	PA	
Landsat	ETM+	USA	15, 30, 60	185	O	R	M	M	S	-			A	A
SPOT	HRV/HRVIR/HRG	French	(2.5), 10, 20	60	O	R	M	(S)		-	PA	A	A	
Terra	ASTER	Japan/USA	15, 30, 90	60	O	R	M	M	M	-			A	
IRS-1C/D	PAN/LISS-3	India	6 / 23	70 / 141	O	R	M	S		-		PA	PA	
JERS-1	OPS (VNIR)	Japan	18*24	75	O	R	M					PA		
ALOS	AVNIR-2	Japan	10	70	O	R	M			-			PA	A
ALOS	PRISM	Japan	2.5	35/70	O	R	S			-			PA	MA
IKONOS	Pan/Multi	USA	0.82 / 3.3	11	O	R	M			-			A	MA
Orbview-3	Pan/Multi	USA	0.82/ 3.3	8	O	R	M			-			PA	MA
QuickBird	Pan/Multi	USA	0.61 / 2.5	17	O	R	M			-			PA	MA
EO-1	ALI	USA	10, 30	185	O	R	M	M		-			PA	
EO-1	Hyperion	USA	30	7.5	O	R	H	H		-			PA	
JERS-1	SAR	Japan	18	75	S	R	-	-	-	L		PA		
ALOS	PALSAR	Japan	10, 100	70, 250-350	S	R	-	-	-	L			PA	MA
ERS-1/2	AMI	Europe	30	100	S	R	-	-	-	C		PA	PA	MA
Envisat	ASAR	Europe	30, 100, 150	100, 400	S	R	-	-	-	C			PA	MA
Radarsat-1/2	SAR	Canada	(3, 8), 10, 30	(20), 50, 100	S	R	-	-	-	C		PA	A	MA
TerraSAR	SAR	Germany	1-3, 3-15	10, 40-60	S	R	-	-	-	X/L			PA	MA
LIDAR														
VCL	VCL	USA	25	8	L	R	S			-			PA	MA

O: optical; S: synthetic aperture radar; L: LIDAR; Co: continental; G: global; R: regional; S: single band; M: multiple band; H: hyper band. A: available for the entire period;

PA: available for a portion of the period; MA: may be available during the period