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Contents

CHAPTER 2

GENERIC METHODOLOGIES APPLICABLE TO MULTIPLE LAND-USE CATEGORIES

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Contents

2 Generic Methodologies Applicable to Multiple Land-use Categories

Equations

Figures

Tables

Boxes

2 GENERIC METHODOLOGIES APPLICABLE TO MULTIPLE LAND-USE CATEGORIES

2.1 INTRODUCTION

Methods to estimate greenhouse gas emissions and removals in the Agriculture, Forestry and Other Land Use (AFOLU) Sector can be divided into two broad categories: 1) methods that can be applied in a similar way for any of the types of land use (i.e., generic methods for Forest Land, Cropland, Grassland, Wetlands, Settlements and Other Land); and 2) methods that only apply to a single land use or that are applied to aggregate data on a national-level, without specifying land use. Chapter 2 provides mainly descriptions of generic methodologies under category (1) for estimating ecosystem carbon stock changes as well as for estimating non-CO_2 fluxes from fire. These methods can be applied for any of the six land-use categories. Generic information on methods includes:

- general framework for applying the methods within specific land-use categories;
- choice of methods, including equations and default values for Tier 1 methods for estimating C stock changes and non-CO_2 emissions;
- general guidance on use of higher Tier methods;
- use of the IPCC Emission Factor Data Base (EFDB); and
- uncertainty estimation.

Specific details and guidance on implementing the methods for each of the land-use and land-use conversion categories, including choosing emission factors, compiling activity data and assessing uncertainty, are given in the chapters on specific land-use categories (see Chapters 4 to 9). Guidance on inventory calculations for each specific land use refers back to this chapter for description of methods where they are generic.

2.2 INVENTORY FRAMEWORK

This section outlines a systematic approach for estimating carbon stock changes (and associated emissions and removals of CO_2) from biomass, dead organic matter, and soils, as well as for estimating non-CO_2 greenhouse gas emissions from fire. General equations representing the level of land-use categories and strata are followed by a short description of processes with more detailed equations for carbon stock changes in specific pools by land-use category. Principles for estimating non-CO_2 emissions and common equations are then given. Specific, operational equations to estimate emissions and removals by processes within a pool and by category, which directly correspond to worksheet calculations, are provided in Sections 2.3 and 2.4.

2.2.1 Overview of carbon stock change estimation

The emissions and removals of CO_2 for the AFOLU Sector, based on changes in ecosystem C stocks, are estimated for each land-use category (including both land remaining in a land-use category as well as land converted to another land use). Carbon stock changes are summarized by Equation 2.1.

EQUATION 2.1
ANNUAL CARBON STOCK CHANGES FOR THE ENTIRE AFOLU SECTOR ESTIMATED AS THE SUM OF CHANGES IN ALL LAND-USE CATEGORIES

$$\Delta C_{AFOLU} = \Delta C_{FL} + \Delta C_{CL} + \Delta C_{GL} + \Delta C_{WL} + \Delta C_{SL} + \Delta C_{OL}$$

Where:

ΔC = carbon stock change

Indices denote the following land-use categories:

AFOLU = Agriculture, Forestry and Other Land Use

FL = Forest Land

CL = Cropland

GL = Grassland

WL = Wetlands

SL = Settlements

OL = Other Land

For each land-use category, carbon stock changes are estimated for all *strata* or subdivisions of land area (e.g., climate zone, ecotype, soil type, management regime etc., see Chapter 3) chosen for a land-use category (Equation 2.2). Carbon stock changes within a stratum are estimated by considering carbon cycle processes between the five carbon pools, as defined in Table 1.1 in Chapter 1. The generalized flowchart of the carbon cycle (Figure 2.1) shows all five pools and associated fluxes including inputs to and outputs from the system, as well as all possible transfers between the pools. Overall, carbon stock changes within a stratum are estimated by adding up changes in all pools as in Equation 2.3. Further, carbon stock changes in soil may be disaggregated as to changes in C stocks in mineral soils and emissions from organic soils. Harvested wood products (HWP) are also included as an additional pool.

EQUATION 2.2
ANNUAL CARBON STOCK CHANGES FOR A LAND-USE CATEGORY AS A SUM OF CHANGES IN EACH STRATUM WITHIN THE CATEGORY

$$\Delta C_{LU} = \sum_{i} \Delta C_{LU_I}$$

Where:

ΔC_{LU} = carbon stock changes for a land-use (LU) category as defined in Equation 2.1.

i = denotes a specific stratum or subdivision within the land-use category (by any combination of species, climatic zone, ecotype, management regime etc., see Chapter 3), i = 1 to n.

EQUATION 2.3
ANNUAL CARBON STOCK CHANGES FOR A STRATUM OF A LAND-USE CATEGORY AS A SUM OF CHANGES IN ALL POOLS

$$\Delta C_{LU_i} = \Delta C_{AB} + \Delta C_{BB} + \Delta C_{DW} + \Delta C_{LI} + \Delta C_{SO} + \Delta C_{HWP}$$

Where:

ΔC_{LU_i} = carbon stock changes for a stratum of a land-use category

Subscripts denote the following carbon pools:

AB = above-ground biomass

BB = below-ground biomass

DW = deadwood

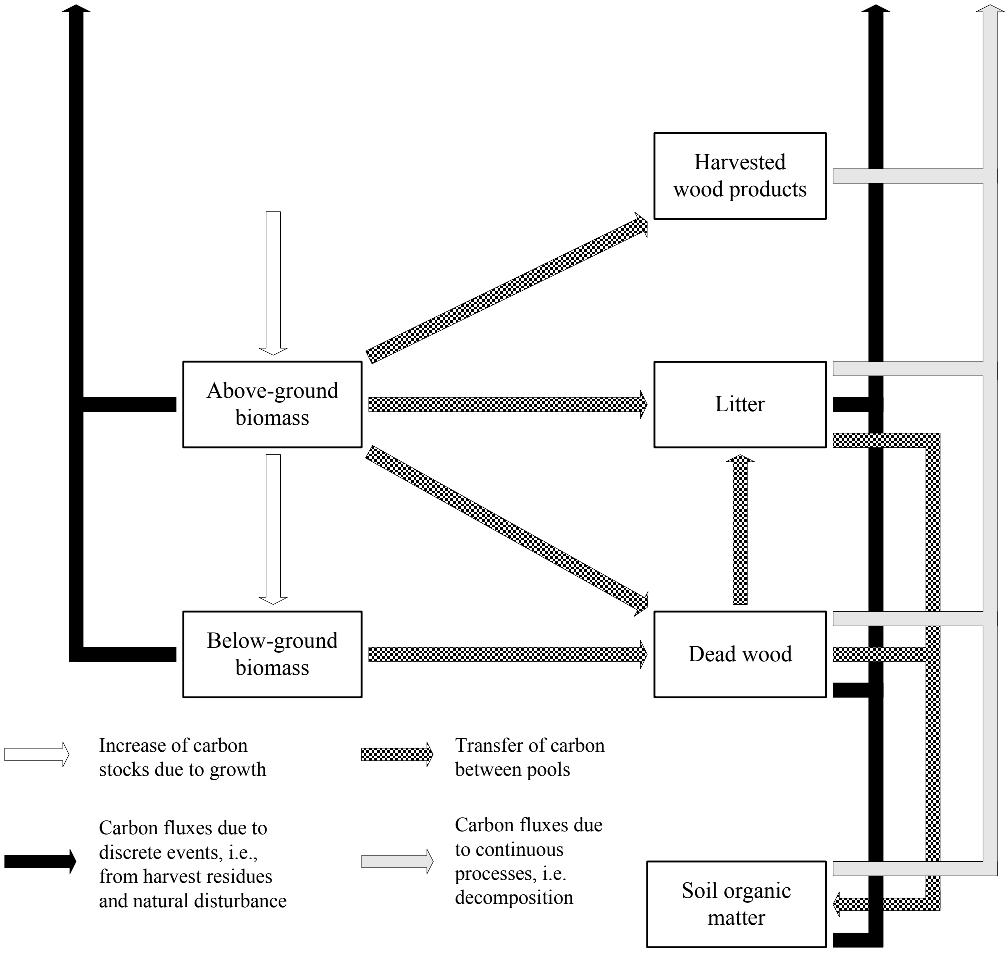
LI = litter

SO = soils

HWP = harvested wood products

Estimating changes in carbon pools and fluxes depends on data and model availability, as well as resources and capacity to collect and analyze additional information (See Chapter 1, Section 1.3.3 on key category analysis). Table 1.1 in Chapter 1 outlines which pools are relevant for each land-use category for Tier 1 methods, including cross references to reporting tables. Depending on country circumstances and which tiers are chosen, stock changes may not be estimated for all pools shown in Equation 2.3. Because of limitations to deriving default data sets to support estimation of some stock changes, Tier 1 methods include several simplifying assumptions:

Figure 2.1 Generalized carbon cycle of terrestrial AFOLU ecosystems showing the flows of carbon into and out of the system as well as between the five C pools within the system.



- change in below-ground biomass C stocks are assumed to be zero under Tier 1 (under Tier 2, country-specific data on ratios of below-ground to above-ground biomass can be used to estimate below-ground stock changes);
- under Tier 1, dead wood and litter pools are often lumped together as 'dead organic matter' (see discussion below); and
- dead organic matter stocks are assumed to be zero for non-forest land-use categories under Tier 1. For Forest Land converted to another land use, default values for estimating dead organic matter carbon stocks are provided in Tier 1.

The carbon cycle includes changes in carbon stocks due to both continuous processes (i.e., growth, decay) and discrete events (i.e., disturbances like harvest, fire, insect outbreaks, land-use change and other events). Continuous processes can affect carbon stocks in all areas in each year, while discrete events (i.e., disturbances) cause emissions and redistribute ecosystem carbon in specific areas (i.e., where the disturbance occurs) and in the year of the event.

Disturbances may also have long-lasting effects, such as decay of wind-blown or burnt trees. For practicality, Tier 1 methods assume that all post-disturbance emissions (less removal of harvested wood products) are estimated as part of the disturbance event, i.e., in the year of the disturbance. For example, rather than estimating the decay of dead organic matter left after a disturbance over a period of several years, all post-disturbance emissions are estimated in the year of the event.

Under Tier 1, it is assumed that the average transfer rate into dead organic matter (dead wood and litter) is equal to the average transfer rate out of dead organic matter, so that the net stock change is zero. This assumption means that dead organic matter (dead wood and litter) carbon stocks need not be quantified under Tier 1 for land areas that remain in a land-use category[1]. The rationale for this approach is that dead organic matter stocks, particularly dead wood, are highly variable and site-specific, depending on forest type and age, disturbance history and management. In addition, data on coarse woody debris decomposition rates are scarce and thus it was deemed that globally applicable default factors and uncertainty estimates can not be developed. Countries experiencing significant changes in forest types or disturbance or management regimes in their forests are encouraged to develop domestic data to estimate the impact from these changes using Tier 2 or 3 methodologies and to report the resulting carbon stock changes and non-CO_2 emissions and removals.

All estimates of changes in carbon stocks, i.e., growth, internal transfers and emissions, are in units of carbon to make all calculations consistent. Data on biomass stocks, increments, harvests, etc. can initially be in units of dry matter that need to be converted to tonnes of carbon for all subsequent calculations. There are two fundamentally different and equally valid approaches to estimating stock changes: 1) the process-based approach, which estimates the net balance of additions to and removals from a carbon stock; and 2) the stock-based approach, which estimates the difference in carbon stocks at two points in time.

Annual carbon stock changes in any pool can be estimated using the process-based approach in Equation 2.4 which sets out the *Gain-Loss Method* that can be applied to all carbon gains or losses. Gains can be attributed to growth (increase of biomass) and to transfer of carbon from another pool (e.g., transfer of carbon from the live biomass carbon pool to the dead organic matter pool due to harvest or natural disturbances). Gains are always marked with a positive (+) sign. Losses can be attributed to transfers of carbon from one pool to another (e.g., the carbon in the slash during a harvesting operation is a loss from the above-ground biomass pool), or emissions due to decay, harvest, burning, etc. Losses are always marked with a negative (-) sign.

EQUATION 2.4
ANNUAL CARBON STOCK CHANGE IN A GIVEN POOL AS A FUNCTION OF GAINS AND LOSSES
(GAIN-LOSS METHOD)

$$\Delta C = \Delta C_G - \Delta C_L$$

Where:

ΔC = annual carbon stock change in the pool, tonnes C yr^{-1}

ΔC_G = annual gain of carbon, tonnes C yr^{-1}

---

[1] Emissions from litter C stocks are accounted for under Tier 1 for forest conversion to other land-use.

ΔC_L = annual loss of carbon, tonnes C yr^{-1}

Note that CO_2 removals are transfers from the atmosphere to a pool, whereas CO_2 emissions are transfers from a pool to the atmosphere. Not all transfers involve emissions or removals, since any transfer from one pool to another is a loss from the donor pool, but is a gain of equal amount to the receiving pool. For example, a transfer from the above-ground biomass pool to the dead wood pool is a loss from the above-ground biomass pool and a gain of equal size for the dead wood pool, which does not necessarily result in immediate CO_2 emission to the atmosphere (depending on the Tier used).

The method used in Equation 2.4 is called the *Gain-Loss Method*, because it includes all processes that bring about changes in a pool. An alternative stock-based approach is termed the *Stock-Difference Method*, which can be used where carbon stocks in relevant pools are measured at two points in time to assess carbon stock changes, as represented in Equation 2.5.

EQUATION 2.5

CARBON STOCK CHANGE IN A GIVEN POOL AS AN ANNUAL AVERAGE DIFFERENCE BETWEEN ESTIMATES AT TWO POINTS IN TIME (STOCK-DIFFERENCE METHOD)

$$\Delta C = \frac{(C_{t_2} - C_{t_1})}{(t_2 - t_1)}$$

Where:

ΔC = annual carbon stock change in the pool, tonnes C yr^{-1}

C_{t_1} = carbon stock in the pool at time t_1, tonnes C

C_{t_2} = carbon stock in the pool at time t_2, tonnes C

If the C stock changes are estimated on a per hectare basis, then the value is multiplied by the total area within each stratum to obtain the total stock change estimate for the pool. In some cases, the activity data may be in the form of country totals (e.g., harvested wood) in which case the stock change estimates for that pool are estimated directly from the activity data after applying appropriate factors to convert to units of C mass. When using the Stock-Difference Method for a specific land-use category, it is important to ensure that the area of land in that category at times t_1 and t_2 is identical, to avoid confounding stock change estimates with area changes.

The process method lends itself to modelling approaches using coefficients derived from empirical research data. These will smooth out inter-annual variability to a greater extent than the stock change method which relies on the difference of stock estimates at two points in time. Both methods are valid so long as they are capable of representing actual disturbances as well as continuously varying trends, and can be verified by comparison with actual measurements.

2.2.2 Overview of non-CO_2 emission estimation

Non-CO_2 emissions are derived from a variety of sources, including emissions from soils, livestock and manure, and from combustion of biomass, dead wood and litter. In contrast to the way CO_2 emissions are estimated from biomass stock changes, the estimate of non-CO_2 greenhouse gases usually involves an emission rate from a source directly to the atmosphere. The rate (Equation 2.6) is generally determined by an emission factor for a specific gas (e.g., CH_4, N_2O) and source category and an area (e.g., for soil or area burnt), population (e.g., for livestock) or mass (e.g., for biomass or manure) that defines the emission source.

EQUATION 2.6

NON-CO_2 EMISSIONS TO THE ATMOSPHERE

$$Emission = A \bullet EF$$

Where:

Emission = non-CO_2 emissions, tonnes of the non-CO_2 gas

A = activity data relating to the emission source (can be area, animal numbers or mass unit, depending on the source type)

EF = emission factor for a specific gas and source category, tonnes per unit of A

Many of the emissions of non-CO_2 greenhouse gases are either associated with a specific land use (e.g., CH_4 emissions from rice) or are typically estimated from national-level aggregate data (e.g., CH_4 emissions from livestock and N_2O emissions from managed soils). Where an emission source is associated with a single land use, the methodology for that emission is described in the chapter for that specific land-use category (e.g., methane from rice in Chapter 5 on Cropland). Emissions that are generally based on aggregated data are dealt with in separate chapters (e.g., Chapter 10 on livestock-related emissions, and Chapter 11 on N_2O emissions from managed soils and CO_2 emissions from liming and urea applications). This chapter describes only methods to estimate non-CO_2 (and CO_2) emissions from biomass combustion, which can occur in several different land-use categories.

2.2.3 Conversion of C stock changes to CO_2 emissions

For reporting purposes, changes in C stock categories (that involve transfers to the atmosphere) can be converted to units of CO_2 emissions by multiplying the C stock change by -44/12. In cases where a significant amount of the carbon stock change is through emissions of CO and CH_4, then these non-CO_2 carbon emissions should be subtracted from the estimated CO_2 emissions or removals using methods provided for the estimation of these gases. In making these estimates, inventory compilers should assess each category to ensure that this carbon is not already covered by the assumptions and approximations made in estimating CO_2 emissions.

It should also be noted that not every stock change corresponds to an emission. The conversion to CO_2 from C, is based on the ratio of molecular weights (44/12). The change of sign (-) is due to the convention that increases in C stocks, i.e. positive (+) stock changes, represent a removal (or 'negative' emission) from the atmosphere, while decreases in C stocks, i.e. negative (-) stock changes, represent a positive emission to the atmosphere.

2.3 GENERIC METHODS FOR CO_2 EMISSIONS AND REMOVALS

As outlined in Section 2.2, emissions and removals of CO_2 within the AFOLU Sector are generally estimated on the basis of changes in ecosystem carbon stocks. These consist of above-ground and below-ground biomass, dead organic matter (i.e., dead wood and litter), and soil organic matter. Net losses in total ecosystem carbon stocks are used to estimate CO_2 emissions to the atmosphere, and net gains in total ecosystem carbon stocks are used to estimate removal of CO_2 from the atmosphere. Inter-pool transfers may be taken into account where appropriate. Changes in carbon stocks may be estimated by direct inventory methods or by process models. Each of the C stocks or pools can occur in any of land-use categories, hence general attributes of the methods that apply to any land-use category are described here. In particular cases, losses in carbon stocks or pools may imply emissions of non-CO_2 gases such as methane, carbon monoxide, non-methane volatile organic carbon and others. The methods for estimating emissions of these gases are provided in Section 2.4. It is *good practice* to check for complete coverage of CO_2 and non-CO_2 emissions due to losses in carbon stocks or pools to avoid omissions or double counting. Specific details regarding the application of these methods within a particular land-use category are provided under the relevant land uses in Chapters 4 to 9.

2.3.1 Change in biomass carbon stocks (above-ground biomass and below-ground biomass)

Plant biomass constitutes a significant carbon stock in many ecosystems. Biomass is present in both above-ground and below-ground parts of annual and perennial plants. Biomass associated with annual and perennial herbaceous (i.e., non-woody) plants is relatively ephemeral, i.e., it decays and regenerates annually or every few years. So emissions from decay are balanced by removals due to re-growth making overall net C stocks in biomass rather stable in the long term. Thus, the methods focus on stock changes in biomass associated with woody plants and trees, which can accumulate large amounts of carbon (up to hundreds of tonnes per ha) over their lifespan. Carbon stock change in biomass on Forest Land is likely to be an important sub-category because of substantial fluxes owing to management and harvest, natural disturbances, natural mortality and forest re-growth. In addition, land-use conversions from Forest Land to other land uses often result in substantial loss of carbon from the biomass pool. Trees and woody plants can occur in any of the six land-use categories although biomass stocks are generally largest on Forest Land. For inventory purposes, changes in C stock in biomass are estimated for (i) land remaining in the same land-use category and (ii) land converted to a new land-use category. The reporting convention is that all emissions and removals associated with a land-use change are reported in the new land-use category.

2.3.1.1 LAND REMAINING IN A LAND-USE CATEGORY

Equation 2.3 includes the five carbon pools for which stock change estimates are required. This section presents methods for estimating biomass carbon gains, losses and net changes. Gains include biomass growth in above-ground and below-ground components. Losses are categorized into wood fellings or harvest, fuelwood gathering, and losses from natural disturbances on managed land such as fire, insect outbreaks and extreme weather events (e.g., hurricanes, flooding). Two methods are provided for estimating carbon stock changes in biomass.

The Gain-Loss Method requires the biomass carbon loss to be subtracted from the biomass carbon gain (Equation 2.7). This underpins the Tier 1 method, for which default values for calculation of increment and losses are provided in this Volume to estimate stock changes in biomass. Higher tier methods use country-specific data to estimate gain and loss rates. For all tiers, these estimates require country-specific activity data, although for Tier 1, these data can be obtained from globally-compiled databases (e.g., FAO statistics).

EQUATION 2.7
ANNUAL CHANGE IN CARBON STOCKS IN BIOMASS
IN LAND REMAINING IN A PARTICULAR LAND-USE CATEGORY (GAIN-LOSS METHOD)

$$\Delta C_B = \Delta C_G - \Delta C_L$$

Where:

ΔC_B = annual change in carbon stocks in biomass (the sum of above-ground and below-ground biomass terms in Equation 2.3) for each land sub-category, considering the total area, tonnes C yr^{-1}

ΔC_G = annual increase in carbon stocks due to biomass growth for each land sub-category, considering the total area, tonnes C yr^{-1}

ΔC_L = annual decrease in carbon stocks due to biomass loss for each land sub-category, considering the total area, tonnes C yr^{-1}

The changes in C stock in biomass for land remaining in the same land-use category (e.g., *Forest Land Remaining Forest Land*) are based on estimates of annual gain and loss in biomass stocks. Countries using any of the three tiers can adopt this method. This method can be used by countries that do not have national inventory systems designed for estimating woody biomass stocks. Default data are provided in land-use category chapters for inventory compilers who do not have access to country-specific data. Worksheets have also been developed using the methods and equations (Annex 1).

The Stock-Difference Method requires biomass carbon stock inventories for a given land area, at two points in time. Annual biomass change is the difference between the biomass stock at time t_2 and time t_1, divided by the number of years between the inventories (Equation 2.8). In some cases, primary data on biomass may be in the form of wood volume data, for example, from forest surveys, in which case factors are provided to convert wood volume to carbon mass units, as shown in Equation 2.8.b.

EQUATION 2.8
ANNUAL CHANGE IN CARBON STOCKS IN BIOMASS
IN LAND REMAINING IN THE SAME LAND-USE CATEGORY (STOCK-DIFFERENCE METHOD)

$$\Delta C_B = \frac{(C_{t_2} - C_{t_1})}{(t_2 - t_1)} \qquad \text{(a)}$$

where

$$C = \sum_{i,j} \{A_{i,j} \bullet V_{i,j} \bullet BCEF_{S_{i,j}} \bullet (1 + R_{i,j}) \bullet CF_{i,j}\} \qquad \text{(b)}$$

Where:

ΔC_B= annual change in carbon stocks in biomass (the sum of above-ground and below-ground biomass terms in Equation 2.3) in land remaining in the same category (e.g., *Forest Land Remaining Forest Land*), tonnes C yr^{-1}

C_{t_2} = total carbon in biomass for each land sub-category at time t_2, tonnes C

C_{t_1} = total carbon in biomass for each land sub-category at time t_1, tonnes C

C = total carbon in biomass for time t_l to t_2

A = area of land remaining in the same land-use category, ha (see note below)

V = merchantable growing stock volume, $m^3\ ha^{-1}$

i = ecological zone i (i = 1 to n)

j = climate domain j (j = 1 to m)

R = ratio of below-ground biomass to above-ground biomass, tonne d.m. below-ground biomass (tonne d.m. above-ground biomass)$^{-1}$

CF = carbon fraction of dry matter, tonne C (tonne d.m.)$^{-1}$

$BCEF_S$ = biomass conversion and expansion factor for expansion of merchantable growing stock volume to above-ground biomass, tonnes above-ground biomass growth (m^3 growing stock volume)$^{-1}$, (see Table 4.5 for Forest Land). $BCEF_S$ transforms merchantable volume of growing stock directly into its above-ground biomass. $BCEF_S$ values are more convenient because they can be applied directly to volume-based forest inventory data and operational records, without the need of having to resort to basic wood densities (D). They provide best results, when they have been derived locally and based directly on merchantable volume. However, if $BCEF_S$ values are not available and if the biomass expansion factor (BEF_S) and D values are separately estimated, the following conversion can be used:

$$BCEF_S = BEF_S \bullet D$$

In applying the *Gain-Loss* or *Stock-Difference Methods*, the relevant area is clearly the area of land remaining in the relevant category at the end of the year for which the inventory is being estimated. Any other land will be in a conversion category (see Section 2.3.1.2). The length of time that land remains in a conversion category after a change in land use is by default 20 years (the time period assumed for carbon stocks to come to equilibrium for the purposes of calculating default coefficients in the *1996 IPCC Guidelines* and retained for *GPG-LULUCF* and used here also, though other periods may be used at higher Tiers according to national circumstances). Under default assumptions therefore land will be transferred from a conversion category to a remaining category after it has been in a given land use for 20 years. Some carbon stock changes will take place in the year of conversion, but nevertheless it is important to be consistent about the period for which land stays in the conversion category or the approaches to land area estimation described in the next Chapter will not work. Stock changes that are completed within 1 year after conversion will be related to the area converted annually and the relevant land areas may need to be treated as a sub-category within the conversion category but nevertheless should remain in the conversion category until the 20 year default or other conversion time period is completed.

The S*tock-Difference Method* will be applicable in countries that have national inventory systems for forests and other land-use categories, where the stocks of different biomass pools are measured at periodic intervals. The stock-difference method requires greater resources and many countries may not have national inventory systems for forests and other land-use categories. This method is suitable to countries adopting a Tier 3 and in some cases a Tier 2 approach, but may not be suitable for countries using a Tier 1 approach due to limitations of data. It is important to make sure that inventory system generates data on gains and losses of biomass carbon pools.

Either of the above two methods can be used for estimating biomass carbon stock changes for all land categories (e.g., *Forest Land Remaining Forest Land*, *Grassland Remaining Grassland*, and *Cropland Remaining Cropland*) where perennial woody biomass may be present. Figure 2.2 can be used to assist inventory agencies in identifying the appropriate tier to estimate changes in biomass carbon stocks.

Note that some biomass losses can lead to emissions of C other than as CO_2, such as biomass consumption and emission as methane (CH_4) by termites and wild mammals.[2] Default Tier 1 methods for these sources have not been developed, and countries wishing to estimate and report these emissions should develop and employ a Tier 3 approach.

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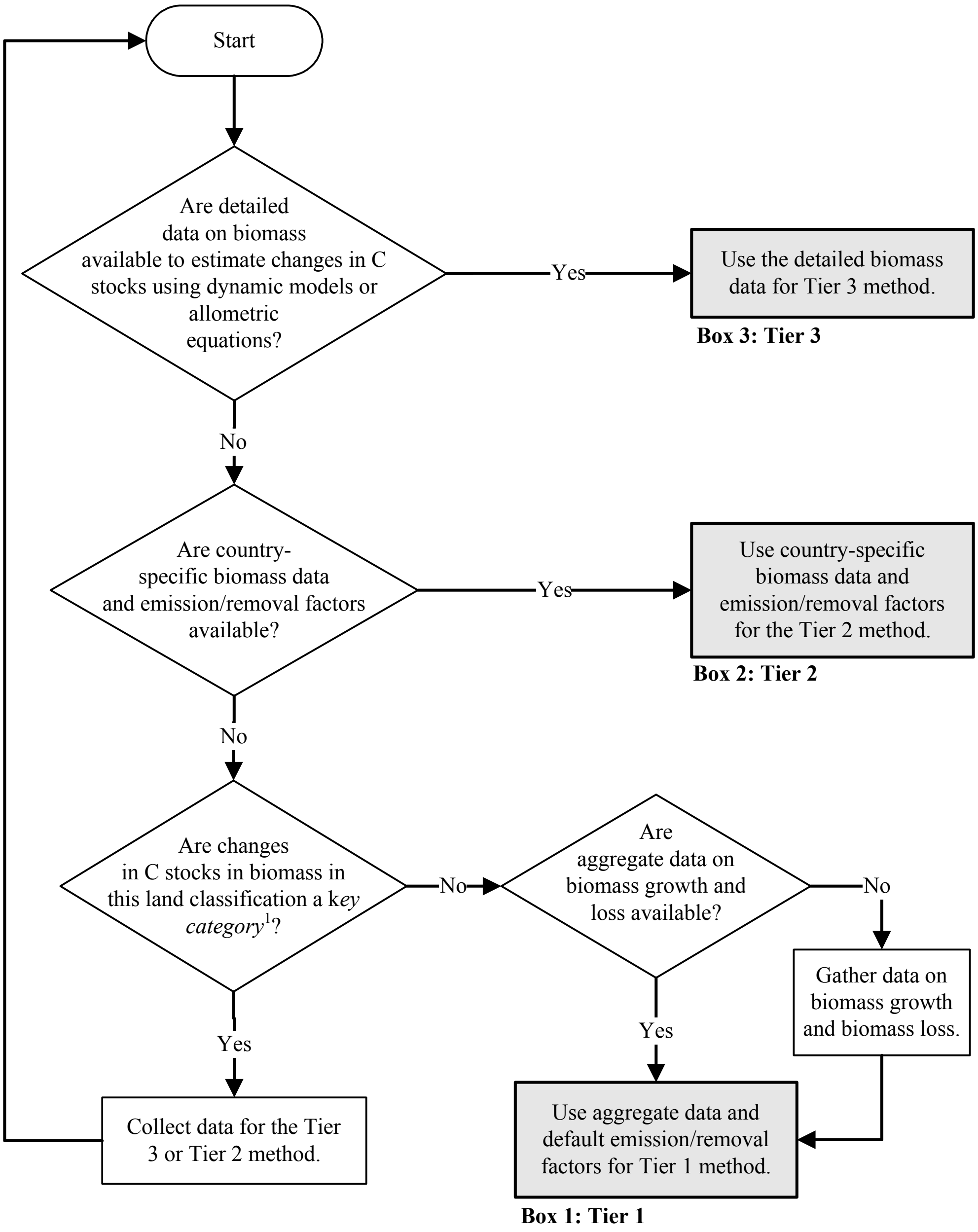
[2] CO_2 and non-CO_2 losses of carbon associated with biomass burning *are* estimated such that carbon emissions are **not** double-counted.

Figure 2.2 **Generic decision tree for identification of appropriate tier to estimate changes in carbon stocks in biomass in a land-use category.**



Note:

1: See Volume 1 Chapter 4, "Methodological Choice and Identification of Key Categories" (noting Section 4.1.2 on limited resources), for discussion of *key categories* and use of decision trees.

A. METHODS FOR ESTIMATING CHANGE IN CARBON STOCKS IN BIOMASS (ΔC_B)

A.1 Estimating annual increase in biomass carbon stocks (Gain-Loss Method), ΔC_G

This is the Tier 1 method that, when combined with default biomass growth rates, allows for any country to calculate the annual increase in biomass, using estimates of area and mean annual biomass increment, for each land-use type and stratum (e.g., climatic zone, ecological zone, vegetation type) (Equation 2.9).

EQUATION 2.9

ANNUAL INCREASE IN BIOMASS CARBON STOCKS DUE TO BIOMASS INCREMENT IN LAND REMAINING IN THE SAME LAND-USE CATEGORY

$$\Delta C_G = \sum_{i,j} (A_{i,j} \bullet G_{TOTAL_{i,j}} \bullet CF_{i,j})$$

Where:

ΔC_G= annual increase in biomass carbon stocks due to biomass growth in land remaining in the same land-use category by vegetation type and climatic zone, tonnes C yr^{-1}

A = area of land remaining in the same land-use category, ha

G_{TOTAL}= mean annual biomass growth, tonnes d. m. ha^{-1} yr^{-1}

i = ecological zone (*i* = 1 to *n*)

j = climate domain (*j* = 1 to *m)*

CF = carbon fraction of dry matter, tonne C (tonne d.m.)$^{-1}$

G_{TOTAL} is the total biomass growth expanded from the above-ground biomass growth (G_w) to include below-ground biomass growth. Following a Tier 1 method, this may be achieved directly by using default values of G_W for naturally regenerated trees or broad categories of plantations together with R, the ratio of below-ground biomass to above-ground biomass differentiated by woody vegetation type. In Tiers 2 and 3, the net annual increment (I_V) can be used with either basic wood density (D) and biomass expansion factor (BEF_I) or directly with biomass conversion and expansion factor ($BCEF_I$) for conversion of annual net increment to above-ground biomass increment for each vegetation type. Equation 2.10 shows the relationships.

EQUATION 2.10

AVERAGE ANNUAL INCREMENT IN BIOMASS

Tier 1

$$G_{TOTAL} = \sum \{G_W \bullet (1 + R)\}$$ Biomass increment data (dry matter) are used directly

Tiers 2 and 3

$$G_{TOTAL} = \sum \{I_V \bullet BCEF_I \bullet (1 + R)\}$$ Net annual increment data are used to estimate G_W by applying a biomass conversion and expansion factor

Where:

G_{TOTAL} = average annual biomass growth above and below-ground, tonnes d. m. ha^{-1} yr^{-1}

G_W = average annual above-ground biomass growth for a specific woody vegetation type, tonnes d. m. ha^{-1} yr^{-1}

R = ratio of below-ground biomass to above-ground biomass for a specific vegetation type, in tonne d.m. below-ground biomass (tonne d.m. above-ground biomass)$^{-1}$. R must be set to zero if assuming no changes of below-ground biomass allocation patterns (Tier 1).

I_V = average net annual increment for specific vegetation type, m^3 ha^{-1} yr^{-1}

$BCEF_I$ = biomass conversion and expansion factor for conversion of net annual increment in volume (including bark) to above-ground biomass growth for specific vegetation type, tonnes above-ground biomass growth (m^3 net annual increment)$^{-1}$, (see Table 4.5 for Forest Land). If $BCEF_I$ values are not available and if the biomass expansion factor (BEF) and basic wood density (D) values are separately estimated, then the following conversion can be used:

$$BCEF_I = BEF_I \bullet D$$

Biomass Expansion Factors (BEF_I)[3] expand merchantable volume to total above-ground biomass volume to account for non-merchantable components of increment. BEF_I is dimensionless.

Estimates for $BCEF_I$ for woody (perennial) biomass on non-forest lands such as Grassland (savanna), Cropland (agro-forestry), orchards, coffee, tea, and rubber may not be readily available. In this case, default values of $BCEF_I$ from one of the forest types closest to the non-forest vegetation can be used to convert merchantable biomass to total biomass. $BCEF_I$ is relevant only to perennial woody tree biomass for which merchantable biomass data are available. For perennial shrubs, grasses and crops, biomass increment data in terms of tonnes of dry matter per hectare may be directly available and in this case use of Equation 2.10 will not be required.

A.2 Estimating annual decrease in biomass carbon stocks due to losses (Gain-Loss Method), ΔC_L

Loss estimates are needed for calculating biomass carbon stock change using the *Gain-Loss Method*. Note that the loss estimate is also needed when using the *Stock–Difference Method* to estimate the transfers of biomass to dead organic matter when higher Tier estimation methods are used (see below). Annual biomass loss is the sum of losses from wood removal (harvest), fuelwood removal (not counting fuelwood gathered from woody debris), and other losses resulting from disturbances, such as fire, storms, and insect and diseases. The relationship is shown in Equation 2.11.

EQUATION 2.11
ANNUAL DECREASE IN CARBON STOCKS DUE TO BIOMASS LOSSES
IN LAND REMAINING IN THE SAME LAND-USE CATEGORY

$$\Delta C_L = L_{wood-removals} + L_{fuelwood} + L_{disturbance}$$

Where:

ΔC_L = annual decrease in carbon stocks due to biomass loss in land remaining in the same land-use category, tonnes C yr^{-1}

$L_{wood-removals}$ = annual carbon loss due to wood removals, tonnes C yr^{-1} (See Equation 2.12)

$L_{fuelwood}$ = annual biomass carbon loss due to fuelwood removals, tonnes C yr^{-1} (See Equation 2.13)

$L_{disturbance}$ = annual biomass carbon losses due to disturbances, tonnes C yr^{-1} (See Equation 2.14)

Equation 2.11 and the following Equations 2.12 to 2.14 are directly applicable to Forest Land. These Equations (2.11 to 2.14) can also be used for estimating losses from Cropland and Grassland, if quantities of wood removal (harvesting), fuelwood removal, and loss due to disturbance are available for perennial woody biomass. In intensively managed as well as highly degraded croplands and grasslands, the perennial woody biomass loss is likely to be small. Default biomass carbon loss values for woody crop species are provided for the Tier 1 cropland methodology (see Table 5.1). It is important to note that wood-removal used in Equation 2.11 should be compared with the input to HWP in Chapter 12 for consistency.

The three terms on the right hand side of Equation 2.11 are obtained as follows:

Loss of biomass and carbon from wood removal (harvesting), $L_{wood-removals}$

The method for estimating the annual biomass carbon loss due to wood-removals is provided in Equation 2.12.

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[3] In some applications, BEFs are used to expand dry-weight of merchantable components or stem biomass to total biomass, excluding or including roots, or convert and expand merchantable or stem volume to above-ground or total biomass (Somogyi *et al*., 2006). As used in this document, biomass expansion factors always transform dry-weight of merchantable components including bark to aboveground biomass, excluding roots.

EQUATION 2.12
ANNUAL CARBON LOSS IN BIOMASS OF WOOD REMOVALS

$$L_{wood-removals} = \{H \bullet BCEF_R \bullet (1+R) \bullet CF\}$$

Where:

$L_{wood\text{-}removals}$ = annual carbon loss due to biomass removals, tonnes C yr^{-1}

H = annual wood removals, roundwood, m^3 yr^{-1}

R = ratio of below-ground biomass to above-ground biomass, in tonne d.m. below-ground biomass (tonne d.m. above-ground biomass)$^{-1}$. R must be set to zero if assuming no changes of below-ground biomass allocation patterns (Tier 1).

CF = carbon fraction of dry matter, tonne C (tonne d.m.)$^{-1}$

$BCEF_R$ = biomass conversion and expansion factor for conversion of removals in merchantable volume to total biomass removals (including bark), tonnes biomass removal (m^3 of removals)$^{-1}$, (see Table 4.5 for Forest Land). However, if $BCEF_R$ values are not available and if the biomass expansion factor for wood removals (BEF_R) and basic wood density (D) values are separately estimated, then the following conversion can be used:

$$BCEF_R = BEF_R \bullet D$$

If country-specific data on roundwood removals are not available, the inventory experts should use FAO statistics on wood harvest. FAO statistical data on wood harvest exclude bark. To convert FAO statistical wood harvest data without bark into merchantable wood removals including bark, multiply by default expansion factor of 1.15.

Loss of biomass and carbon from fuelwood removal, $L_{fuelwood}$

Fuelwood removal will often be comprised of two components. First, removal for fuelwood of living trees and parts of trees such as tops and branches, where the tree itself remains in the forest, will reduce the carbon in the biomass of growing stock and should be treated as biomass carbon loss. The second component is gathering of dead wood and logging slash. This will reduce the dead organic matter carbon pool. If it is possible it is *good practice* to estimate the two components separately. The biomass carbon loss due to fuelwood removal of live trees is estimated using Equation 2.13.

EQUATION 2.13
ANNUAL CARBON LOSS IN BIOMASS OF FUELWOOD REMOVAL

$$L_{fuelwood} = [\{FG_{trees} \bullet BCEF_R \bullet (1+R)\} + FG_{part} \bullet D] \bullet CF$$

Where:

$L_{fuelwood}$ = annual carbon loss due to fuelwood removals, tonnes C yr^{-1}

FG_{trees} = annual volume of fuelwood removal of whole trees, m^3 yr^{-1}

FG_{part} = annual volume of fuelwood removal as tree parts, m^3 yr^{-1}

R = ratio of below-ground biomass to above-ground biomass, in tonne d.m. below-ground biomass (tonne d.m. above-ground biomass)$^{-1}$; R must be set to zero if assuming no changes of below-ground biomass allocation patterns. (Tier 1)

CF = carbon fraction of dry matter, tonne C (tonne d.m.)$^{-1}$

D = basic wood density, tonnes d.m. m^{-3}

$BCEF_R$ = biomass conversion and expansion factor for conversion of removals in merchantable volume to biomass removals (including bark), tonnes biomass removal (m^3 of removals)$^{-1}$, (see Table 4.5 for Forest Land). If $BCEF_R$ values are not available and if the biomass expansion factor for wood removals (BEF_R) and basic wood density (D) values are separately estimated, then the following conversion can be used:

$$BCEF_R = BEF_R \bullet D$$

Biomass Expansion Factors (BEF_R) expand merchantable wood removals to total aboveground biomass volume to account for non-merchantable components of the tree, stand and forest. BEF_R is dimensionless.

If country-specific data on roundwood removals are not available, the inventory experts should use FAO statistics on wood harvest. It should be noted that FAO statistical data on wood harvest exclude bark. To convert FAO statistical wood harvest data without bark into merchantable wood removals including bark, multiply by default expansion factor of 1.15.

Wood harvest can comprise both wood and fuelwood removals (i.e., wood removals in Equation 2.12 can include both wood and fuelwood removal), or fuelwood removals can be reported separately using, both Equations 2.12 and 2.13. To avoid double counting, it is *good practice* to check how fuelwood data are represented in the country and to use the equation that is most appropriate for national conditions. Furthermore, the wood harvest from forests becomes an input to HWP (Chapter 12). Therefore, it is *good practice* to check for consistent representation of wood-harvest data in Equations 2.12 and 2.13 and those in Chapter 12.

Loss of biomass and carbon from disturbance, $L_{disturbance}$

A generic approach for estimating the amount of carbon lost from disturbances is provided in Equation 2.14. In the specific case of losses from fire on managed land, including wildfires and controlled fires, this method should be used to provide input to the methodology to estimate CO_2 and non-CO_2 emissions from fires.

EQUATION 2.14

ANNUAL CARBON LOSSES IN BIOMASS DUE TO DISTURBANCES

$$L_{disturbance} = \{A_{disturbance} \bullet B_W \bullet (1 + R) \bullet CF \bullet fd\}$$

Where:

$L_{disturbances}$ = annual other losses of carbon, tonnes C yr^{-1} (Note that this is the amount of biomass that is lost from the total biomass. The partitioning of biomass that is transferred to dead organic matter and biomass that is oxidized and released to the atmosphere is explained in Equations 2.15 and 2.16).

$A_{disturbance}$ = area affected by disturbances, ha yr^{-1}

B_W = average above-ground biomass of land areas affected by disturbances, tonnes d.m. ha^{-1}

R = ratio of below-ground biomass to above-ground biomass, in tonne d.m. below-ground biomass (tonne d.m. above-ground biomass)$^{-1}$. R must be set to zero if no changes of below-ground biomass are assumed (Tier 1)

CF = carbon fraction of dry matter, tonne C (tonnes d.m.)$^{-1}$

fd = fraction of biomass lost in disturbance (see note below)

Note: The parameter fd defines the proportion of biomass that is lost from the biomass pool: a stand-replacing disturbance will kill all (fd = 1) biomass while an insect disturbance may only remove a portion (e.g. fd = 0.3) of the average biomass C density. Equation 2.14 does not specify the fate of the carbon removed from the biomass carbon stock. The Tier 1 assumption is that all of $L_{disturbances}$ is emitted in the year of disturbance. Higher Tier methods assume that some of this carbon is emitted immediately and some is added to the dead organic matter pools (dead wood, litter) or HWP.

The amounts of biomass carbon transferred to different fates can be defined using a disturbance matrix that can be parameterized to define the impacts of different disturbance types (Kurz *et al.*, 1992). It is *good practice*, if possible, to develop and use a disturbance matrix (Table 2.1) for each biomass, dead organic matter and soil carbon pool, the proportion of the carbon remaining in that pool, and the proportions transferred to other pools, to harvested wood products and to the atmosphere, during the disturbance event. The proportions in each row always sum to 1 to ensure conservation of carbon. The value entered in cell A is the proportion of above-ground biomass remaining after a disturbance (or 1 – fd, where fd is defined in Equation 2.14). The Tier 1 assumption is that all of fd is emitted in the year of disturbance: therefore the value entered in cell F is fd. For higher Tiers, only the proportion emitted in the year is entered in cell F and the remainder is added to cells B and C in the case of fire, and B, C, and E in the case of harvest. It is *good practice* to develop disturbance matrix even under Tier 1 to ensure that all carbon pool transfers are considered, though all biomass carbon is assumed to be emitted in the year of land conversion. It is important to note that some of the transfers could be small or insignificant.

TABLE 2.1
EXAMPLE OF A SIMPLE MATRIX (TIER 2) FOR THE IMPACTS OF DISTURBANCES ON CARBON POOLS

To: From:	Above-ground biomass	Below-ground biomass	Dead wood	Litter	Soil organic matter	Harvested wood products	Atmo-sphere	Sum of row (must equal 1)
Above-ground biomass	**A**	■	**B**	**C**	**D**	**E**	**F**	**1**
Below-ground biomass	■					■		**1**
Dead wood	■	■						**1**
Litter	■	■	■			■		**1**
Soil organic matter	■	■	■	■		■		**1**

Enter the proportion of each pool on the left side of the matrix that is transferred to the pool at the top of each column. All of the pools on the left side of the matrix must be fully populated and the values in each row must sum to 1.

Impossible transitions are blacked out.

Note: Letters A to F are cell labels that are referenced in the text.

2.3.1.2 LAND CONVERTED TO A NEW LAND-USE CATEGORY

The methods for estimation of emissions and removals of carbon resulting from land-use conversion from one land-use category to another are presented in this section. Possible conversions include conversion from non-forest to Forest Land, Cropland and Forest Land to Grassland, and Grassland and Forest Land to Cropland.

The CO_2 emissions and removals on land converted to a new land-use category include annual changes in carbon stocks in above-ground and below-ground biomass. Annual carbon stock changes for each of these pools can be estimated by using Equation 2.4 ($\Delta C_B = \Delta C_G - \Delta C_L$), where ΔC_G is the annual gain in carbon, and ΔC_L is the annual loss of carbon. ΔC_B can be estimated separately for each land use (e.g., Forest Land, Cropland, Grassland) and management category (e.g., natural forest, plantation), by specific strata (e.g., climate or forest type).

METHODS FOR ESTIMATING CHANGE IN CARBON STOCKS IN BIOMASS (ΔC_B)

i) Annual increase in carbon stocks in biomass, ΔC_G

Tier 1: Annual increase in carbon stocks in biomass due to land converted to another land-use category can be estimated using Equation 2.9 described above for lands remaining in a category. Tier 1 employs a default assumption that there is no change in initial biomass carbon stocks due to conversion. This assumption can be applied if the data on previous land uses are not available, which may be the case when land area totals are estimated using Approach 1 or 2 described in Chapter 3 (non-spatially explicit land area data). This approach implies the use of default parameters in Section 4.5 (Chapter 4). The area of land converted can be categorized based on management practices e.g., intensively managed plantations and grasslands or extensively managed (low input) plantations, grasslands or abandoned croplands that revert back to forest and should be kept in conversion category for 20 years or another time interval. If the previous land use on a converted area is known, then the Tier 2 method described below can be used.

ii) Annual decrease in carbon stocks in biomass due to losses, ΔC_L

Tier 1: The annual decrease in C stocks in biomass due to losses on converted land (wood removals or fellings, fuelwood collection, and disturbances) can be estimated using Equations 2.11 to 2.14. As with increases in carbon stocks, Tier 1 follows the default assumption that there is no change in initial carbon stocks in biomass, and it can be applied for the areas that are estimated with the use of Approach 1 or 2 in Chapter 3, and default parameters in Section 4.5.

iii) Higher tiers for estimating change in carbon stocks in biomass, (ΔC_B)

Tiers 2 and 3: Tier 2 (and 3) methods use nationally-derived data and more disaggregated approaches and (or) process models, which allow for more precise estimates of changes in carbon stocks in biomass. In Tier 2, Equation 2.4 is replaced by Equation 2.15, where the changes in carbon stock are calculated as a sum of increase in carbon stock due to biomass growth, changes due to actual conversion (difference between biomass stocks before and after conversion), and decrease in carbon stocks due to losses.

EQUATION 2.15

ANNUAL CHANGE IN BIOMASS CARBON STOCKS ON LAND CONVERTED TO OTHER LAND-USE CATEGORY (TIER 2)

$$\Delta C_B = \Delta C_G + \Delta C_{CONVERSION} - \Delta C_L$$

Where:

ΔC_B = annual change in carbon stocks in biomass on land converted to other land-use category, in tonnes C yr^{-1}

ΔC_G = annual increase in carbon stocks in biomass due to growth on land converted to another land-use category, in tonnes C yr^{-1}

$\Delta C_{CONVERSION}$ = initial change in carbon stocks in biomass on land converted to other land-use category, in tonnes C yr^{-1}

ΔC_L = annual decrease in biomass carbon stocks due to losses from harvesting, fuel wood gathering and disturbances on land converted to other land-use category, in tonnes C yr^{-1}

Conversion to another land category may be associated with a change in biomass stocks, e.g., part of the biomass may be withdrawn through land clearing, restocking or other human-induced activities. These initial changes in carbon stocks in biomass ($\Delta C_{CONVERSION}$) are calculated with the use of Equation 2.16 as follows:

EQUATION 2.16

INITIAL CHANGE IN BIOMASS CARBON STOCKS ON LAND CONVERTED TO ANOTHER LAND CATEGORY

$$\Delta C_{CONVERSION} = \sum_i \{(B_{AFTER_i} - B_{BEFORE_i}) \bullet \Delta A_{TO\_OTHERS_i}\} \bullet CF$$

Where:

$\Delta C_{CONVERSION}$ = initial change in biomass carbon stocks on land converted to another land category, tonnes C yr^{-1}

B_{AFTER_i} = biomass stocks on land type *i* immediately after the conversion, tonnes d.m. ha^{-1}

B_{BEFORE_i} = biomass stocks on land type *i* before the conversion, tonnes d.m. ha^{-1}

$\Delta A_{TO\_OTHERS_i}$ = area of land use *i* converted to another land-use category in a certain year, ha yr^{-1}

CF = carbon fraction of dry matter, tonne C (tonnes d.m.)$^{-1}$

i = type of land use converted to another land-use category

The calculation of $\Delta C_{CONVERSION}$ may be applied separately to estimate carbon stocks occurring on specific types of land (ecosystems, site types, etc.) before the conversion. The $\Delta A_{TO\_OTHERS_i}$ refers to a particular inventory year for which the calculations are made, but the land affected by conversion should remain in the conversion category for 20 years or other period used in the inventory. Inventories using higher Tier methods can define a disturbance matrix (Table 2.1) for land-use conversion to quantify the proportion of each carbon pool before conversion that is transferred to other pools, emitted to the atmosphere (e.g., slash burning), or otherwise removed during harvest or land clearing.

Owing to the use of country specific data and more disaggregated approaches, the Equations 2.15 and 2.16 provide for more accurate estimates than Tier 1 methods, where default data are used. Additional improvement or accuracy would be achieved by using national data on areas of land-use transitions and country-specific carbon stock values. Therefore, Tier 2 and 3 approaches should be inclusive of estimates that use detailed area data and country specific carbon stock values.

2.3.2 Change in carbon stocks in dead organic matter

Dead organic matter (DOM) comprises dead wood and litter (See Table 1.1). Estimating the carbon dynamics of dead organic matter pools allows for increased accuracy in the reporting of where and when carbon emissions and removals occur. For example, only some of the carbon contained in biomass killed during a biomass burning is emitted into the atmosphere in the year of the fire. Most of the biomass is added to dead wood, litter and soil pools (dead fine roots are included in the soil) from where the C will be emitted over years to decades, as the dead organic matter decomposes. Decay rates differ greatly between regions, ranging from high in warm and moist environments to low in cold and dry environments. Although the carbon dynamics of dead organic matter pools are well understood qualitatively, countries may find it difficult to obtain actual data with national coverage on dead organic matter stocks and their dynamics.

In forest ecosystems, DOM pools tend to be largest following stand-replacing disturbances due to the addition of residual above-ground and below-ground (roots) biomass. In the years after the disturbance, DOM pools decline as carbon loss through decay exceeds the rate of carbon addition through litterfall, mortality and biomass turnover. Later in stand development, DOM pools increase again. Representing these dynamics requires separate estimation of age-dependent inputs and outputs associated with stand dynamics and disturbance-related inputs and losses. These more complex estimation procedures require higher Tier methods.

2.3.2.1 LAND REMAINING IN A LAND-USE CATEGORY

The Tier 1 assumption for both dead wood and litter pools for all land-use categories is that their stocks are not changing over time if the land remains within the same land-use category. Thus, the carbon in biomass killed during a disturbance or management event (less removal of harvested wood products) is assumed to be released entirely to the atmosphere in the year of the event. This is equivalent to the assumption that the carbon in non-merchantable and non-commercial components that are transferred to dead organic matter is equal to the amount of carbon released from dead organic matter to the atmosphere through decomposition and oxidation. Countries can use higher tier methods to estimate the carbon dynamics of dead organic matter. This section describes estimation methods if Tier 2 (or 3) methods are used.

Countries that use Tier 1 methods to estimate DOM pools in land remaining in the same land-use category, report zero changes in carbon stocks or carbon emissions from those pools. Following this rule, CO_2 emissions resulting from the combustion of dead organic matter during fire are not reported, nor are the increases in dead organic matter carbon stocks in the years following fire. However, emissions of non-CO_2 gases from burning of DOM pools are reported. Tier 2 methods for estimation of carbon stock changes in DOM pools calculate the changes in dead wood and litter carbon pools (Equation 2.17). Two methods can be used: either track inputs and outputs (the *Gain-Loss Method*, Equation 2.18) or estimate the difference in DOM pools at two points in time (*Stock-Difference Method*, Equation 2.19). These estimates require either detailed inventories that include repeated measurements of dead wood and litter pools, or models that simulate dead wood and litter dynamics. It is *good practice* to ensure that such models are tested against field measurements and are documented. Figure 2.3 provides the decision tree for identification of the appropriate tier to estimate changes in carbon stocks in dead organic matter.

Equation 2.17 summarizes the calculation to estimate the annual changes in carbon stock in DOM pools:

EQUATION 2.17
ANNUAL CHANGE IN CARBON STOCKS IN DEAD ORGANIC MATTER

$$\Delta C_{DOM} = \Delta C_{DW} + \Delta C_{LT}$$

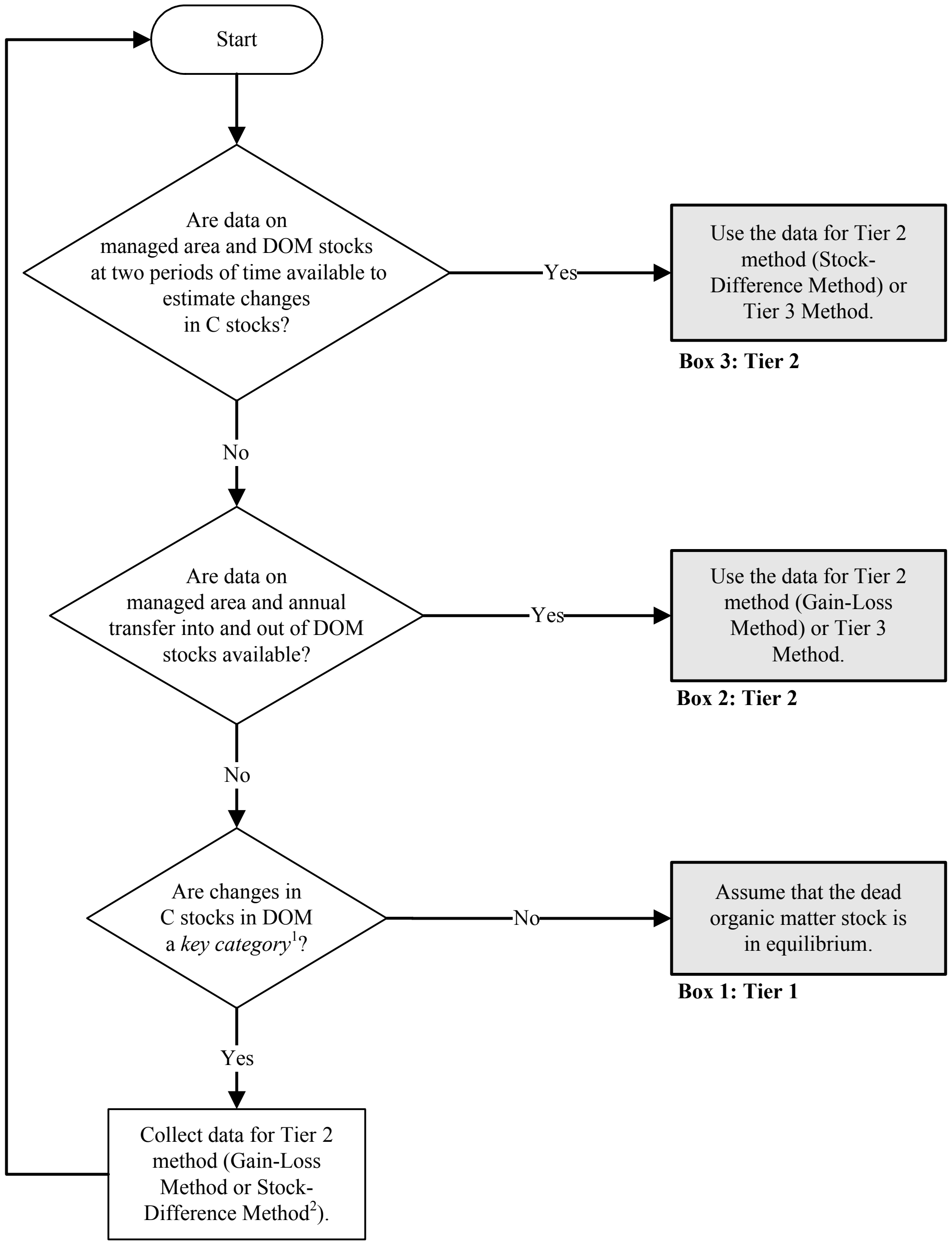
Where:

ΔC_{DOM} = annual change in carbon stocks in dead organic matter (includes dead wood and litter), tonnes C yr^{-1}

ΔC_{DW} = change in carbon stocks in dead wood, tonnes C yr^{-1}

ΔC_{LT} = change in carbon stocks in litter, tonnes C yr^{-1}

Figure 2.3 **Generic decision tree for identification of appropriate tier to estimate changes in carbon stocks in dead organic matter for a land-use category**



Note:

1: See Volume 1 Chapter 4, "Methodological Choice and Identification of Key Categories" (noting Section 4.1.2 on limited resources), for discussion of *key categories* and use of decision trees.

2: The two methods are defined in Equations 2.18 and 2.19, respectively.

The changes in carbon stocks in the dead wood and litter pools for an area remaining in a land-use category between inventories can be estimated using two methods, described in Equation 2.18 and Equation 2.19. The same equation is used for dead wood and litter pools, but their values are calculated separately.

EQUATION 2.18
ANNUAL CHANGE IN CARBON STOCKS IN DEAD WOOD OR LITTER (GAIN-LOSS METHOD)

$$\Delta C_{DOM} = A \bullet \{(DOM_{in} - DOM_{out}) \bullet CF\}$$

Where:

ΔC_{DOM} = annual change in carbon stocks in the dead wood/litter pool, tonnes C yr^{-1}

A = area of managed land, ha

DOM_{in} = average annual transfer of biomass into the dead wood/litter pool due to annual processes and disturbances, tonnes d.m. ha^{-1} yr^{-1} (see next Section for further details).

DOM_{out} = average annual decay and disturbance carbon loss out of dead wood or litter pool, tonnes d.m. ha^{-1} yr^{-1}

CF = carbon fraction of dry matter, tonne C (tonne d.m.)$^{-1}$

The net balance of DOM pools specified in Equation 2.18, requires the estimation of both the inputs and outputs from annual processes (litterfall and decomposition) and the inputs and losses associated with disturbances. In practice, therefore, Tier 2 and Tier 3 approaches require estimates of the transfer and decay rates as well as activity data on harvesting and disturbances and their impacts on DOM pool dynamics. Note that the biomass inputs into DOM pools used in Equation 2.18 are a subset of the biomass losses estimated in Equation 2.7. The biomass losses in Equation 2.7 contain additional biomass that is removed from the site through harvest or lost to the atmosphere, in the case of fire.

The method chosen depends on available data and will likely be coordinated with the method chosen for biomass carbon stocks. Transfers into and out of a dead wood or litter pool for Equation 2.18 may be difficult to estimate. The stock difference method described in Equation 2.19 can be used by countries with forest inventory data that include DOM pool information, other survey data sampled according to the principles set out in Annex 3A.3 (Sampling) in Chapter 3, and/or models that simulate dead wood and litter dynamics.

EQUATION 2.19
ANNUAL CHANGE IN CARBON STOCKS IN DEAD WOOD OR LITTER (STOCK-DIFFERENCE METHOD)

$$\Delta C_{DOM} = \left[A \bullet \frac{(DOM_{t_2} - DOM_{t_1})}{T} \right] \bullet CF$$

Where:

ΔC_{DOM} = annual change in carbon stocks in dead wood or litter, tonnes C yr^{-1}

A = area of managed land, ha

DOM_{t1} = dead wood/litter stock at time t_1 for managed land, tonnes d.m. ha^{-1}

DOM_{t2} = dead wood/litter stock at time t_2 for managed land, tonnes d.m. ha^{-1}

$T = (t_2 - t_1)$ = time period between time of the second stock estimate and the first stock estimate, yr

CF = carbon fraction of dry matter (default = 0.37 for litter), tonne C (tonne d.m.)$^{-1}$

Note that whenever the stock change method is used (e.g., in Equation 2.19), the area used in the carbon stock calculations at times t_1 and t_2 must be identical. If the area is not identical then changes in area will confound the estimates of carbon stocks and stock changes. It is *good practice* to use the area at the end of the inventory period (t_2) to define the area of land remaining in the land-use category. The stock changes on all areas that change land-use category between t_1 and t_2 are estimated in the new land-use category, as described in the sections on land converted to a new land category.

INPUT OF BIOMASS TO DEAD ORGANIC MATTER

Whenever a tree is felled, non-merchantable and non-commercial components (such as tops, branches, leaves, roots, and noncommercial trees) are left on the ground and transferred to dead organic matter pools. In addition, annual mortality can add substantial amounts of dead wood to that pool. For Tier 1 methods, the assumption is that the carbon contained in all biomass components that are transferred to dead organic matter pools will be released in the year of the transfer, whether from annual processes (litterfall and tree mortality), land management activities, fuelwood gathering, or disturbances. For estimation procedures based on higher Tiers, it is necessary to estimate the amount of biomass carbon that is transferred to dead organic matter. The quantity of biomass transferred to DOM is estimated using Equation 2.20.

EQUATION 2.20
ANNUAL CARBON IN BIOMASS TRANSFERRED TO DEAD ORGANIC MATTER

$$DOM_{in} = \{L_{mortality} + L_{slash} + (L_{disturbance} \bullet f_{BLol})\}$$

Where:

DOM_{in} = total carbon in biomass transferred to dead organic matter, tonnes C yr^{-1}

$L_{mortality}$ = annual biomass carbon transfer to DOM due to mortality, tonnes C yr^{-1} (See Equation 2.21)

L_{slash} = annual biomass carbon transfer to DOM as slash, tonnes C yr^{-1} (See Equations 2.22)

$L_{disturbances}$ = annual biomass carbon loss resulting from disturbances, tonnes C yr^{-1} (See Equation 2.14)

f_{BLol} = fraction of biomass left to decay on the ground (transferred to dead organic matter) from loss due to disturbance. As shown in Table 2.1, the disturbance losses from the biomass pool are partitioned into the fractions that are added to dead wood (cell B in Table 2.1) and to litter (cell C), are released to the atmosphere in the case of fire (cell F) and, if salvage follows the disturbance, transferred to HWP (cell E).

Note: If root biomass increments are counted in Equation 2.10, then root biomass losses must also be counted in Equations 2.20, and 2.22.

Examples of the terms on the right hand side of Equation 2.20 are obtained as follows:

Transfers to dead organic matter from mortality, $L_{mortality}$

Mortality is caused by competition during stand development, age, diseases, and other processes that are not included as disturbances. Mortality cannot be neglected when using higher Tier estimation methods. In extensively managed stands without periodic partial cuts, mortality from competition during the stem exclusion phase, may represent 30-50% of total productivity of a stand during its lifetime. In regularly tended stands, additions to the dead organic matter pool from mortality may be negligible because partial cuts extract forest biomass that would otherwise be lost to mortality and transferred to dead organic matter pools. Available data for increment will normally report net annual increment, which is defined as net of losses from mortality. Since in this text, net annual growth is used as a basis to estimate biomass gains, mortality must not be subtracted again as a loss from biomass pools. Mortality must, however, be counted as an addition to the dead wood pool for Tier 2 and Tier 3 methods.

The equation for estimating mortality is provided in Equation 2.21:

EQUATION 2.21
ANNUAL BIOMASS CARBON LOSS DUE TO MORTALITY

$$L_{mortality} = \sum (A \bullet G_W \bullet CF \bullet m)$$

Where:

$L_{mortality}$ = annual biomass carbon loss due to mortality, tonnes C yr^{-1}

A = area of land remaining in the same land use, ha

G_w = above-ground biomass growth, tonnes d.m. ha^{-1} yr^{-1} (see Equation 2.10)

CF = carbon fraction of dry matter, tonne C (tonne d.m.)$^{-1}$

m = mortality rate expressed as a fraction of above-ground biomass growth

When data on mortality rates are expressed as proportion of growing stock volume, then the term Gw in Equation 2.21 should be replaced with growing stock volume to estimate annual transfer to DOM pools from mortality.

Mortality rates differ between stages of stand development and are highest during the stem exclusion phase of stand development. They also differ with stocking level, forest type, management intensity and disturbance history. Thus, providing default values for an entire climatic zone is not justified because the variation within a zone will be much larger than the variation between zones.

Annual carbon transfer to slash, L_{slash}

This involves estimating the quantity of slash left after wood removal or fuelwood removal and transfer of biomass from total annual carbon loss due to wood harvest (Equation 2.12). The estimate for logging slash is given in Equation 2.22 and which is derived from Equation 2.12 as explained below:

EQUATION 2.22
ANNUAL CARBON TRANSFER TO SLASH

$$L_{slash} = \left[\{ H \bullet BCEF_R \bullet (1+R) \} - \{ H \bullet D \} \right] \bullet CF$$

Where:

L_{slash} = annual carbon transfer from above-ground biomass to slash, including dead roots, tonnes C yr^{-1}

H = annual wood harvest (wood or fuelwood removal), m^3 yr^{-1}

$BCEF_R$ = biomass conversion and expansion factors applicable to wood removals, which transform merchantable volume of wood removal into above-ground biomass removals, tonnes biomass removal (m^3 of removals)$^{-1}$. If $BCEF_R$ values are not available and if BEF and Density values are separately estimated then the following conversion can be used:

$$BCEF_R = BEF_R \bullet D$$

- D is basic wood density, tonnes d.m. m^{-3}
- Biomass Expansion Factors (BEF_R) expand merchantable wood removals to total aboveground biomass volume to account for non-merchantable components of the tree, stand and forest. BEF_R is dimensionless.

R = ratio of below-ground biomass to above-ground biomass, in tonne d.m. below-ground biomass (tonne d.m. above-ground biomass)$^{-1}$. R must be set to zero if root biomass increment is not included in Equation 2.10 (Tier 1)

CF = carbon fraction of dry matter, tonne C (tonne d.m.)$^{-1}$

Fuelwood gathering that involves the removal of live tree parts does not generate any additional input of biomass to dead organic matter pools and is not further addressed here.

Inventories using higher Tier methods can also estimate the amount of logging slash remaining after harvest by defining the proportion of above-ground biomass that is left after harvest (enter these proportions in cells B and C of Table 2.1 for harvest disturbance) and by using the approach defined in Equation 2.14. In this approach, activity data for the area harvested would also be required.

2.3.2.2 LAND CONVERSION TO A NEW LAND-USE CATEGORY

The reporting convention is that all carbon stock changes and non-CO_2 greenhouse gas emissions associated with a land-use change be reported in the new land-use category. For example, in the case of conversion of Forest Land to Cropland, both the carbon stock changes associated with the clearing of the forest as well as any subsequent carbon stock changes that result from the conversion are reported under the Cropland category.

The Tier 1 assumption is that DOM pools in non-forest land categories after the conversion are zero, i.e., they contain no carbon. The Tier 1 assumption for land converted from forest to another land-use category is that all DOM carbon losses occur in the year of land-use conversion. Conversely, conversion to Forest Land results in buildup of litter and dead wood carbon pools starting from zero carbon in those pools. DOM carbon gains on land converted to forest occur linearly, starting from zero, over a transition period (default assumption is 20 years). This default period may be appropriate for litter carbon stocks, but in temperate and boreal regions it is probably too short for dead wood carbon stocks. Countries that use higher Tier methods can accommodate longer transition periods by subdividing the remaining category to accommodate strata that are in the later stages of transition.

The estimation of carbon stock changes during transition periods following land-use conversion requires that annual cohorts of the area subject to land-use change be tracked for the duration of the transition period. For example, DOM stocks are assumed to increase for 20 years after conversion to Forest Land. After 20 years, the area converted enters the category *Forest Land Remaining Forest Land*, and no further DOM changes are assumed, if a Tier 1 approach is applied. Under Tier 2 and 3, the period of conversion can be varied depending on vegetation and other factors that determine the time required for litter and dead wood pools to reach steady state.

Higher Tier estimation methods can use non-zero estimates of litter and dead wood pools in the appropriate land-use categories or subcategories. For example, settlements and agro-forestry systems can contain some litter and dead wood pools, but because management, site conditions, and many other factors influence the pool sizes, no global default values can be provided here. Higher Tier methods may also estimate the details of dead organic matter inputs and outputs associated with the land-use change.

The conceptual approach to estimating changes in carbon stocks in dead wood and litter pools is to estimate the difference in C stocks in the old and new land-use categories and to apply this change in the year of the conversion (carbon losses), or to distribute it uniformly over the length of the transition period (carbon gains) Equation 2.23:

EQUATION 2.23

ANNUAL CHANGE IN CARBON STOCKS IN DEAD WOOD AND LITTER DUE TO LAND CONVERSION

$$\Delta C_{DOM} = \frac{(C_n - C_o) \bullet A_{on}}{T_{on}}$$

Where:

ΔC_{DOM} = annual change in carbon stocks in dead wood or litter, tonnes C yr^{-1}

C_o = dead wood/litter stock, under the old land-use category, tonnes C ha^{-1}

C_n = dead wood/litter stock, under the new land-use category, tonnes C ha^{-1}

A_{on} = area undergoing conversion from old to new land-use category, ha

T_{on} = time period of the transition from old to new land-use category, yr. The Tier 1 default is 20 years for carbon stock increases and 1 year for carbon losses.

Inventories using a Tier 1 method assume that all carbon contained in biomass killed during a land-use conversion event (less harvested products that are removed) is emitted directly to the atmosphere and none is added to dead wood and litter pools. Tier 1 methods also assume that dead wood and litter pool carbon losses occur entirely in the year of the transition.

Countries using higher Tier methods can modify C_o in Equation 2.23 by first accounting for the immediate effects of the land-use conversion in the year of the event. In this case, they would add to C_o the carbon from biomass killed and transferred to the dead wood and litter pools and remove from C_o any carbon released from dead wood and litter pools, e.g., during slash burning. In that case C_o in Equation 2.23 would represent the dead wood or litter carbon stocks immediately after the land-use conversion. C_o will transit to C_n over the transition period, using linear or more complex dynamics. A disturbance matrix (Table 2.1) can be defined to account for the pool transitions and releases during the land-use conversion, including the additions and removals to C_o.

Countries using a Tier 1 approach can apply the Tier 1 default carbon stock estimates for litter, and if available dead wood pools, provided in Table 2.2, but should recognize that these are broad-scale estimates with considerable uncertainty when applied at the country level. Table 2.2 is incomplete because of the paucity of published data. A review of the literature has identified several problems. The IPCC definitions of dead organic matter carbon stocks include litter and dead wood. The litter pool contains all litter plus fine woody debris up to a diameter limit of 10 cm (see Chapter 1, Table 1.1). Published litter data generally do not include the fine woody debris component, so the litter values in Table 2.2 are incomplete.

There are numerous published studies of coarse woody debris (Harmon and Hua, 1991; Karjalainen and Kuuluvainen, 2002) and a few review papers (e.g., Harmon *et al.*, 1986), and but to date only two studies are found to provide regional dead wood carbon pool estimates that are based on sample plot data. Krankina *et al.* (2002) included several regions in Russia and reported coarse woody debris (> 10 cm diameter) estimates of 2 to

7 Mg C ha^{-1}. Cooms *et al.* (2002) reported regional carbon pools based on a statistical sample design for a small region in New Zealand. Regional compilations for Canada (Shaw *et al.*, 2005) provide estimates of litter carbon pools based on a compilation of statistically non-representative sample plots, but do not include estimates of dead wood pools. Review papers such as Harmon *et al.* (1986) compile a number of estimates from the literature. For example, their Table 5 lists a range of coarse woody debris values for temperate deciduous forests of 11 – 38 Mg dry matter ha^{-1} and for temperate coniferous forests of 10 – 511 Mg dry matter ha^{-1}. It is, however, statistically invalid to calculate a mean from these compilations as they are not representative samples of the dead wood pools in a region.

While it is the intent of these IPCC Guidelines to provide default values for all variables used in Tier 1 methodologies, it is currently not feasible to provide estimates of regional defaults values for litter (including fine woody debris < 10 cm diameter) and dead wood (> 10 cm diameter) carbon stocks. Litter pool estimates (excluding fine woody debris) are provided in Table 2.2. Tier 1 methodology only requires the estimates in Table 2.2 for lands converted from Forest Land to any other land-use category (carbon losses) and for lands converted to Forest Land (carbon gains). Tier 1 methods assume that litter and dead wood pools are zero in all non-forest categories and therefore transitions between non-forest categories involve no carbon stock changes in these two pools.

TABLE 2.2
TIER 1 DEFAULT VALUES FOR LITTER AND DEAD WOOD CARBON STOCKS

Climate	**Forest type**			
	Broadleaf deciduous	**Needleleaf evergreen**	**Broadleaf deciduous**	**Needleleaf evergreen**
	Litter carbon stocks of mature forests		**Dead wood carbon stocks of mature forests**	
	(tonnes C ha^{-1})		**(tonnes C ha^{-1})**	
Boreal, dry	25 (10 - 58)	31 (6 - 86)	n.a.[b]	n.a
Boreal, moist	39 (11 - 117)	55 (7 - 123)	n.a	n.a
Cold Temperate, dry	28 (23 - 33)[a]	27 (17 - 42) [a]	n.a	n.a
Cold temperate, moist	16 (5 - 31) [a]	26 (10 - 48) [a]	n.a	n.a
Warm Temperate, dry	28.2 (23.4 - 33.0)[a]	20.3 (17.3 - 21.1)[a]	n.a	n.a
Warm temperate, moist	13 (2 - 31) [a]	22 (6 - 42)[a]	n.a	n.a
Subtropical	2.8 (2 - 3)	4.1	n.a	n.a
Tropical	2.1 (1 - 3)	5.2	n.a	n.a

Source:

Litter: Note that these values do not include fine woody debris. Siltanen *et al.*, 1997; and Smith and Heath, 2001; Tremblay *et al.*, 2002; and Vogt *et al.*,1996, converted from mass to carbon by multiplying by conversion factor of 0.37 (Smith and Heath, 2001).

Dead Wood: No regional estimates of dead wood pools are currently available – see text for further comments

[a] Values in parentheses marked by superscript “a” are the 5th and 95th percentiles from simulations of inventory plots, while those without superscript “a” indicate the entire range.

[b] n.a. denotes ‘not available’

2.3.3 Change in carbon stocks in soils

Although both organic and inorganic forms of C are found in soils, land use and management typically has a larger impact on organic C stocks. Consequently, the methods provided in these guidelines focus mostly on soil organic C. Overall, the influence of land use and management on soil organic C is dramatically different in a mineral versus an organic soil type. Organic (e.g., peat and muck) soils have a minimum of 12 to 20 percent organic matter by mass (see Chapter 3 Annex 3A.5, for the specific criteria on organic soil classification), and develop under poorly drained conditions of wetlands (Brady and Weil, 1999). All other soils are classified as mineral soil types, and typically have relatively low amounts of organic matter, occurring under moderate to well drained conditions, and predominate in most ecosystems except wetlands. Discussion about land-use and management influences on these contrasting soil types is provided in the next two sections.

MINERAL SOILS

Mineral soils are a carbon pool that is influenced by land-use and management activities. Land use can have a large effect on the size of this pool through activities such as conversion of native Grassland and Forest Land to Cropland, where 20-40% of the original soil C stocks can be lost (Mann, 1986; Davidson and Ackerman, 1993; Ogle *et al.*, 2005). Within a land-use type, a variety of management practices can also have a significant impact on soil organic C storage, particularly in Cropland and Grassland (e.g., Paustian *et al.*, 1997; Conant *et al.*, 2001; Ogle *et al.*, 2004 and 2005). In principle, soil organic C stocks can change with management or disturbance if the net balance between C inputs and C losses from soil is altered. Management activities influence organic C inputs through changes in plant production (such as fertilization or irrigation to enhance crop growth), direct additions of C in organic amendments, and the amount of carbon left after biomass removal activities, such as crop harvest, timber harvest, fire, or grazing. Decomposition largely controls C outputs and can be influenced by changes in moisture and temperature regimes as well as the level of soil disturbance resulting from the management activity. Other factors also influence decomposition, such as climate and edaphic characteristics. Specific effects of different land-use conversions and management regimes are discussed in the land-use specific chapters (Chapters 4 to 9).

Land-use change and management activity can also influence soil organic C storage by changing erosion rates and subsequent loss of C from a site; some eroded C decomposes in transport and CO_2 is returned to the atmosphere, while the remainder is deposited in another location. The net effect of changing soil erosion through land management is highly uncertain, however, because an unknown portion of eroded C is stored in buried sediments of wetlands, lakes, river deltas and coastal zones (Smith *et al.*, 2001).

ORGANIC SOILS

Inputs of organic matter can exceed decomposition losses under anaerobic conditions, which are common in undrained organic soils, and considerable amounts of organic matter can accumulate over time. The carbon dynamics of these soils are closely linked to the hydrological conditions, including available moisture, depth of the water table, and reduction-oxidation conditions (Clymo, 1984; Thormann *et al.*, 1999). Species composition and litter chemistry can also influence those dynamics (Yavitt *et al.*, 1997).

Carbon stored in organic soils will readily decompose when conditions become aerobic following soil drainage (Armentano and Menges, 1986; Kasimir-Klemedtsson *et al.*, 1997). Drainage is a practice used in agriculture and forestry to improve site conditions for plant growth. Loss rates vary by climate, with drainage under warmer conditions leading to faster decomposition rates. Losses of CO_2 are also influenced by drainage depth; liming; the fertility and consistency of the organic substrate; and temperature (Martikainen *et al.*, 1995). Greenhouse gas inventories capture this effect of management.

While drainage of organic soils typically releases CO_2 to the atmosphere (Armentano and Menges, 1986), there can also be a decrease in emissions of CH_4 that occur in un-drained organic soils (Nykänen *et al.*, 1995). However, CH_4 emissions from un-drained organic soils are not addressed in the inventory guidelines with the exception of a few cases in which the wetlands are managed (See Chapter 7, Wetlands). Similarly, national inventories typically do not estimate the accumulation of C in the soil pool resulting from the accumulation of plant detritus in un-drained organic soils. Overall, the rates of C gain are relatively slow in wetland environments with organic soils (Gorham, 1991), and any attempt to estimate C gains, even those created through wetland restoration, would also need to address the increase in CH_4 emissions. See additional guidance in Chapter 7 Wetlands.

2.3.3.1 SOIL C ESTIMATION METHODS (LAND REMAINING IN A LAND-USE CATEGORY AND LAND CONVERSION TO A NEW LAND USE)

Soil C inventories include estimates of soil organic C stock changes for mineral soils and CO_2 emissions from organic soils due to enhanced microbial decomposition caused by drainage and associated management activity. In addition, inventories can address C stock changes for soil inorganic C pools (e.g., calcareous grasslands that become acidified over time) if sufficient information is available to use a Tier 3 approach. The equation for estimating the total change in soil C stocks is given in Equation 2.24:

EQUATION 2.24
ANNUAL CHANGE IN CARBON STOCKS IN SOILS

$$\Delta C_{Soils} = \Delta C_{Mineral} - L_{Organic} + \Delta C_{Inorganic}$$

Where:

ΔC_{Soils} = annual change in carbon stocks in soils, tonnes C yr^{-1}

$\Delta C_{Mineral}$ = annual change in organic carbon stocks in mineral soils, tonnes C yr^{-1}

$L_{Organic}$ = annual loss of carbon from drained organic soils, tonnes C yr^{-1}

$\Delta C_{Inorganic}$ = annual change in inorganic carbon stocks from soils, tonnes C yr^{-1} (assumed to be 0 unless using a Tier 3 approach)

For Tier 1 and 2 methods, soil organic C stocks for mineral soils are computed to a default depth of 30 cm. Greater depth can be selected and used at Tier 2 if data are available, but Tier 1 factors are based on 30 cm depth. Residue/litter C stocks are not included because they are addressed by estimating dead organic matter stocks. Stock changes in organic soils are based on emission factors that represent the annual loss of organic C throughout the profile due to drainage. No Tier 1 or 2 methods are provided for estimating the change in soil inorganic C stocks due to limited scientific data for derivation of stock change factors; thus the net flux for inorganic C stocks is assumed to be zero. Tier 3 methods can be used to refined estimates of the C stock changes in mineral and organic soils and for soil inorganic C pools.

It is possible that countries will use different tiers to prepare estimates for mineral soils, organic soils, and soil inorganic C, given availability of resources. Thus, stock changes for mineral and organic soils and for inorganic C pools (Tier 3 only) are discussed separately. A generalized decision tree in Figures 2.4 and 2.5 can be used to assist inventory compilers in determining the appropriate tier for estimating stock changes for mineral and organic soil C, respectively.

Tier 1 Approach: Default Method

Mineral soils

For mineral soils, the default method is based on changes in soil C stocks over a finite period of time. The change is computed based on C stock after the management change relative to the carbon stock in a reference condition (i.e., native vegetation that is not degraded or improved). The following assumptions are made:

(i) Over time, soil organic C reaches a spatially-averaged, stable value specific to the soil, climate, land-use and management practices; and

(ii) Soil organic C stock changes during the transition to a new equilibrium SOC occurs in a linear fashion.

Assumption (i), that under a given set of climate and management conditions soils tend towards an equilibrium carbon content, is widely accepted. Although, soil carbon changes in response to management changes may often be best described by a curvilinear function, assumption (ii) greatly simplifies the Tier 1 methodology and provides a good approximation over a multi-year inventory period, where changes in management and land-use conversions are occurring throughout the inventory period.

Using the default method, changes in soil C stocks are computed over an inventory time period. Inventory time periods will likely be established based on the years in which activity data are collected, such as 1990, 1995, 2000, 2005 and 2010, which would correspond to inventory time periods of 1990-1995, 1995-2000, 2000-2005, 2005-2010. For each inventory time period, the soil organic C stocks are estimated for the first (SOC_{0-T}) and last year (SOC_0) based on multiplying the reference C stocks by stock change factors. Annual rates of carbon stock change are estimated as the difference in stocks at two points in time divided by the time dependence of the stock change factors.

EQUATION 2.25

ANNUAL CHANGE IN ORGANIC CARBON STOCKS IN MINERAL SOILS

$$\Delta C_{Mineral} = \frac{(SOC_0 - SOC_{(0-T)})}{D}$$

$$SOC = \sum_{c,s,i} \left(SOC_{REF_{c,s,i}} \bullet F_{LU_{c,s,i}} \bullet F_{MG_{c,s,i}} \bullet F_{I_{c,s,i}} \bullet A_{c,s,i} \right)$$

(Note: T is used in place of D in this equation if T is ≥ 20 years, see note below)

Where:

$\Delta C_{Mineral}$ = annual change in carbon stocks in mineral soils, tonnes C yr^{-1}

SOC_0 = soil organic carbon stock in the last year of an inventory time period, tonnes C

$SOC_{(0-T)}$ = soil organic carbon stock at the beginning of the inventory time period, tonnes C

SOC_0 and $SOC_{(0-T)}$ are calculated using the SOC equation in the box where the reference carbon stocks and stock change factors are assigned according to the land-use and management activities and corresponding areas at each of the points in time (time = 0 and time = 0-T)

T = number of years over a single inventory time period, yr

D = Time dependence of stock change factors which is the default time period for transition between equilibrium SOC values, yr. Commonly 20 years, but depends on assumptions made in computing the factors F_{LU}, F_{MG} and F_I. If T exceeds D, use the value for T to obtain an annual rate of change over the inventory time period (0-T years).

c = represents the climate zones, *s* the soil types, and *i* the set of management systems that are present in a country.

SOC_{REF} = the reference carbon stock, tonnes C ha^{-1} (Table 2.3)

F_{LU} = stock change factor for land-use systems or sub-system for a particular land-use, dimensionless

[Note: F_{ND} is substituted for F_{LU} in forest soil C calculation to estimate the influence of natural disturbance regimes.

F_{MG} = stock change factor for management regime, dimensionless

F_I = stock change factor for input of organic matter, dimensionless

A = land area of the stratum being estimated, ha. All land in the stratum should have common biophysical conditions (i.e., climate and soil type) and management history over the inventory time period to be treated together for analytical purposes.

Inventory calculations are based on land areas that are stratified by climate regions (see Chapter 3 Annex 3A.5, for default classification of climate), and default soils types as shown in Table 2.3 (see Chapter 3, Annex 3A.5, for default classification of soils). The stock change factors are very broadly defined and include: 1) a land-use factor (F_{LU}) that reflects C stock changes associated with type of land use, 2) a management factor (F_{MG}) representing the principal management practice specific to the land-use sector (e.g., different tillage practices in croplands), and 3) an input factor (F_I) representing different levels of C input to soil. As mentioned above, F_{ND} is substituted for F_{LU} in Forest Land to account for the influence of natural disturbance regimes (see Chapter 4, Section 4.2.3 for more discussion). The stock change factors are provided in the soil C sections of the land-use chapters. Each of these factors represents the change over a specified number of years (D), which can vary across sectors, but is typically invariant within sectors (e.g., 20 years for the cropland systems). In some inventories, the time period for inventory (T years) may exceed D, and under those cases, an annual rate of change in C stock may be obtained by dividing the product of [($SOC_0 - SOC_{(0-T)}$) ● A] by T, instead of D. See the soil C sections in the land-use chapters for detailed step-by-step guidance on the application of this method.

TABLE 2.3
DEFAULT REFERENCE (UNDER NATIVE VEGETATION) SOIL ORGANIC C STOCKS (SOC_{REF}) FOR MINERAL SOILS
(TONNES C HA^{-1} IN 0-30 CM DEPTH)

Climate region	HAC soils[1]	LAC soils[2]	Sandy soils[3]	Spodic soils[4]	Volcanic soils[5]	Wetland soils[6]
Boreal	68	NA	10[#]	117	20[#]	146
Cold temperate, dry	50	33	34	NA	20[#]	87
Cold temperate, moist	95	85	71	115	130	
Warm temperate, dry	38	24	19	NA	70[#]	88
Warm temperate, moist	88	63	34	NA	80	
Tropical, dry	38	35	31	NA	50[#]	86
Tropical, moist	65	47	39	NA	70[#]	
Tropical, wet	44	60	66	NA	130[#]	
Tropical montane	88*	63*	34*	NA	80*	

Note: Data are derived from soil databases described by Jobbagy and Jackson (2000) and Bernoux *et al.* (2002). Mean stocks are shown. A nominal error estimate of ±90% (expressed as 2x standard deviations as percent of the mean) are assumed for soil-climate types. NA denotes 'not applicable' because these soils do not normally occur in some climate zones.

[#] Indicates where no data were available and default values from *1996 IPCC Guidelines* were retained.

* Data were not available to directly estimate reference C stocks for these soil types in the tropical montane climate so the stocks were based on estimates derived for the warm temperate, moist region, which has similar mean annual temperatures and precipitation.

[1] Soils with high activity clay (HAC) minerals are lightly to moderately weathered soils, which are dominated by 2:1 silicate clay minerals (in the World Reference Base for Soil Resources (WRB) classification these include Leptosols, Vertisols, Kastanozems, Chernozems, Phaeozems, Luvisols, Alisols, Albeluvisols, Solonetz, Calcisols, Gypsisols, Umbrisols, Cambisols, Regosols; in USDA classification includes Mollisols, Vertisols, high-base status Alfisols, Aridisols, Inceptisols).

[2] Soils with low activity clay (LAC) minerals are highly weathered soils, dominated by 1:1 clay minerals and amorphous iron and aluminium oxides (in WRB classification includes Acrisols, Lixisols, Nitisols, Ferralsols, Durisols; in USDA classification includes Ultisols, Oxisols, acidic Alfisols).

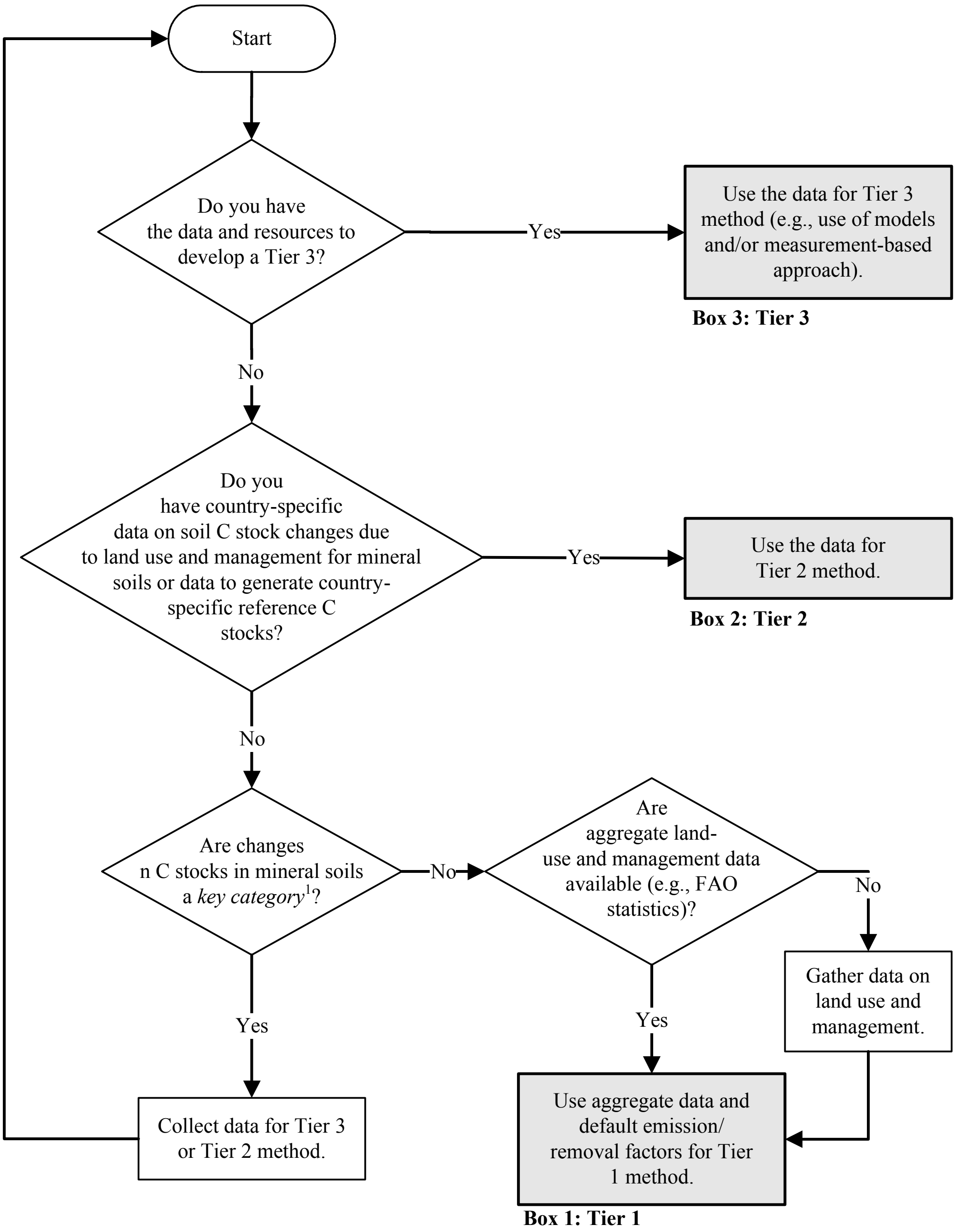
[3] Includes all soils (regardless of taxonomic classification) having > 70% sand and < 8% clay, based on standard textural analyses (in WRB classification includes Arenosols; in USDA classification includes Psamments).

[4] Soils exhibiting strong podzolization (in WRB classification includes Podzols; in USDA classification Spodosols)

[5] Soils derived from volcanic ash with allophanic mineralogy (in WRB classification Andosols; in USDA classification Andisols)

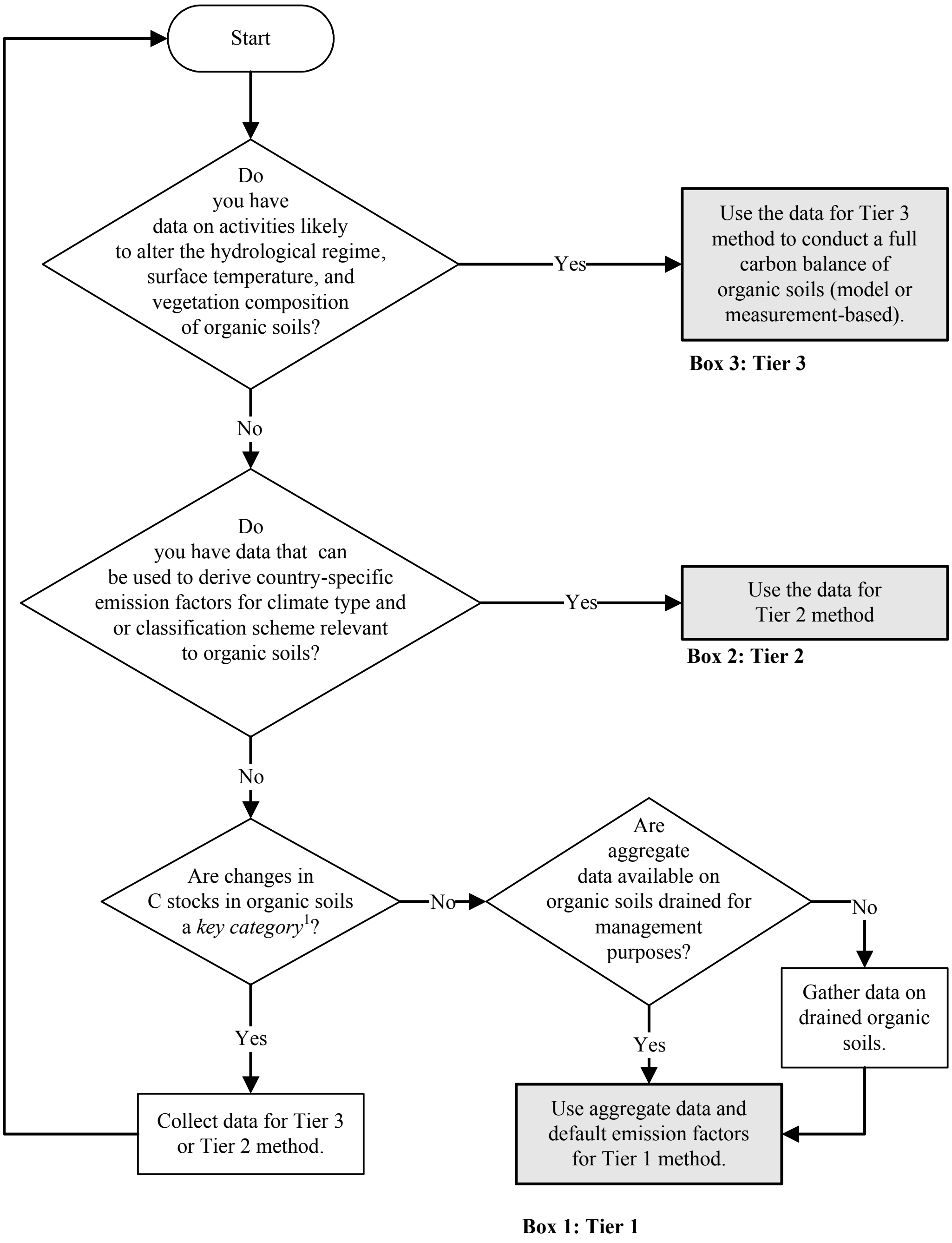
[6] Soils with restricted drainage leading to periodic flooding and anaerobic conditions (in WRB classification Gleysols; in USDA classification Aquic suborders).

Figure 2.4 **Generic decision tree for identification of appropriate tier to estimate changes in carbon stocks in mineral soils by land-use category**



Note:
1: See Volume 1 Chapter 4, "Methodological Choice and Identification of Key Categories" (noting Section 4.1.2 on limited resources), for discussion of *key categories* and use of decision trees.

Figure 2.5 Generic decision tree for identification of appropriate tier to estimate changes in carbon stocks in organic soils by land-use category



Note:

1: See Volume 1 Chapter 4, "Methodological Choice and Identification of Key Categories" (noting Section 4.1.2 on limited resources), for discussion of *key categories* and use of decision trees.

When applying the Tier 1 or even Tier 2 method using Equation 2.25, the type of land-use and management activity data has a direct influence on the formulation of the equation (See Box 2.1). Activity data collected with Approach 1 fit with Formulation A, while activity data collected with Approach 2 or 3 will fit with Formulation B (See Chapter 3 for additional discussion on the Approaches for activity data collection).

BOX 2.1
ALTERNATIVE FORMULATIONS OF EQUATION 2.25 FOR APPROACH 1 ACTIVITY DATA VERSUS APPROACH 2 OR 3 ACTIVITY DATA WITH TRANSITION MATRICES

Two alternative formulations are possible for Equation depending on the Approach used to collected activity data, including

Formulation A (Approach 1 for Activity Data Collection)

$$\Delta C_{Mineral} = \frac{\left[\sum_{c,s,i}\left(SOC_{REF_{c,s,i}} \bullet F_{LU_{c,s,i}} \bullet F_{MG_{c,s,i}} \bullet F_{I_{c,s,i}} \bullet A_{c,s,i}\right)\right]_0 - \left[\sum_{c,s,i}\left(SOC_{REF_{c,s,i}} \bullet F_{LU_{c,s,i}} \bullet F_{MG_{c,s,i}} \bullet F_{I_{c,s,i}} \bullet A_{c,s,i}\right)\right]_{(0-T)}}{D}$$

Formulation B (Approaches 2 and 3 for Activity Data Collection)

$$\Delta C_{Mineral} = \frac{\sum_{c,s,p}\left[\left\{\begin{array}{l}\left(SOC_{REF_{c,s,p}} \bullet F_{LU_{c,s,p}} \bullet F_{MG_{c,s,p}} \bullet F_{I_{c,s,p}}\right)_0 - \\ \left(SOC_{REF_{c,s,p}} \bullet F_{LU_{c,s,p}} \bullet F_{MG_{c,s,p}} \bullet F_{I_{c,s,p}}\right)_{(0-T)}\end{array}\right\} \bullet A_{c,s,p}\right]}{D}$$

Where:

p = parcel of land

See the description of other terms under the Equation 2.25.

Activity data may only be available using Approach 1 for data collection (Chapter 3). These data provide the total area at two points in time for climate, soil and land-use/management systems, without quantification of the specific transitions in land use and management over the inventory time period (i.e., only the aggregate or net change is known, not the gross changes in activity). With Approach 1 activity data, mineral C stock changes are computed using formulation A of Equation 2.25. In contrast, activity data may be collected based on surveys, remote sensing imagery or other data providing not only the total areas for each land management system, but also the specific transitions in land use and management over time on individual parcels of land. These are considered Approach 2 and 3 activity data in Chapter 3, and soil C stock changes are computed using formulation B of Equation 2.25. Formulation B contains a summation by land parcel (i.e., "*p*" represents land parcels in formulation B rather than the set of management systems "*i*") that allows the inventory compiler to compute the changes in C stocks on a land parcel by land parcel basis.

Special consideration is needed if using Approach 1 activity data (see Chapter 3) as the basis for estimating land-use and management effects on soil C stocks, using Equation 2.25. Approach 1 data do not track individual land transitions, and so SOC stock changes are computed for inventory time periods equivalent to D years, or as close as possible to D, which is 20 years in the Tier 1 method. For example, Cropland may be converted from full tillage to no-till management between 1990 and 1995, and Formulation A (see Box 2.1) would estimate a gain in soil C for that inventory time period. However, assuming that the same parcel of land remains in no-till between 1995 and 2000, no additional gain in C would be computed (i.e., the stock for 1995 would be based on no-till management and it would not differ from the stock in 2000 (SOC_0), which is also based on no-till management).

If using the default approach, there would be an error in this estimation because the change in soil C stocks occurs over 20 years (i.e., D = 20 years). Therefore, $SOC_{(0-T)}$ is estimated for the most distant time that is used in the inventory calculations up to D years before the last year in the inventory time periods (SOC_0). For example, assuming D is 20 and the inventory is based on activity data from 1990, 1995, 2000, 2005 and 2010, $SOC_{(0-T)}$ will be computed for 1990 to estimate the change in soil organic C for each of the other years, (i.e., 1995, 2000, 2005 and 2010). The year for estimating $SOC_{(0-T)}$ in this example will not change until activity data are gathered at 2011 or later (e.g., computing the C stock change for 2011 would be based on the most distant year up to, but not exceeding D, which in this example would be 1995).

If transition matrices are available (i.e., Approach 2 or 3 activity data), the changes can be estimated between each successive year. From the example above, some no-till land may be returned to full tillage management between 1995 and 2000. In this case, the gain in C storage between 1990 and 1995 for the land base returned to full tillage would need to be discounted between 1995 and 2000. Further, no additional change in the C stocks would be necessary for land returned to full tillage after 2000 (assuming tillage management remained the same). Only land remaining in no-till would continue to gain C up to 2010 (i.e., assuming D is 20 years). Hence, inventories using transition matrices from Approach 2 and 3 activity data will need to be more careful in dealing with the time periods over which gains or losses of SOC are computed. See Box 2.2 for additional details. The application of the soil C estimation approach is much simpler if only using aggregated statistics with Approach 1 activity data. However, it is *good practice* for countries to use transition matrices from Approach 2 and 3 activity data if that information is available because the more detailed statistics will provide an improved estimate of annual changes in soil organic C stocks.

There may be some cases in which activity data are collected over time spans longer than the time dependence of the stock change factors (D), such as every 30 years with a D of 20. For those cases, the annual stock changes can be estimated directly between each successive year of activity data collection (e.g., 1990, 2020 and 2050) without over- or under-estimating the annual change rate, as long as T is substituted for D in Equation 2.25.

Organic soils

The basic methodology for estimating C emissions from organic (e.g., peat-derived) soils is to assign an annual emission factor that estimates the losses of C following drainage. Drainage stimulates oxidation of organic matter previously built up under a largely anoxic environment. Specifically, the area of drained and managed organic soils under each climate type is multiplied by the associated emission factor to derive an estimate of annual CO_2 emissions (source), as presented in Equation 2.26:

EQUATION 2.26

ANNUAL CARBON LOSS FROM DRAINED ORGANIC SOILS (CO_2)

$$L_{Organic} = \sum_{c} (A \bullet EF)_c$$

Where:

$L_{Organic}$ = annual carbon loss from drained organic soils, tonnes C yr^{-1}

A = land area of drained organic soils in climate type *c,* ha

Note: A is the same area (F_{os}) used to estimate N_2O emissions in Chapter 11, Equations 11.1 and 11.2

EF = emission factor for climate type *c*, tonnes C ha^{-1} yr^{-1}

See the soil C sections in the land-use chapters for a detailed step-by-step guidance on the application of this method.

BOX 2.2
COMPARISON BETWEEN USE OF APPROACH 1 AGGREGATE STATISTICS AND APPROACH 2 OR 3 ACTIVITY DATA WITH TRANSITION MATRICES

Assume a country where a fraction of the land is subjected to land-use changes, as shown in the following table, where each line represents one land unit with an area of 1 Mha (F = Forest Land; C = Cropland; G = Grassland):

Land Unit ID	1990	1995	2000	2005	2010	2015	2020
1	F	C	C	C	C	C	C
2	F	C	C	C	G	G	G
3	G	C	C	C	C	G	G
4	G	G	F	F	F	F	F
5	C	C	C	C	G	G	G
6	C	C	G	G	G	C	C

For simplicity, it is assumed that the country has a single soil type, with a SOC_{Ref} (0-30 cm) value of 77 tonnes C ha^{-1}, corresponding to forest vegetation. Values for F_{LU} are 1.00, 1.05 and 0.92 for F, G and C, respectively. F_{MG} and F_I are assumed to be equal to 1. Time dependence of stock change factors (D) is 20 years. Finally, land-use is assumed to be in equilibrium in 1990 (i.e., no changes in land-use occurred during the 20 years prior to 1990). When using Approach 1 activity data (i.e., aggregate statistical data), annual changes in carbon stocks are computed for every inventory year following Equation 2.25 above. The following table shows the results of calculations:

	1990	1995	2000	2005	2010	2015	2020
F (Mha)	2	0	1	1	1	1	1
G (Mha)	2	1	1	1	3	3	3
C (Mha)	2	5	4	4	2	2	2
SOC_0 (Mt C)	**458**	**436**	**442**	**442**	**462**	**462**	**462**
$SOC_{(0-T)}$ (Mt C)	458	458	458	458	458	436	442
$\Delta C_{Mineral}$ (Mt C yr^{-1})	**0**	**-1.1**	**-0.8**	**-0.8**	**0.2**	**1.3**	**1.0**

If Approach 2 or 3 data are used in which land-use changes are explicitly known, carbon stocks can be computed taking into account historical changes for every individual land unit. The total carbon stocks for the sum of all units is compared with the most immediate previous inventory year, rather than with the inventory of 20 years before- to estimate annual changes in carbon stocks:

	1990	1995	2000	2005	2010	2015	2020
SOC_0 (Mt C) for unit 1	77.0	75.5	74.0	72.5	71.0	71.0	71.0
SOC_0 (Mt C) for unit 2	77.0	75.5	74.0	72.5	75.0	77.5	80.0
SOC_0 (Mt C) for unit 3	81.0	78.5	76.0	73.5	71.0	73.5	76.0
SOC_0 (Mt C) for unit 4	81.0	81.0	80.0	79.0	78.0	77.0	77.0
SOC_0 (Mt C) for unit 5	71.0	71.0	71.0	71.0	73.5	76.0	78.5
SOC_0 (Mt C) for unit 6	71.0	71.0	73.5	76.0	78.5	76.0	73.5
SOC_0 (Mt C)	**458**	**453**	**449**	**445**	**447**	**451**	**456**
$SOC_{(0-T)}$ (Mt C)	458	458	453	449	445	447	451
$\Delta C_{CC_{Mineral}}$ (Mt C yr^{-1})	**0**	**-1.1**	**-0.8**	**-0.8**	**0.5**	**0.8**	**1.0**

Both methods yield different estimates of carbon stocks, and use of Approach 2 or 3 data with transition matrices would be more accurate than use of Approach 1 aggregate statistics. However, estimates of annual changes of carbon stocks would generally not be very different, as shown in this example. The effect of underlying data approaches on the estimates differ more when there are multiple changes in land-use on the same piece of land (as in land units 2, 3 and 6 in the example above). It is noteworthy that Approach 1, 2 and 3 activity data produce the same changes in C stocks if the systems reach a new equilibrium, which occurs with no change in land-use and management for a 20 year time period using the Tier 1 method. Consequently, no carbon stock increases or losses are inadvertently lost when applying the methods for Approach 1, 2 or 3 activity data, but the temporal dynamics do vary somewhat as demonstrated above.

Soil inorganic C

The effects of land-use and management activities on soil inorganic C stocks and fluxes are linked to site hydrology and depend on specific mineralogy of the soil. Further, accurate estimation of the effects requires following the fate of discharged dissolved inorganic C and base cations from the managed land, at least until they are fully captured in the oceanic inorganic C cycle. Thus, a comprehensive hydrogeochemical analysis that tracks the fate of dissolved CO_2, carbonate and bicarbonate species and base cations (e.g., Ca and Mg) applied to, within, and discharged from, managed land over the long term is needed to accurately estimate net stock changes. Such an analysis requires a Tier 3 approach.

Tier 2 Approach: Incorporating country-specific data

A Tier 2 approach is a natural extension of the Tier 1 method that allows an inventory to incorporate country-specific data, while using the default equations given for mineral and organic soils. It is *good practice* for countries to use a Tier 2 approach, if possible, even if they are only able to better specify certain components of the Tier 1 default approach. For example, a country may only have data to derive country-specific reference C stocks, which would then be used with default stock change factors to estimate changes in soil organic C stocks for mineral soils.

Mineral soils

Country-specific data can be used to improve four components of the Tier 1 inventory approach for estimating stock changes in mineral soils, including derivation of region or country-specific stock change factors and/or reference C stocks, in addition to improving the specification of management systems, climate, or soil categories (e.g., Ogle *et al.*, 2003; Vanden Bygaart *et al.*, 2004; Tate *et al.*, 2005). Inventory compilers can choose to derive specific values for all of these components, or any subset, which would be combined with default values provided in the Tier 1 method to complete the inventory calculations using Equation 2.25. Also, Tier 2 uses the same procedural steps for calculations as provided for Tier 1.

1) *Defining management systems.* Although the same management systems may be used in a Tier 2 inventory as found in the Tier 1 method, the default systems can be disaggregated into a finer categorization that better represents management impacts on soil organic C stocks in a particular country based on empirical data (i.e., stock change factors vary significantly for the proposed management systems). Such an undertaking, however, is only possible if there is sufficient detail in the underlying data to classify the land area into the finer, more detailed set of management systems.

2) *Climate regions and soil types.* Countries that have detailed soil classifications and climatic data have the option of developing country-specific classifications. Moreover, it is considered *good practice* to specify better climate regions and soil types during the development of a Tier 2 inventory if the new classification improves the specification of reference C stocks and/or stock change factors. In practice, reference C stocks and/or stock change factors should differ significantly among the proposed climate regions and soil types based on an empirical analysis. Note that specifying new climate regions and/or soil types requires the derivation of country-specific reference C stocks and stock change factors. The default reference C stocks and stock change factors are only appropriate for inventories using the default climate and soil types.

3) *Reference C stocks.* Deriving country-specific reference C stocks (SOC_{Ref}) is another possibility for improving an inventory using a Tier 2 approach (Bernoux *et al.*, 2002). Using country-specific data for estimating reference stocks will likely produce more accurate and representative values. The derivation of country-specific reference soil C stocks can be done from measurements of soils, for example, as part of a country's soil survey. It is important that reliable taxonomic descriptions be used to group soils into categories. There are three additional considerations in deriving the country-specific values, including possible specification of country-specific soil categories and climate regions (i.e., instead of using the IPCC default classification), choice of reference condition, and depth increment over which the stocks are estimated. Stocks are computed by multiplying the proportion of organic carbon (i.e., %C divided by 100) by the depth increment (default is 30 cm), bulk density, and the proportion of coarse-fragment free soil (i.e., < 2mm fragments) in the depth increment (Ogle *et al.*, 2003). The coarse fragment-free proportion is on a mass basis (i.e., mass of coarse fragment-free soil/total mass of the soil).

The reference condition is the land-use/cover category that is used for evaluating the relative effect of land-use change on the amount of soil C storage (e.g., relative difference in C storage between a reference condition, such as native lands, and another land use, such as croplands, forming the basis for F_{LU} in Equation 2.25). In the Tier 1 method, the reference condition is native lands (i.e., non-degraded, unimproved lands under native vegetation), and it is likely that many countries will use this same reference in a Tier 2 approach. However, another land use can be selected for the reference, and this would be considered *good practice* if it allows for a more robust assessment of country-specific reference stock values. Reference stocks should be consistent across the land uses (i.e., Forest Land, Cropland, Grassland, Settlements, and Other Land), requiring coordination among the various teams conducting soil C inventories for the AFOLU Sector.

Another consideration in deriving country-specific reference C stocks is the possibility of estimating C storage to a greater depth in the soil (i.e., lower in the profile). Default stocks given in Table 2.3 account for soil organic C in the top 30 cm of a soil profile. It is *good practice* to derive reference C stocks to a greater depth if there is sufficient data, and if it is clear that land-use change and management have a significant impact over the proposed depth increment. Any change in the depth for reference C stocks will require derivation of new stock change factors, given that the defaults are also based on impacts to a 30 cm depth.

4) *Stock change factors.* An important advancement for a Tier 2 approach is the estimation of country-specific stock change factors (F_{LU}, F_{MG} and F_I). The derivation of country-specific factors can be accomplished using experimental/measurement data and computer model simulation. In practice, deriving stock change factors involves estimating a response ratio for each study or observation (i.e., the C stocks in different input or management classes are divided by the value for the nominal practice, respectively).

Optimally, stock change factors are based on experimental/measurement data in the country or surrounding region, by estimating the response ratios from each study and then analyzing those values using an appropriate statistical technique (e.g., Ogle *et al.*, 2003 and 2004; VandenBygaart *et al.*, 2004). Studies may be found in published literature, reports and other sources, or inventory compilers may choose to conduct new experiments. Regardless of the data source, it is *good practice* that the plots being compared have similar histories and management as well as similar topographic position, soil physical properties and be located in close proximity. Studies should provide C stocks (i.e., mass per unit area to a specified depth) or the information needed to estimate SOC stocks (i.e., percent organic matter together with bulk density; proportion of rock in soil, which is often measured as the greater than 2mm fraction and by definition contains no soil organic C). If percent organic matter is available instead of percent organic carbon, a conversion factor of 0.58 can be used to estimate the C content. Moreover, it is *good practice* that the measurements of soil C stocks are taken on an equivalent mass basis (e.g., Ellert *et al.*, 2001; Gifford and Roderick, 2003). In order to use this method, the inventory compiler will need to determine a depth to measure the C stock for the nominal land use or practice, such as native lands or conventional tillage. This depth will need to be consistent with the depth for the reference C stocks. The soil C stock for the land-use or management change is then measured to a depth with the equivalent mass of soil.

Another option for deriving country-specific values is to simulate stock change factors from advanced models (Bhatti *et al.*, 2001). To demonstrate the use of advanced models, simulated stock change factors can be compared to with measured changes in C stocks from experiments. It is good practice to provide the results of model evaluation, citing published papers in the literature and/or placing the results in the inventory report. This method is considered a Tier 2 approach because it relies on the stock change factor concept and the C estimation method elaborated in the Tier 1 approach.

Derivation of country-specific management factors (F_{MG}) and input factors (F_I), either with empirical data or advanced models, will need to be consistent with the management system classification. If more systems are specified for the inventory, unique factors will need to be derived representing the finer categories for a particular land use.

Another consideration in deriving country-specific stock change factors is their associated time dependence (D in Equation 2.25), which determines the number of years over which the majority of a soil organic C stock change occurs, following a management change. It is possible to use the default time dependence (D) for the land-use sector (e.g., 20 years for cropland), but the dependence can be changed if sufficient data are available to justify a different time period. In addition, the method is designed to use the same time dependence (D) for all stock change factors as presented in Equation 2.25. If different periods are selected for F_{LU}, F_{MG} and F_I, it will be necessary to compute the influence of land use, management and inputs separately and divide the associated stock change dependence. This can be accomplished by modifying Equation 2.25 so that SOC at time T and 0-T is computed individually for each of the stock change factors (i.e., SOC is computed with F_{LU} only, then computed with F_{MG}, and finally computed with F_I). The differences are computed for the stocks associated with land use, management, and input, dividing by their respective D values, and then the changes are summed.

Changes in C stocks normally occur in a non-linear fashion, and it is possible to further develop the time dependence of stock change factors to reflect this pattern. For changes in land use or management that cause a decrease in soil C content, the rate of change is highest during the first few years, and progressively declines with time. In contrast, when soil C is increasing due to land-use or management change, the rate of accumulation tends to follow a sigmoidal curve, with rates of change being slow at the beginning, then increasing and finally decreasing with time. If historical changes in land-use or management practices are explicitly tracked by re-surveying the same locations (i.e., Approach 2 or 3 activity data, see Chapter 3), it may be possible to implement a Tier 2 method that incorporates the non-linearity of changes in soil C stock.

Similar to time dependence, the depth over which impacts are measured may vary from the default approach. However, it is important that the reference C stocks (SOC_{Ref}) and stock change factors (F_{LU}, F_{MG}, F_I) be determined to a common depth, and that they are consistent across each land-use sector in order to deal with conversions among uses without artificially inflating or deflating the soil C stock change estimates. It is *good practice* to document the source of information and underlying basis for the new factors in the reporting process.

Organic soils

A Tier 2 approach for CO_2 emissions associated with drainage of organic soils incorporates country-specific information into the inventory to estimate the emissions using Equation 2.26 (see the previous Tier 1 section for additional discussion on the general equations and application of this method). Also, Tier 2 uses the same procedural steps for calculations as provided for Tier 1. Potential improvements to the Tier 1 approach may include: 1) a derivation of country-specific emission factors, 2) specification of climate regions considered more suitable for the country, or 3) a finer, more detailed classification of management systems attributed to a land-use category.

Derivation of country-specific emission factors is *good practice* if experimental data are available. Moreover, it is *good practice* to use a finer classification for climate and management systems if there are significant differences in measured C loss rates among the proposed classes. Note that any derivation must be accompanied with sufficient land-use/management activity and environmental data to represent the proposed climate regions and management systems at the national scale. Developing the Tier 2 inventory for organic soils has similar considerations as mineral soils discussed in previous section.

Country-specific emission factors for organic soils can be based on measurements of annual declines in C stocks for the whole soil profile. Another alternative is to use land subsidence as a surrogate measure for C loss following drainage (e.g., Armentano and Menges, 1986). C loss is computed as a the fraction of the annual subsidence attributed to oxidation of organic matter, C content of the mineralized organic matter, and bulk density of the soil (Ogle *et al.*, 2003).

Soil inorganic C

See discussion for this sub-category under Tier 1.

Tier 3: Advanced estimation systems

Tier 3 approaches for soil C involve the development of an advanced estimation system that will typically better capture annual variability in fluxes, unlike Tier 1 and 2 approaches that mostly assume a constant annual change in C stocks over an inventory time period based on a stock change factor. Essentially, Tiers 1 and 2 represent land-use and management impacts on soil C stocks as a linear shift from one equilibrium state to another. To understand the implications better, it is important to note that soil C stocks typically do not exist in an absolute equilibrium state or change in a linear manner through a transition period, given that many of the driving variables affecting the stocks are dynamic, periodically changing at shorter time scales before a new “near” equilibrium is reached. Tier 3 approaches can address this non-linearity using more advanced models than Tiers 1 and 2 methods, and/or by developing a measurement-based inventory with a monitoring network. In addition, Tier 3 inventories are capable of capturing longer-term legacy effects of land use and management. In contrast, Tiers 1 and 2 approaches typically only address the most recent influence of land use and management, such as the last 20 years for mineral C stocks. See Section 2.5 (Generic Guidance for Tier 3 methods) for additional discussion on Tier 3 methods beyond the text given below.

Mineral soils

Model-based approaches can use mechanistic simulation models that capture the underlying processes driving carbon gains and losses from soils in a quantitative framework, such as the influence of land use and management on processes controlling carbon input resulting from plant production and litter fall as well as microbial decomposition (e.g., McGill, 1996; Smith *et al.*, 1997b; Smith *et al.*, 2000; Falloon and Smith, 2002; and Tate *et al.*, 2005). Note that Tier 3 methods provide the only current opportunity to explicitly estimate the impact of soil erosion on C fluxes. In addition, Tier 3 model-based approaches may represent C transfers between biomass, dead biomass and soils, which are advantageous for ensuring conservation of mass in predictions of C stock changes in these pools relative to CO_2 removals and emissions to the atmosphere.

Tier 3 modelling approaches are capable of addressing the influence of land use and management with a dynamic representation of environmental conditions that affect the processes controlling soil C stocks, such as weather, edaphic characteristics, and other variables. The impact of land use and management on soil C stocks can vary as environmental conditions change, and such changes are not captured in lower Tiers, which may create biases in those results. Consequently, Tier 3 approaches are capable of providing a more accurate estimation of C stock changes associated with land-use and management activity.

For Tier 3 approaches, a set of benchmark sites will be needed to evaluate model results. Ideally, a series of permanent, benchmark monitoring sites would be established with statistically replicated design, capturing the major climatic regions, soil types, and management systems as well as system changes, and would allow for repeated measurements of soil organic C stocks over time (Smith, 2004a). Monitoring is based on re-sampling plots every 3 to 5 years or each decade; shorter sampling frequencies are not likely to produce significant differences due to small annual changes in C stocks relative to the large total amount of C in a soil (IPCC, 2000; Smith, 2004b).

In addition to model-based approaches, Tier 3 methods afford the opportunity to develop a measurement-based inventory using a similar monitoring network as needed for model evaluation. However, measurement networks, which serve as the basis for a complete inventory, will have a considerably larger sampling density to minimize uncertainty, and to represent all management systems and associated land-use changes, across all climatic regions and major soil types (Sleutel *et al.*, 2003; Lettens *et al.*, 2004). Measurement networks can be based on soil sampling at benchmark sites or flux tower networks. Flux towers, such as those using eddy covariance systems (Baldocchi *et al.*, 2001), constitute a unique case in that they measure the *net* exchange of CO_2 between the atmosphere and land surface. Thus, with respect to changes in C stocks for the soil pool, flux tower measurement networks are subject to the following caveats: 1) towers need to occur at a sufficient density to represent fluxes for the entire country; 2) flux estimates need to be attributed to individual land-use sectors and specific land-use and management activities; and 3) CO_2 fluxes need to be further attributed to individual pools including stock changes in soils (also biomass and dead organic matter). Additional considerations about soil measurements are given in the previous section on Tier 2 methods for mineral soils (See stock change factor discussion).

It is important to note that measurement based inventories represent full C estimation approaches, addressing all influences on soil C stocks. Partial estimation of only land-use and management effects may be difficult.

Organic soils

Similar to mineral soils, CO_2 emissions attributed to land use and management of organic soils can be estimated with a model or measurement based approach. Dynamic, mechanistic-based models will typically be used to simulate underlying processes, while capturing the influence of land use and management, particularly the effect of variable levels of drainage on decomposition. The same considerations that were mentioned for mineral soils are also important for model- and measurement-based approaches addressing soil C stock changes attributed to management of organic soils.

Soil inorganic C

A Tier 3 approach may be further developed to estimate fluxes associated with management impacts on soil inorganic C pools. For example, irrigation can have an impact on soil inorganic C stocks and fluxes, but the direction and magnitude depends on the source and nature of irrigation water and the source, amount, and fate of discharged dissolved inorganic C. In arid and semi-arid regions, gypsum ($CaSO_4 \cdot 2H_2O$) amendments can lead to an increase in soil inorganic C stocks depending on the amount of Ca^{2+} that replaces Na^+ on soil colloids, relative to reaction with bicarbonate and precipitation of calcite ($CaCO_3$). Other land-use and management activities, such as deforestation/afforestation and soil acidifying management practices can also affect soil inorganic C stocks. However, these changes can cause gains or losses of C in this pool depending on site-specific conditions and the amount attributable to the activity can be small.

Few models currently exist for estimating changes in soil inorganic C due to land use and management, and so a Tier 3 approach may require considerable time and resources to implement. Where data and knowledge are sufficient and activities that significantly change soil inorganic C stocks are prevalent, it is *good practice* for countries to do a comprehensive hydro-geochemical analysis that includes all important land-use and management activities to estimate their effect on soil inorganic C stocks. A modelling approach would need to isolate the land-use and management activities from non-anthropogenic effects. Alternatively, a measurement-based approach can be used by periodically sampling benchmark sites in managed lands for determining inorganic C stocks in situ, or possibly CO_2 fluxes, in combination with a monitoring network for soil organic C as discussed above for mineral soils. However, the amount and fate of dissolved inorganic C would require further measurements, modelling, or simplifying assumptions, such as all leaching losses of inorganic C are assumed to be emitted as CO_2 to the atmosphere.

2.4 NON-CO_2 EMISSIONS

There are significant emissions of non-greenhouse gases from biomass burning, livestock and manure management, or soils. N_2O emissions from soils are covered in Chapter 11, where guidance is given on methods that can be applied nationally (i.e., irrespective of land-use types) if a country chooses to use national scale activity data. The guidance on CH_4 and N_2O emissions from livestock and manure are addressed only in Chapter 10 because emissions do not depend on land characteristics. A generic approach to estimating greenhouse gas emissions from fire (both CO_2 and non-CO_2 gases) is described below, with land-use specific enhancements given in the Forest Land, Grassland and Cropland chapters. It is good practice to check for complete coverage of CO_2 and non-CO_2 emissions due to losses in carbon stocks and pools to avoid omissions or double counting.

Emissions from fire include not only CO_2, but also other greenhouse gases, or precursors of greenhouse gases, that originate from incomplete combustion of the fuel. These include carbon monoxide (CO), methane (CH_4), non-methane volatile organic compounds (NMVOC) and nitrogen (e.g., N_2O, NO_x) species (Levine, 1994). In the *1996 IPCC Guidelines* and *GPG2000*, non-CO_2 greenhouse gas emissions from fire in savannas and burning of crop residues were addressed along with emissions from Forest Land and Grassland conversion. The methodology differed somewhat by vegetation type, and fires in Forest Land were not included. In the *GPG-LULUCF*, emissions (CO_2 and non-CO_2) from fires were addressed, particularly in the chapter covering Forest Land (losses of carbon resulting from disturbances). In the Cropland and Grassland chapters, only non-CO_2 emissions were considered, with the assumption that the CO_2 emissions would be counterbalanced by CO_2 removals from the subsequent re-growth of the vegetation within one year. This assumption implies maintenance of soil fertility – an assumption which countries may ignore if they have evidence of fertility decline due to fire. In Forest Land, there is generally a lack of synchrony (non-equivalence of CO_2 emissions and removals in the year of reporting).

These Guidelines provide a more generic approach for estimating emissions from fire. Fire is treated as a disturbance that affects not only the biomass (in particular, above-ground), but also the dead organic matter (litter and dead wood). The term `biomass burning` is widely used and is retained in these Guidelines, but acknowledging that fuel components other than live biomass are often very significant, especially in forest systems. For Cropland and Grassland having little woody vegetation, reference is usually made to biomass burning, since biomass is the main pool affected by the fire.

Countries should apply the following principles when estimating greenhouse gas emissions resulting from fires in Forest Land, Cropland and Grassland:

- Coverage of reporting: Emissions (CO_2 and non- CO_2) need to be reported for all fires (prescribed fires and wildfires) on managed lands (the exception is CO_2 from Grassland, as discussed below). Where there is a land-use change, any greenhouse gas emission from fire should be reported under the new land-use category (transitional category). Emissions from wildfires (and escaped prescribed fires) that occur on unmanaged lands do not need to be reported, unless those lands are followed by a land-use change (i.e., become managed land).
- Fire as a management tool (prescribed burning): greenhouse gas emissions from the area burnt are reported, and if the fire affects unmanaged land, greenhouse gas emissions should also be reported if the fire is followed by a land-use change.
- Equivalence (synchrony) of CO_2 emissions and removals: CO_2 net emissions should be reported where the CO_2 emissions and removals for the biomass pool are not equivalent in the inventory year. For grassland biomass burning and burning of agriculture residues, the assumption of equivalence is generally reasonable. However, woody vegetation may also burn in these land categories, and greenhouse gas emissions from those sources should be reported using a higher Tier method. Further, in many parts of the world, grazing is the predominant land use in Forest Land that are regularly burnt (e.g., grazed woodlands and savannas), and care must be taken before assuming synchrony in such systems. For Forest Land, synchrony is unlikely if significant woody biomass is killed (i.e., losses represent several years of growth and C accumulation), and the net emissions should be reported. Examples include: clearing of native forest and conversion to agriculture and/or plantations and wildfires in Forest Land.
- Fuels available for combustion: Factors that reduce the amount of fuels available for combustion (e.g., from grazing, decay, removal of biofuels, livestock feed, etc.) should be accounted for. A mass balance approach should be adopted to account for residues, to avoid underestimation or double counting (refer to Section 2.3.2).
- Annual reporting: despite the large inherent spatial and temporal variability of fire (in particular that from wildfires), countries should estimate and report greenhouse gas emissions from fire on an annual basis.

These Guidelines provide a comprehensive approach for estimating carbon stock changes and non-CO_2 emissions resulting from fire in the Forest Land (including those resulting from forest conversion), and non-CO_2 emissions in the Cropland and Grassland. Non-CO_2 emissions are addressed for the following five types of burning: (1) grassland burning (which includes perennial woody shrubland and savanna burning); (2) agricultural residues burning; (3) burning of litter, understory and harvest residues in Forest Land, (4) burning following forest clearing and conversion to agriculture; and (5) other types of burning (including those resulting from wildfires). Direct emissions of CO_2 are also addressed for items (3) and (4) and (5). Since estimating emissions in these different categories have many elements in common, this section provides a generic approach to estimate CO_2 and non-CO_2 emissions from fire, to avoid repetition in specific land-use sections that address emissions from fire in these Guidelines.

Prescribed burning of savannas is included under the grassland biomass burning section (Chapter 6, Grassland, Section 6.3.4). It is important to avoid double counting when estimating greenhouse gas emissions from savannas that have a vegetation physiognomy characteristic of Forest Land. An example of this is the cerradão (dense woodland) formation in Brazil which, although being a type of savanna, is included under Forest Land, due to its biophysical characteristics.

In addition to the greenhouse gas emissions from combustion, fires may lead to the creation of an inert carbon stock (charcoal or char). Post-fire residues comprise unburned and partially burnt components, as well as a small amount of char that due to its chemical nature is highly resistant to decomposition. The knowledge of the rates of char formation under contrasting burning conditions and subsequent turnover rates is currently too limited (Forbes *et al.*, 2006; Preston and Schmidt, 2006) to allow development of a reliable methodology for inventory purposes, and hence is not included in these Guidelines. A technical basis for further methodological development is included in Appendix 1.

Additionally, although emissions of NMVOC also occur as a result of fire, they are not addressed in the present Guidelines due to the paucity of the data and size of uncertainties in many of the key parameters needed for the estimation, which prevent the development of reliable emission estimates.

METHOD DESCRIPTION

Each relevant section in these Guidelines includes a three-tiered approach to address CO_2 (where applicable) and non-CO_2 greenhouse gas emissions from fire. The choice of Tier can be made following the steps in the decision tree presented in Figure 2.6. Under the Tier 1 approach, the formulation presented in Equation 2.27 can be applied to estimate CO_2 and non-CO_2 emissions from fire, using the default data provided in this chapter and in the relevant land-use sections of these Guidelines. Higher Tiers involve a more refined application of Equation 2.27.

Since Tier 1 methodology adopts a simplified approach to estimating the dead organic matter pool (see Section 2.3.2), certain assumptions must be made when estimating net greenhouse gas emissions from fire in those systems (e.g. Forest Land, and Forest Land converted to another land use), where dead organic matter can be a major component of the fuel burnt. Emissions of CO_2 from dead organic matter are assumed to be zero in forests that are burnt, but not killed by fire. If the fire is of sufficient intensity to kill a portion of the forest stand, under Tier 1 methodology, the C contained in the killed biomass is assumed to be immediately released to the atmosphere. This Tier 1 simplification may result in an overestimation of actual emissions in the year of the fire, if the amount of biomass carbon killed by the fire is greater than the amount of dead wood and litter carbon consumed by the fire.

Non-CO_2 greenhouse gas emissions are estimated for all fire situations. Under Tier 1, non-CO_2 emissions are best estimated using the actual fuel consumption provided in Table 2.4, and appropriate emission factors (Table 2.5) (i.e., not including newly killed biomass as a component of the fuel consumed). Clearly, if fire in forests contributes significantly to net greenhouse gas emissions, countries are encouraged to develop a more complete methodology (higher tiers) which includes the dynamics of dead organic matter and improves the estimates of direct and post-fire emissions.

For Forest Land converted to another land uses, organic matter burnt is derived from both newly felled vegetation and existing dead organic matter, and CO_2 emissions should be reported. In this situation, estimates of total fuel consumed (Table 2.4) can be used to estimate emissions of CO_2 and non- greenhouse gases using Equation 2.27. Care must be taken, however, to ensure that dead organic matter carbon losses during the land-use conversion are not double counted in Equations 2.27 (as losses from burning) and Equation 2.23 (as losses from decay).

A generic methodology to estimate the emissions of individual greenhouse gases for any type of fire is summarized in Equation 2.27.

EQUATION 2.27
ESTIMATION OF GREENHOUSE GAS EMISSIONS FROM FIRE

$$L_{fire} = A \bullet M_B \bullet C_f \bullet G_{ef} \bullet 10^{-3}$$

Where:

L_{fire} = amount of greenhouse gas emissions from fire, tonnes of each GHG e.g., CH_4, N_2O, etc.

A = area burnt, ha

M_B = mass of fuel available for combustion, tonnes ha^{-1}. This includes biomass, ground litter and dead wood. When Tier 1 methods are used then litter and dead wood pools are assumed zero, except where there is a land-use change (see Section 2.3.2.2).

C_f = combustion factor, dimensionless (default values in Table 2.6)

G_{ef} = emission factor, g kg^{-1} dry matter burnt (default values in Table 2.5)

Note: Where data for M_B and C_f are not available, a default value for the amount of fuel actually burnt (the product of M_B and C_f) can be used (Table 2.4) under Tier 1 methodology.

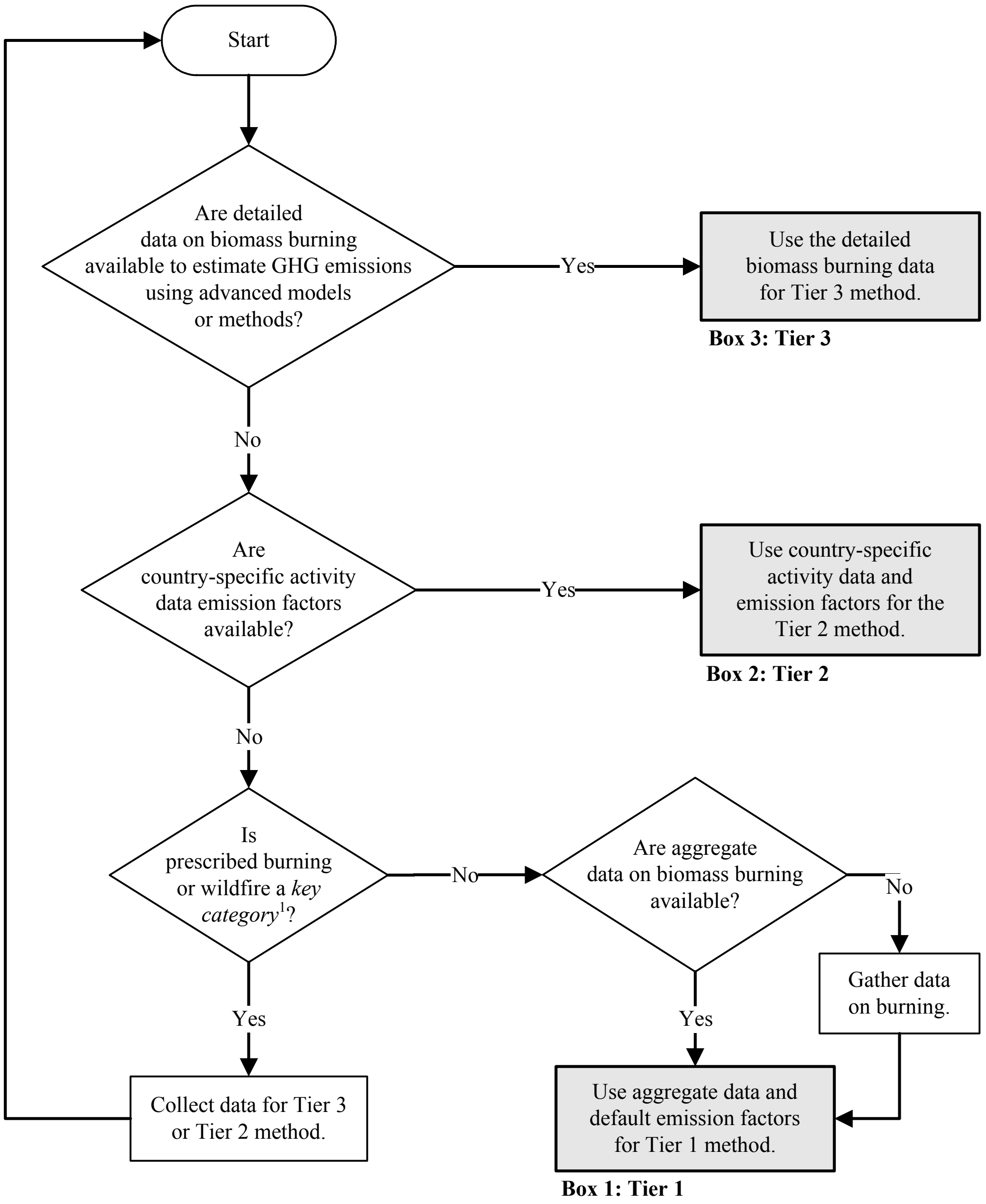
For CO_2 emissions, Equation 2.27 relates to Equation 2.14, which estimates the annual amount of live biomass loss from any type of disturbance.

The amount of fuel that can be burnt is given by the area burnt and the density of fuel present on that area. The fuel density can include biomass, dead wood and litter, which vary as a function of the type, age and condition of the vegetation. The type of fire also affects the amount of fuel available for combustion. For example, fuel available for low-intensity ground fires in forests will be largely restricted to litter and dead organic matter on the surface, while a higher-intensity ‘crown fire’ can also consume substantial amounts of tree biomass.

The combustion factor is a measure of the proportion of the fuel that is actually combusted, which varies as a function of the size and architecture of the fuel load (i.e., a smaller proportion of large, coarse fuel such as tree stems will be burnt compared to fine fuels, such as grass leaves), the moisture content of the fuel and the type of fire (i.e., intensity and rate of spread which is markedly affected by climatic variability and regional differences as reflected in Table 2.6). Finally, the emission factor gives the amount of a particular greenhouse gas emitted per unit of dry matter combusted, which can vary as a function of the carbon content of the biomass and the completeness of combustion. For species with high N concentrations, NO_x and N_2O emissions from fire can vary as a function of the N content of the fuel. A comprehensive review of emission factors was conducted by Andreae and Merlet (2001) and is summarized in Table 2.5.

Tier 2 methods employ the same general approach as Tier 1 but make use of more refined country-derived emission factors and/or more refined estimates of fuel densities and combustion factors than those provided in the default tables. Tier 3 methods are more comprehensive and include considerations of the dynamics of fuels (biomass and dead organic matter).

Figure 2.6 **Generic decision tree for identification of appropriate tier to estimate greenhouse gas emissions from fire in a land-use category**



Note:
1: See Volume 1 Chapter 4, "Methodological Choice and Identification of Key Categories" (noting Section 4.1.2 on limited resources), for discussion of *key categories* and use of decision trees.

TABLE 2.4
FUEL (DEAD ORGANIC MATTER PLUS LIVE BIOMASS) BIOMASS CONSUMPTION VALUES (TONNES DRY MATTER HA^{-1}) FOR FIRES IN A RANGE OF VEGETATION TYPES

(To be used in Equation 2.27 , to estimate the product of quantities ' $M_B \bullet C_f$ ' , i.e., an absolute amount)

Vegetation type	Subcategory	Mean	SE	References
Primary tropical forest (slash and burn)	Primary tropical forest	83.9	25.8	7, 15, 66, 3, 16, 17, 45
	Primary open tropical forest	163.6	52.1	21,
	Primary tropical moist forest	160.4	11.8	37, 73
	Primary tropical dry forest	-	-	66
All primary tropical forests		**119.6**	**50.7**	
Secondary tropical forest (slash and burn)	Young secondary tropical forest (3-5 yrs)	8.1	-	61
	Intermediate secondary tropical forest (6-10 yrs)	41.1	27.4	61, 35
	Advanced secondary tropical forest (14-17 yrs)	46.4	8.0	61, 73
All secondary tropical forests		**42.2**	**23.6**	66, 30
All Tertiary tropical forest		**54.1**	**-**	66, 30
Boreal forest	Wildfire (general)	52.8	48.4	2, 33, 66
	Crown fire	25.1	7.9	11, 43, 66, 41, 63, 64
	Surface fire	21.6	25.1	43, 69, 66, 63, 64, 1
	Post logging slash burn	69.6	44.8	49, 40, 66, 18
	Land clearing fire	87.5	35.0	10, 67
All boreal forest		**41.0**	**36.5**	43, 45, 69, 47
Eucalypt forests	Wildfire	53.0	53.6	66, 32, 9
	Prescribed fire – (surface)	16.0	13.7	66, 72, 54, 60, 9
	Post logging slash burn	168.4	168.8	25, 58, 46
	Felled, wood removed, and burned (land-clearing fire)	132.6	-	62, 9
All Eucalypt forests		**69.4**	**100.8**	
Other temperate forests	Wildfire	19.8	6.3	32, 66
	Post logging slash burn	77.5	65.0	55, 19, 14, 27, 66
	Felled and burned (land-clearing fire)	48.4	62.7	53, 24, 71
All "other" temperate forests		**50.4**	**53.7**	43, 56

TABLE 2.4 (CONTINUED)
FUEL (DEAD ORGANIC MATTER PLUS LIVE BIOMASS) BIOMASS CONSUMPTION VALUES (TONNES DRY MATTER HA^{-1}) FOR FIRES IN A RANGE OF VEGETATION TYPES

(To be used in Equation 2.27 , to estimate the product of quantities ' $M_B \bullet C_f$ ' , i.e., an absolute amount)

Vegetation type	Subcategory	Mean	SE	References
Shrublands	Shrubland (general)	26.7	4.2	43
	Calluna heath	11.5	4.3	26, 39
	Sagebrush	5.7	3.8	66
	Fynbos	12.9	0.1	70, 66
All Shrublands		**14.3**	**9.0**	
Savanna woodlands (early dry season burns)*	Savanna woodland	2.5	-	28
	Savanna parkland	2.7	-	57
All savanna woodlands (early dry season burns)		**2.6**	**0.1**	
Savanna woodlands (mid/late dry season burns)*	Savanna woodland	3.3	-	57
	Savanna parkland	4.0	1.1	57, 6, 51
	Tropical savanna	6	1.8	52, 73
	Other savanna woodlands	5.3	1.7	59, 57, 31
All savanna woodlands (mid/late dry season burns)*		**4.6**	**1.5**	
Savanna Grasslands/ Pastures (early dry season burns)*	Tropical/sub-tropical grassland	2.1	-	28
	Grassland	-	-	48
All savanna grasslands (early dry season burns)*		**2.1**	**-**	
Savanna Grasslands/ Pastures (mid/late dry season burns)*	Tropical/sub-tropical grassland	5.2	1.7	9, 73, 12, 57
	Grassland	4.1	3.1	43, 9
	Tropical pasture~	23.7	11.8	4, 23, 38, 66
	Savanna	7.0	2.7	42, 50, 6, 45, 13, 65
All savanna grasslands (mid/late dry season burns)*		**10.0**	**10.1**	
Other vegetation types	Peatland	41	1.4	68, 33
	Tundra	10	-	33
Agricultural residues (post harvest field burning)	Wheat residues	4.0		see Note b
	Maize residues	10.0		see Note b
	Rice residues	5.5		see Note b
	Sugarcane [a]	6.5		see Note b

* Surface layer combustion only

~ Derived from slashed tropical forest (includes unburned woody material)

[a] For sugarcane, data refer to burning before harvest of the crop.

[b] Expert assessment by authors.

TABLE 2.5
EMISSION FACTORS (g kg^{-1} DRY MATTER BURNT) FOR VARIOUS TYPES OF BURNING. VALUES ARE MEANS ± SD AND ARE BASED ON THE COMPREHENSIVE REVIEW BY ANDREAE AND MERLET (2001)
(To be used as quantity 'G_{ef}' in Equation 2.27)

Category	CO_2	CO	CH_4	N_2O	NO_X
Savanna and grassland	1613 ± 95	65 ± 20	2.3 ± 0.9	0.21 ± 0.10	3.9 ± 2.4
Agricultural residues	1515 ± 177	92 ± 84	2.7	0.07	2.5 ± 1.0
Tropical forest	1580 ± 90	104 ± 20	6.8 ± 2.0	0.20	1.6 ± 0.7
Extra tropical forest	1569 ± 131	107 ± 37	4.7 ± 1.9	0.26 ±0.07	3.0 ± 1.4
Biofuel burning	1550 ± 95	78 ± 31	6.1 ± 2.2	0.06	1.1 ± 0.6

Note: The "extra tropical forest' category includes all other forest types.

Note: For combustion of non-woody biomass in Grassland and Cropland, CO_2 emissions do not need to be estimated and reported, because it is assumed that annual CO_2 removals (through growth) and emissions (whether by decay or fire) by biomass are in balance (see earlier discussion on synchrony in Section 2.4.

TABLE 2.6
COMBUSTION FACTOR VALUES (PROPORTION OF PREFIRE FUEL BIOMASS CONSUMED) FOR FIRES IN A RANGE OF VEGETATION TYPES
(Values in column 'mean' are to be used for quantity C_f in Equation 2.27)

Vegetation type	Subcategory	Mean	SD	References
Primary tropical forest (slash and burn)	Primary tropical forest	0.32	0.12	7, 8, 15, 56, 66, 3, 16, 53, 17, 45,
	Primary open tropical forest	0.45	0.09	21
	Primary tropical moist forest	0.50	0.03	37, 73
	Primary tropical dry forest	-	-	66
All primary tropical forests		**0.36**	**0.13**	
Secondary tropical forest (slash and burn)	Young secondary tropical forest (3-5 yrs)	0.46	-	61
	Intermediate secondary tropical forest (6-10 yrs)	0.67	0.21	61, 35
	Advanced secondary tropical forest (14-17 yrs)	0.50	0.10	61, 73
All secondary tropical forests		**0.55**	**0.06**	56, 66, 34, 30
All tertiary tropical forest		**0.59**	**-**	66, 30
Boreal forest	Wildfire (general)	0.40	0.06	33
	Crown fire	0.43	0..21	66, 41, 64, 63
	surface fire	0.15	0.08	64, 63
	Post logging slash burn	0.33	0.13	49, 40, 18
	Land clearing fire	0.59	-	67
All boreal forest		**0.34**	**0.17**	45, 47
Eucalyptus forests	Wildfire	-	-	
	Prescribed fire – (surface)	0.61	0.11	72, 54, 60, 9
	Post logging slash burn	0.68	0.14	25, 58, 46
	Felled and burned (land-clearing fire)	0.49	-	62
All Eucalyptus forests		**0.63**	**0.13**	
Other temperate forests	Post logging slash burn	0.62	0.12	55, 19, 27, 14
	Felled and burned (land-clearing fire)	0.51	-	53, 24, 71
All "other" temperate forests		**0.45**	**0.16**	53, 56

TABLE 2.6 (CONTINUED)

COMBUSTION FACTOR VALUES (PROPORTION OF PREFIRE FUEL BIOMASS CONSUMED) FOR FIRES IN A RANGE OF VEGETATION TYPES

(Values in column 'mean' are to be used for quantity C_f in Equation 2.27)

Vegetation type	Subcategory	Mean	SD	References
Shrublands	Shrubland (general)	0.95	-	44
	Calluna heath	0.71	0.30	26, 56, 39
	Fynbos	0.61	0.16	70, 44
All shrublands		**0.72**	**0.25**	
Savanna woodlands (early dry season burns)*	Savanna woodland	0.22	-	28
	Savanna parkland	0.73	-	57
	Other savanna woodlands	0.37	0.19	22, 29
All savanna woodlands (early dry season burns)		**0.40**	**0.22**	
Savanna woodlands (mid/late dry season burns)*	Savanna woodland	0.72	-	66, 57
	Savanna parkland	0.82	0.07	57, 6, 51
	Tropical savanna	0.73	0.04	52, 73, 66, 12
	Other savanna woodlands	0.68	0.19	22, 29, 44, 31, 57
All savanna woodlands (mid/late dry season burns)*		**0.74**	**0.14**	
Savanna Grasslands/ Pastures (early dry season burns)*	Tropical/sub-tropical grassland	0.74	-	28
	Grassland	-	-	48
All savanna grasslands (early dry season burns)*		**0.74**	**-**	
Savanna Grasslands/ Pastures (mid/late dry season burns)*	Tropical/sub-tropical grassland	0.92	0.11	44, 73, 66, 12, 57
	Tropical pasture[~]	0.35	0.21	4, 23, 38, 66
	Savanna	0.86	0.12	53, 5, 56, 42, 50, 6, 45, 13, 44, 65, 66
All savanna grasslands (mid/late dry season burns)*		**0.77**	**0.26**	
Other vegetation types	Peatland	0.50	-	20, 44
	Tropical Wetlands	0.70	-	44
Agricultural residues (Post harvest field burning)	Wheat residues	0.90	-	see Note b
	Maize residues	0.80	-	see Note b
	Rice residues	0.80	-	see Note b
	Sugarcane[a]	0.80	-	see Note b

[*] Surface layer combustion only

[~] Derived from slashed tropical forest (includes unburned woody material)

[a] For sugarcane, data refer to burning before harvest of the crop.

[b] Expert assessment by authors.

2.5 ADDITIONAL GENERIC GUIDANCE FOR TIER 3 METHODS

The guidelines in this volume focus mainly on Tier 1 methods, along with general guidance to assist with the development of a Tier 2 inventory. Less attention is given to Tier 3 methods, but some general guidance is provided in this section. Tier 3 inventories are advanced systems using measurements and/or modelling, with the goal of improving the estimation of greenhouse gas (GHG) emissions and removals, beyond what is possible with Tier 1 or 2 approaches. In this section, guidelines are elaborated that provide a sound scientific basis for the development of Tier 3 Inventories. *These guidelines do not limit the selection of Tier 3 sampling schemes or modelling approaches*, but provide general guidance to assist the inventory developer in the implementation. Specific issues surrounding Tier 3 approaches for individual source categories may be provided later in the volume, and supplement the general guidance found in this section.

2.5.1 Measurement-based Tier 3 inventories

Inventories can be based on direct measurements of C stock changes from which emissions and removals of carbon are estimated. Measurement of some non-CO_2 greenhouse gas emissions is possible, but because of the high spatial and temporal variability of non-CO_2 emissions, Tier 3 methods will likely combine process models with measurements to estimate non-CO_2 emissions. Purely measurement-based inventories, e.g., based on repeated measurements using a national forest inventory can derive carbon stock change estimates without relying on process models, but they do require appropriate statistical models for the spatial and temporal scaling of plot measurements to a national inventory. Approaches based on dynamic models (e.g., process-based models) to estimate national emissions will be discussed in Section 2.5.2. In general, six steps are involved with implementation of a Tier 3 measurement-based inventory.

Step 1. *Develop sampling scheme*. Sampling schemes can be developed using a variety of approaches, but typically involve some level of randomization of sampling sites within strata. (Even inventories based on a regular grid typically select the starting point of the grid at random). Inventory compilers will determine an appropriate approach given the size of their country, key environmental variables (e.g., climate) and management systems in their region. The latter two may serve as stratification variables, assuming the sampling scheme is not completely random. In addition, it is *good practice* for sampling to provide wide spatial coverage of emissions and/or removals for a particular key source category.

The inventory compiler should establish an appropriate time period over which sites will be re-sampled if using a repeated measures design. The timing of re-measurement will depend on the rate of stock changes or non-CO_2 greenhouse gas emissions. For example, re-measurement periods in boreal and some temperate regions, where trees grow slowly and DOM pools change little in single years, can be longer than in environments where carbon dynamics are more rapid. Where fluxes are measured directly, greater temporal and spatial variability will require more frequent or more intensive sampling to capture fluxes which might otherwise be missing from the measurement record.

Some approaches do not include re-sampling of the same sites. Such designs are acceptable, but may limit the statistical power of the analysis, and therefore lead to greater uncertainty. It is likely that a repeated measures design will provide a better basis for estimating carbon stock changes or emissions in most countries.

It is *good practice* to develop a methodology handbook explaining the sampling scheme as part of Step 1. This handbook can be useful for those involved with the measurements, laboratory analyses and other aspects of the process, as well as possibly providing supporting material for documentation purposes.

Step 2. *Select sampling sites*. Specific sampling sites will be located based on sampling design. It is *good practice* to have alternative sites for sampling in case it is not possible to sample some original locations. In a repeated measures design, the sites will become a monitoring network that is periodically re-sampled.

Determining sampling locations will likely involve the use of a geographic information system. A geographic database may include a variety of environmental and management data, such as climate, soils, land use, and livestock operations, depending on the source category and stratification. If key data are not available at the national scale, the inventory developer should re-evaluate the design and stratification (if used) in Step 1 and possibly modify the sampling design.

Sampling may require coordination among different national ministries, provincial or state governments, corporate and private land owners. Establishing relationships among these stakeholders can be undertaken before collecting initial samples. Informing stakeholders about ongoing monitoring may also be helpful and lead to greater success in implementing monitoring programs.

Step 3. *Collect initial samples.* Once the final set of sites are determined, a sampling team can visit those locations, establish plots and collect initial samples. The initial samples will provide initial carbon stocks, or serve as the first measure of emissions. It is *good practice* to establish field measurement and laboratory protocols before the samples are collected. In addition, it may be helpful to take geographic coordinates of plot locations or sample points with a global positioning system, and, if repeated measures are planned, to permanently mark the location for ease of finding and re-sampling the site in the future.

It is *good practice* to take relevant measurements and notes of the environmental conditions and management at the site. This will confirm that the conditions were consistent with the design of the sampling scheme, and also may be used in data analysis (Step 5). If a stratified sampling approach is used, and it becomes apparent that many or most sites are not consistent with the expected environmental conditions and management systems, it is *good practice* to repeat Step 1, re-evaluating and possibly modifying the sampling scheme based on the new information.

Step 4. *Re-sample the monitoring network on a periodic basis.* For repeated measures designs, sampling sites will be periodically re-sampled in order to evaluate trends in carbon stocks or non-CO_2 emissions over an inventory time period. The time between re-measurement will depend on the rate of stock changes or the variability in emissions, the resources available for the monitoring program, and the design of the sampling scheme.

If destructive sampling is involved, such as removing a soil core or biomass sample, it is *good practice* to re-sample at the same site but not at the exact location in which the sample was removed during the past. Destructive sampling the exact location is likely to create bias in the measurements. Such biases would compromise the monitoring and produce results that are not representative of national trends.

Step 5. *Analyze data and determine carbon stock changes/non-CO_2 emissions, and infer national emissions and removal estimates and measures of uncertainty.* It is *good practice* to select an appropriate statistical method for data analysis based on the sampling design. The overall result of the statistical analysis will be estimates of carbon stock changes or measurements of emissions from which the national emission and removal estimates can be derived. It is *good practice* to also include estimates of uncertainty, which will include measurement errors in the sample collection and laboratory processing (i.e., the latter may be addressed using standards and through cross-checking results with independent labs), sampling variance associated with monitoring design and other relevant sources of uncertainty (see discussion for each source category later in this volume in addition to the uncertainty chapter in Volume 1). The analysis may include scaling of measurements to a larger spatial or temporal domain, which again will depend on the design of the sampling scheme. Scaling may range from simple averaging or weighted averaging to more detailed interpolation/extrapolation techniques.

To obtain national estimates of stock changes or emission of non-CO_2 greenhouse gases, it is often necessary to extrapolate measurements using models that take into consideration environmental conditions, management and other activity data. While the net changes of carbon-based greenhouse gasses can (at least in theory) be estimated purely by repeated measurements of carbon stocks, statistical and other models are often employed to assist in the scaling of plot measures to national estimates. National emission estimates of non-CO_2 greenhouse gases are unlikely to be derived from measurements alone because of the expense and difficulty in obtaining the measurement. For example, N_2O emissions from forest fires cannot be measured empirically but are typically inferred from samples, activity data on the area burnt, and fuel consumption estimates. In contrast, soil N_2O emissions can be readily estimated using chambers, but it would be very expensive to establish a network with the sampling intensity needed to provide national emission estimates based solely on measurements without use of models for extrapolation.

It is *good practice* to analyze emissions relative to environmental conditions in addition to the contribution of various management practices to those trends. Interpretation of the patterns will be useful in evaluating possibilities for future mitigation.

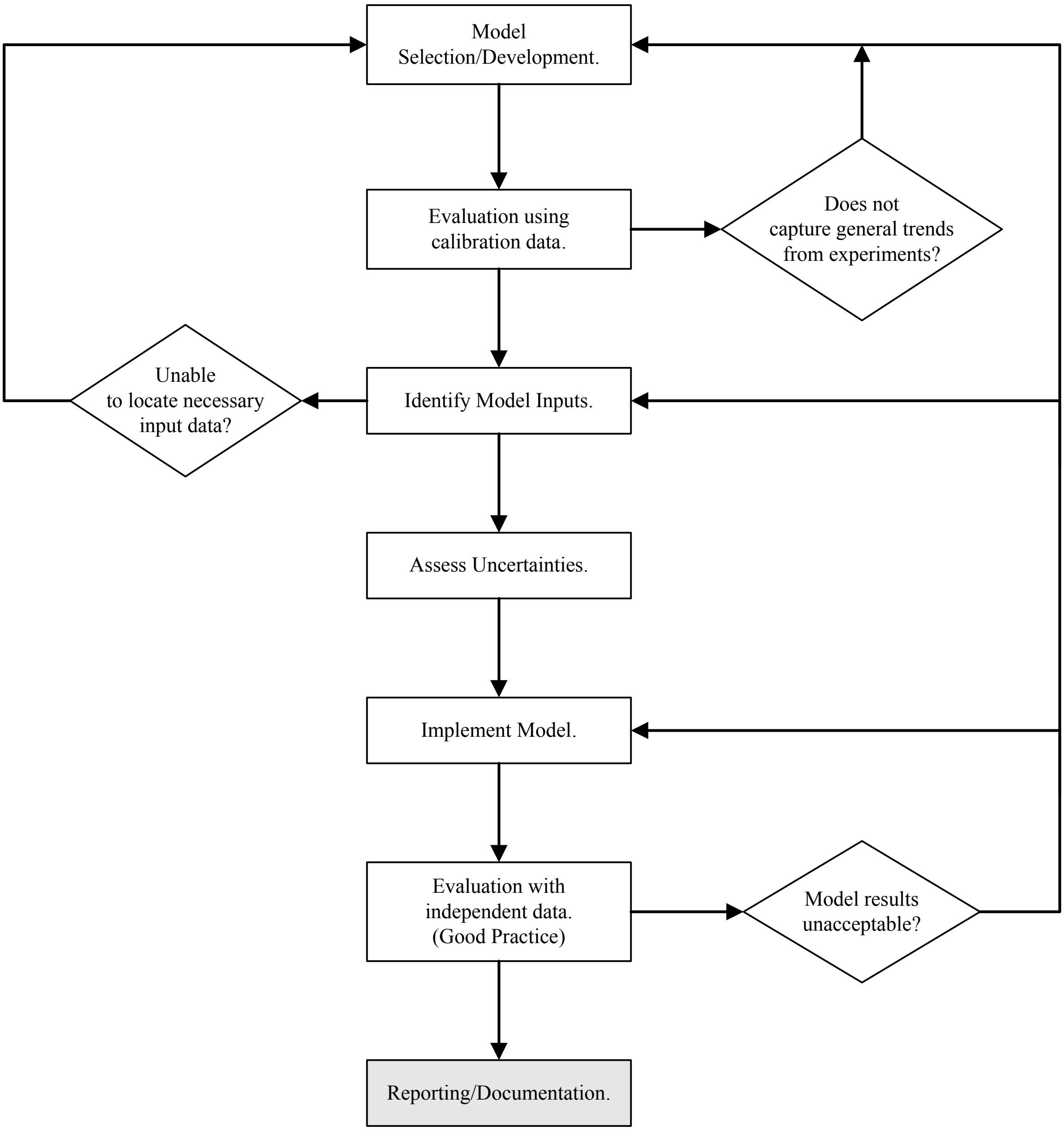
Step 6. *Reporting and Documentation.* It is *good practice* to assemble inventory results in a systematic and transparent manner for reporting purposes. Documentation may include a description of the sampling scheme and statistical methods, sampling schedule (including re-sampling), stock change and emissions estimates and the interpretation of emission trends (e.g., contributions of management activities). In addition, QA/QC should be completed and documented in the report, including quality assurance procedures in which peer-reviewers not involved with the analysis evaluate the methodology. For details on QA/QC, reporting and documentation, see the section dealing with the specific source category later in this volume, as well as information provided in Volume 1, Chapter 6.

2.5.2 Model-based Tier 3 inventories

Model-based inventories are developed using empirical, process-based or other types of advanced models. It is *good practice* to have independent measurements to confirm that the model is capable of estimating emissions and removals in the source categories of interest (Prisley and Mortimer, 2004). In general, seven steps are used to implement a Tier 3 model-based inventory (Figure 2.7).

Step 1. *Select/develop a model for calculating the stock changes and/or greenhouse gas emissions.* A model should be selected or developed that more accurately represents stock changes or non-CO_2 greenhouse gas emissions than is possible with Tiers 1 and 2 approaches. As part of this decision, it is *good practice* to consider the availability of input data (Steps 3) and the computing resources needed to implement the model (Step 5).

Figure 2.7 **Steps to develop a Tier 3 model-based inventory estimation system**



Step 2. *Evaluation with calibration data.* This is a critical step for inventory development in which model results are compared directly with measurements that were used for model calibration/parameterization (e.g., Falloon and Smith, 2002). Comparisons can be made using statistical tests and/or graphically, with the goal of demonstrating that the model effectively simulates measured trends for a variety of conditions in the source category of interest. It is *good practice* to ensure that the model responds appropriately to variations in activity data and that the model is able to report results by land-use category as per the conventions laid out in Chapter 3. Re-calibration of the model or modifications to the structure (i.e., algorithms) may be necessary if the model does not capture general trends or there are large systematic biases. In some cases, a new model may be selected or developed based on this evaluation. Evaluation results are an important component of the reporting documentation, justifying the use of a particular model for quantifying emissions in a source category.

Step 3. *Gather spatio-temporal data on activities and relevant environmental conditions that are needed as inputs to a model.* Models, even those used in Tiers 1 and 2 approaches, require specific input information in order to estimate greenhouse gas emissions and removals associated with a source category. These inputs may range from weather and soils data to livestock number, forest types, natural disturbances or cropping management practices. It is *good practice* for the input data to be consistent with spatio-temporal scale of the model (i.e., algorithms). For example, if a model operates on a daily time step then the input data should provide information about daily variation in the environmental characteristic or activity data. In some cases, input data may be a limiting factor in model selection, requiring some models to be discarded as inappropriate given the available activity and/or environmental data.

Step 4. *Quantify uncertainties.* Uncertainties are due to imperfect knowledge about the activities or processes leading to greenhouse gas fluxes, and are typically manifested in the model structure and inputs. Consequently, uncertainty analyses are intended to provide a rigorous measure of the confidence attributed to a model estimate based on uncertainties in the model structure and inputs, generating a measure of variability in the carbon stock changes or non-CO_2 greenhouse gas fluxes. Volume 1, Chapter 3 provides specific guidance on appropriate methods for conducting these analyses. Additional information may also be provided for specific source categories later in this volume.

Step 5. *Implement the model.* The major consideration for this step is that there are enough computing resources and personnel time to prepare the input data, conduct the model simulations, and analyze the results. This will depend on the efficiency of the programming script, complexity of the model, as well as the spatial and temporal extent and resolution of the simulations. In some cases, limitations in computing resources may constrain the complexity and range of spatial or temporal resolution that can be used in implementing at the national scale (i.e., simulating at finer spatial and temporal scales will require greater computing resources).

Step 6. *Evaluation with independent data.* It is important to realise the difference between Steps 2 and 6. Step 2 involves testing model output with field data that were used as a basis for calibration (i.e., parameterization). In contrast, evaluation with independent data is done with a completely independent set of data from model calibration, providing a more rigorous assessment of model components and results. Optimally, independent evaluation should be based on measurements from a monitoring network or from research sites that were not used to calibrate model parameters. The network would be similar in principle to a series of sites that are used for a measurement-based inventory. However, the sampling does not need to be as dense because the network is not forming the basis for estimating carbon stock changes or non-CO_2 greenhouse gas fluxes, as in a purely measurement-based inventory, but is used to check model results.

In some cases, independent evaluation may demonstrate that the model-based estimation system is inappropriate due to large and unpredictable differences between model results and the measured trends from the monitoring network. Problems may stem from one of three possibilities: errors in the implementation step, poor input data, or an inappropriate model. Implementation problems typically arise from computer programming errors, while model inputs may generate erroneous results if these data are not representative of management activity or environmental conditions. In these two cases, it is *good practice* for the inventory developer to return to either Steps 3 or 6 depending on the issue. It seems less likely that the model would be inappropriate if Step 2 was deemed reasonable. However, if this is the case, it is *good practice* to return to the model selection/development phase (Step 1).

During Step 2 that follows the selection/development step, it is *good practice* to avoid using the independent evaluation data to re-calibrate or refine algorithms. If this occurs, these data would no longer be suitable for independent evaluation, and therefore not serve the purpose for Step 6 in this inventory approach.

Step 7. *Reporting and Documentation.* It is *good practice* to assemble inventory results in a systematic and transparent manner for reporting purposes. Documentation may include a description of the model, summary of model input data sources, model evaluation results including sources of experiments and/or measurements data from monitoring network, stock change and emissions estimates and the interpretation of emission trends (i.e., contributions of management activities). QA/QC should be completed and documented in the report. For details on QA/QC, reporting and documentation, see the section dealing with the specific source category later in this volume, as well as information provided in Volume 1, Chapter 6.

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CHAPTER 4

FOREST LAND

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Contents

Figures

Tables

Boxes

4 FOREST LAND

4.1 INTRODUCTION

This chapter provides methods for estimating greenhouse gas emissions and removals due to changes in biomass, dead organic matter and soil organic carbon on Forest Land and *Land Converted to Forest Land*. It builds on the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (*1996 IPCC Guidelines*) and the Good Practice Guidance for Land Use, Land-Use Change and Forestry (*GPG-LULUCF*). The chapter:

- addresses all five carbon pools identified in Chapter 1 and transfers of carbon between different pools within the same land areas;
- includes carbon stock changes on managed forests due to human activities such as establishing and harvesting plantations, commercial felling, fuelwood gathering and other management practices, in addition to natural losses caused by fire, windstorms, insects, diseases, and other disturbances;
- provides simple (Tier 1) methods and default values and outline approaches for higher tier methods for the estimation of carbon stock changes;
- provides methods to estimate non-CO_2 greenhouse gas emissions from biomass burning (other non-CO_2 emissions such as N_2O emissions from soils are covered in Chapter 11);
- should be used together with generic description of methods and equations from Chapter 2, and the approaches for obtaining consistent area data described in Chapter 3.

The *Guidelines* provide methods for estimating and reporting sources and sinks of greenhouse gases only for managed forests, as defined in Chapter 1. Countries should consistently apply national definitions of managed forests over time. National definitions should cover all forests subject to human intervention, including the full range of management practices from protecting forests, raising plantations, promoting natural regeneration, commercial timber production, non-commercial fuelwood extraction, and abandonment of managed land.

This chapter does not include harvested wood products (HWP) which are covered by Chapter 12 of this Volume.

Managed Forest Land is partitioned into two sub categories and the guidance and methodologies are given separately in two sections:

- Section 4.2 Forest Land Remaining Forest Land
- Section 4.3 Land Converted to Forest Land

Section 4.2 covers the methodology that applies to lands that have been Forest Land for more than the transition period required to reach new soil carbon levels (default is 20 years). Section 4.3 applies to lands converted to Forest Land within that transition period. The 20-year interval is taken as a default length of transition period for carbon stock changes following land-use change. It is *good practice* to differentiate national forest lands by the above two categories. The actual length of transition period depends on natural and ecological circumstances of a particular country or region and may differ from 20 years.

Unmanaged forests, which are brought under management, enter the inventory and should be included in the *Land Converted to Forest Land*. Unmanaged forests which are converted to other land uses enter the inventory under their post conversion land-use categories with the appropriate transition period for the new land-use category.

If there are no data on land conversion and the period involved are available, the default assumption is that all managed forest land belongs to the category *Forest Land Remaining Forest Land* and greenhouse gas (GHG) emissions and removals are estimated using guidance given in Section 4.2.

Relevant carbon pools and non-CO_2 gases

The relevant carbon pools and non-CO_2 gases for which methods are provided are given below:

- Biomass (above-ground and below-ground biomass)
- Dead organic matter (dead wood and litter)
- Soil organic matter
- Non-CO_2 gases (CH_4, CO, N_2O, NO_X)

The selection of carbon pools or non-CO_2 gases for estimation will depend on the significance of the pool and tier selected for each land-use category.

Forest land-use classification

Greenhouse gas emissions and removals per hectare vary according to site factors, forest or plantation types, stages of stand development and management practices. It is *good practice* to stratify Forest Land into various sub categories to reduce the variation in growth rate and other forest parameters and to reduce uncertainty (Box 4.1). As a default, the *Guidelines* use the most recent ecological zone (see Table 4.1 in Section 4.5 and Figure 4.1 in this chapter) and forest cover (see Table 4.2 in Section 4.5 and Figure 4.2 in this chapter) classifications, developed by the Food and Agriculture Organization (FAO, 2001). National experts should use more detailed classifications for their countries, if available and suitable, given the other data requirements.

BOX 4.1
LEVELS OF DETAIL

Stratification of forest types into homogeneous sub-categories, and if possible at regional or sub-regional level within a country, reduces the uncertainty of estimates of greenhouse gas emissions and removals. For simplicity and clarity, this chapter discusses estimation of emissions and removals at national level and for a relatively small number of subcategories of Forest Land. This level of detail is designed to match the available sources of default input data, carbon contents and other assumptions. It is important, however, for users of these Guidelines to understand that they are encouraged to carry out the greenhouse gas emissions inventory calculations at a finer level of detail, if possible. Many countries have more detailed information available about forests and land-use change than were used in constructing default values in this Chapter. These data should be used, if suitable, for the following reasons:

1. Geographic detail at regional rather than national level

Experts may find that greenhouse gas estimation for various regions within a country are necessary to capture important geographic variations in ecosystem types, biomass densities, fractions of cleared biomass which are burnt, etc.

2. Finer detail by subcategory

Experts may subdivide the recommended land-use categories and subcategories to reflect important differences in climate, ecology or species, forest types, land-use or forestry practices, fuelwood gathering patterns, etc.

In all cases, working at finer levels of disaggregation does not change the basic nature of the method of estimations, although additional data and assumptions will generally be required beyond the defaults provided in this Chapter. Once greenhouse gas emissions are estimated, using the most appropriate level of detail determined by the national experts, results should also be aggregated up to the national level and the standard categories requested in these *Guidelines*. This will allow for comparability of results among all participating countries. Generally, the data and assumptions used for finer levels of detail should also be reported to ensure transparency and repeatability of methods.

Terminology

The terminology used in the methods for estimating biomass stocks and changes need to be consistent with the terminologies and definitions used by the Food and Agriculture Organization (FAO). FAO is the main source of activity data and emission factors for forest and other land-use categories in Tier 1 level calculations. Examples of terminology from FAO are: biomass growth, mean annual increment, biomass loss, and wood-removal. The Glossary in Annex 4A.1 includes definitions of these terminologies.

Figure 4.1. **Global ecological zones, based on observed climate and vegetation patterns (FAO, 2001). Data for geographic information systems available at http://www.fao.org.**

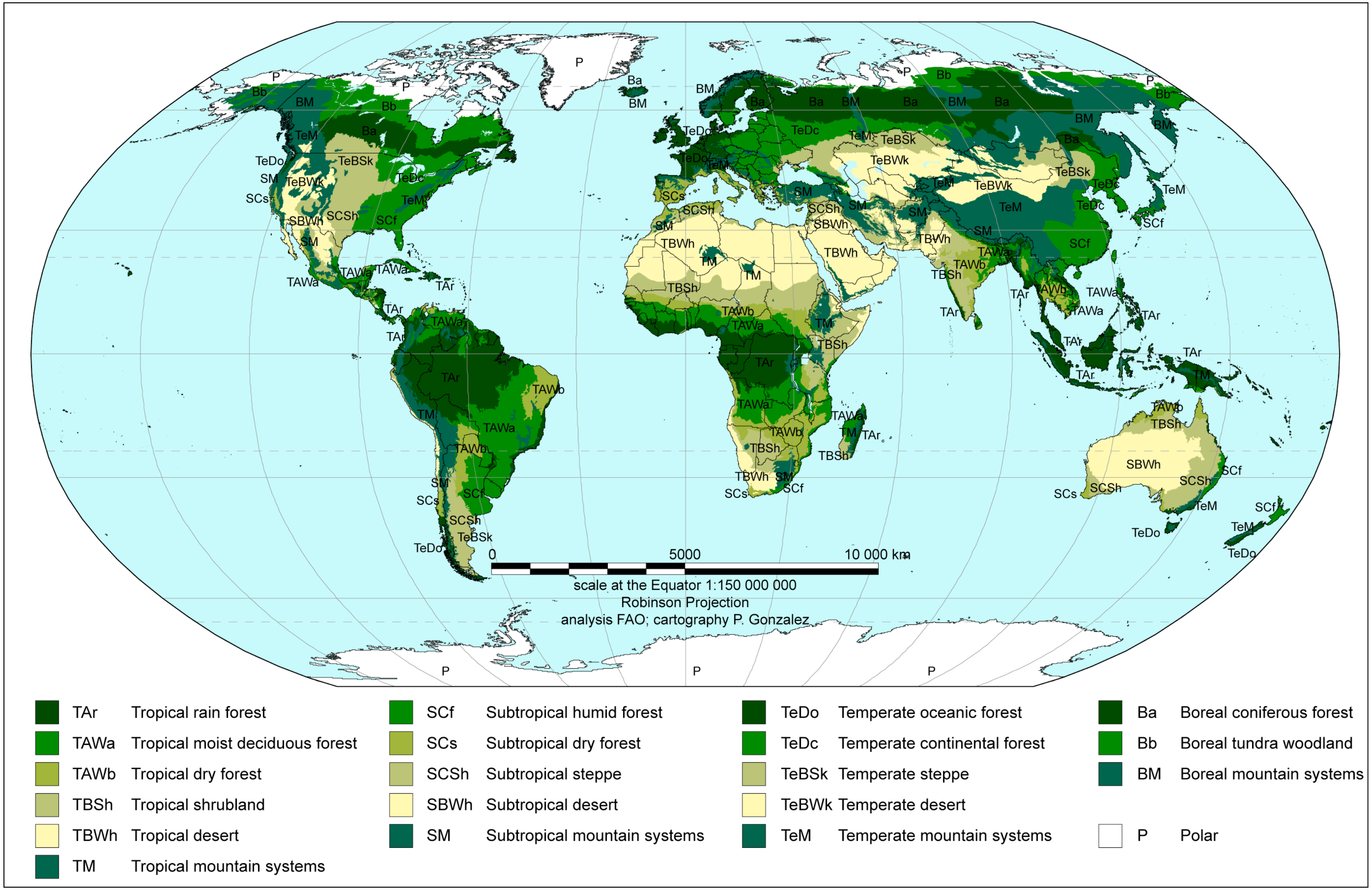
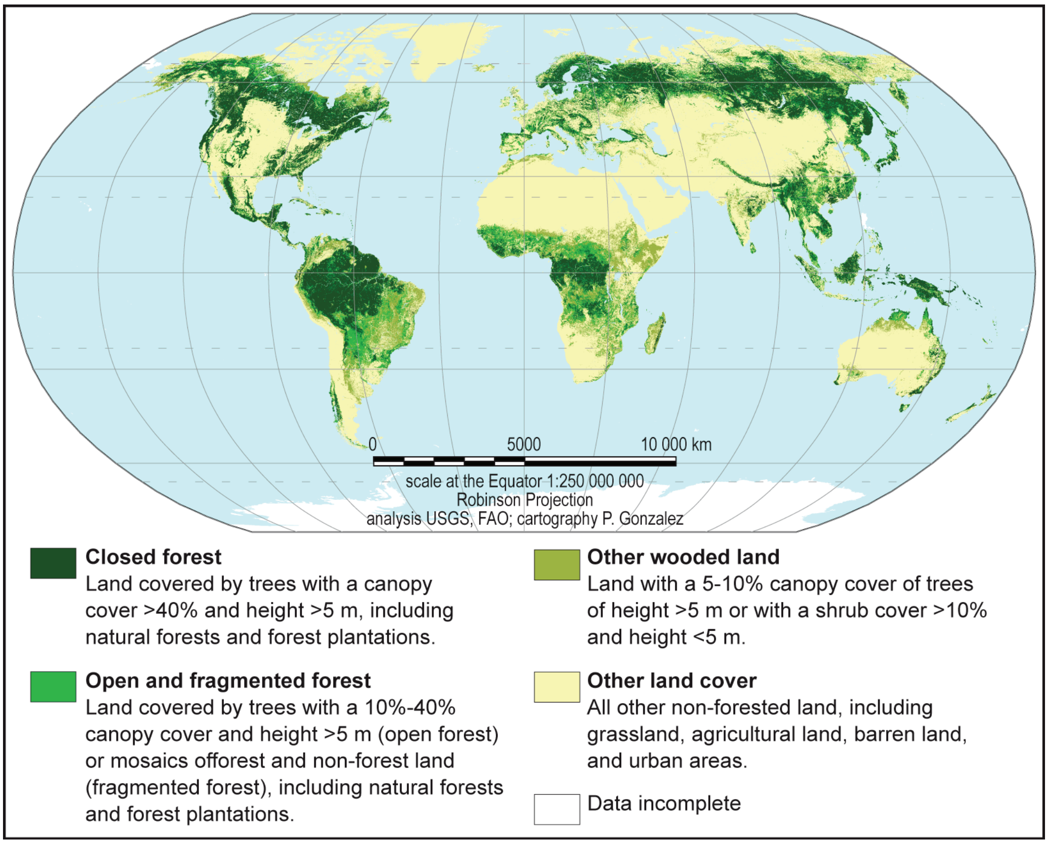


Figure 4.2 **Global forest and land cover 1995. Original spatial resolution of the forest data is 1 km^2 (analysis U.S. Geological Survey (Loveland *et al.*, 2000) and FAO (2001)). Data for geographic information systems available at http://edc.usgs.gov.**



4.2 FOREST LAND REMAINING FOREST LAND

This section deals with managed forests that have been under Forest Land for over 20 years (default), or for over a country-specific transition period. Greenhouse gas inventory for *Forest Land Remaining Forest Land* (FF) involves estimation of changes in carbon stock from five carbon pools (i.e., above-ground biomass, below-ground biomass, dead wood, litter, and soil organic matter), as well as emissions of non-CO_2 gases. Methods for estimating greenhouse gas emissions and removals for lands converted to Forest Land in the past 20 years (e.g., from Cropland and Grassland) are presented in Section 4.3. The set of general equations to estimate the annual carbon stock changes on Forest Land are given in Chapter 2.

4.2.1 Biomass

This section presents methods for estimating biomass gains and losses. Gains include total (above-ground and below-ground) biomass growth. Losses are roundwood removal/harvest, fuelwood removal/harvest/gathering, and losses from disturbances by fire, insects, diseases, and other disturbances. When such losses occur, below-ground biomass is also reduced and transformed to dead organic matter (DOM).

4.2.1.1 CHOICE OF METHOD

Chapter 2 describes two methods, namely, *Gain-Loss Method* based on estimates of annual change in biomass from estimates of biomass gain and loss (Equation 2.7) and a *Stock-Difference Method* which estimates the difference in total biomass carbon stock at time t_2 and time t_1 (Equation 2.8).

The biomass gain-loss method is applicable for all tiers although the stock-difference method is more suited to Tiers 2 and 3. This is because, in general, the stock-difference method will provide more reliable estimates for relatively large increases or decreases of biomass or where very accurate forest inventories are carried out. For areas with a mix of stands of different forest types, and/or where biomass change is very small compared to the total amount of biomass, the inventory error under the stock-difference method may be larger than the expected change. Unless periodic inventories give estimates on stocks of dead organic matter, in addition to growing stock, one should be aware that other data on mortality and losses will still be required for estimating the transfer to dead organic matter, harvested wood products and emissions caused by disturbances. Subsequent inventories must also allow identical area coverage in order to get reliable results when using the stock-difference method. The choice of using gain-loss or stock-difference method at the appropriate tier level will therefore be a matter of expert judgment, taking into account the national inventory systems, availability of data and information from ecological surveys, forest ownership patterns, activity data, conversion and expansion factors as well as cost-benefit analysis.

The decision tree as shown in Figure 1.2 in Chapter 1 should be used to guide choice between the Tiers. This promotes efficient use of available resources, taking into account whether the biomass of this category is a significant carbon pool or a key category as described in Volume 1, Chapter 4.

Tier-1 Method (Biomass Gain-Loss Method)

Tier 1 is feasible even when country-specific estimates of activity data and emission/removal factors are not available, and works when changes of the carbon pool in biomass on *Forest Land Remaining Forest Land* are relatively small. The method requires the biomass carbon loss to be subtracted from the biomass carbon gain (Equation 2.7). The annual change in carbon stocks in biomass can be estimated using the gain-loss method, where the annual increase in carbon stocks due to biomass growth and annual decrease in carbon stocks due to biomass losses are estimated:

- The annual increase in biomass carbon stock is estimated using Equation 2.9, where area under each forest sub-category is multiplied by mean annual increment in tonnes of dry matter per hectare per year.
- Since the biomass growth is usually in terms of merchantable volume or above-ground biomass, the below-ground biomass is estimated with a below-ground biomass to above-ground biomass ratio (Equation 2.10). Alternatively, merchantable volume (m^3) can be converted directly to total biomass using biomass conversion and expansion factors ($BCEF_I$), (Equation 2.10).
- If $BCEF_I$ values are not available and if the biomass expansion factor (BEF) and basic wood density (D) values are separately estimated, then the following conversion can be used:

$$BCEF_I = BEF_I \bullet D$$

Biomass Expansion Factors (BEF_I) expand merchantable volume to total aboveground biomass volume to account for non-merchantable components of the tree, stand and forest. BEF_I is dimensionless.

- The average above-ground biomass of forest areas affected by disturbances are given in Tables 4.7 and 4.8; net average annual above-ground biomass growth values are provided in Tables 4.9, 4.10, and 4.12; net volume annual increment values are provided in Tables 4.11A and 4.11B; wood density is given in Tables 4.13 and 4.14; and below-ground biomass to above-ground biomass ratios (R) are given in Table 4.4. Refer to Box 4.2 for detailed explanation on how to convert and expand volumes of growing stock, increment and wood removals to biomass.
- In some ecosystems, basic wood density (D) can influence spatial patterns of forest biomass (Baker *et al.*, 2004b). Tier 1 users who do not have measurements of wood density at the desired sub-strata level can estimate wood density by estimating the proportion of total forest biomass contributed by the 2-3 dominant species and using species-specific wood density values (Tables 4.13 and 4.14) to calculate a weighted average wood density value.
- Annual biomass loss or decrease in biomass carbon stocks is estimated using Equation 2.11, which requires estimates of annual carbon loss due to wood removals (Equation 2.12), fuelwood removal (Equation 2.13) and disturbances (Equation 2.14). Transfer of biomass to dead organic matter is estimated using Equation 2.20, based on estimates of annual biomass carbon lost due to mortality (Equation 2.21), annual carbon transfer to slash (Equation 2.22).
- Biomass estimates are converted to carbon values using carbon fraction of dry matter (Table 4.3).

When either the biomass stock or its change in a category (or sub-category) is significant or a key category, it is *good practice* to select a higher tier methodology for estimation. The choice of Tier 2 or 3 method depends on the types and accuracy of data and models available, level of spatial disaggregation of activity data and national circumstances.

If using activity data collected via Approach 1 (see Chapter 3), and it is not possible to use supplementary data to identify the amount of land converted *from* and *to* Forest Land, the inventory compiler should estimate C stocks in biomass on all Forest Land using the Tier 1 method described above for *Forest Land Remaining Forest Land*.

Tier 2

Tier 2 can be used in countries where country-specific estimates of activity data and emission/removal factors are available or can be gathered at reasonable cost. Tier 2, same as Tier 1, uses Equations 2.7 to 2.14 (excluding Equation 2.8). Species-specific wood density values (Tables 4.13 and 4.14) permit the calculation of biomass from species-specific forest inventory data. It is possible to use the stock-difference method (Equation 2.8) at Tier 2 where the necessary country-specific data are available

Tier 3

Tier 3 approach for biomass carbon stock change estimation allows for a variety of methods, including process-based models. Implementation may differ from one country to another, due to differences in inventory methods, forest conditions and activity data. Transparent documentation of the validity and completeness of the data, assumptions, equations and models used is therefore a critical issue at Tier 3. Tier 3 requires use of detailed national forest inventories when the stock-difference method is used (Equation 2.8). They may be supplemented by allometric equations and models (for example, Chambers *et al.* (2001) and Baker *et al.* (2004a) for the Amazon; Jenkins *et al.* (2004) and Kurz and Apps (2006) for North America; and Zianis *et al.* (2005) for Europe), calibrated to national circumstances that allow for direct estimation of biomass growth.

BOX 4.2
BIOMASS CONVERSION AND EXPANSION FACTORS FOR ASSESSING BIOMASS AND CARBON IN FORESTS[1]

Forest inventories and operational records usually document growing stock, net annual increment or wood removals in m^3 of merchantable volume. This excludes non-merchantable above-ground components such as tree tops, branches, twigs, foliage, sometimes stumps, and below-ground components (roots).

Assessments of biomass and carbon stocks and changes, on the other hand, focus on total biomass, biomass growth and biomass removals (harvest), including non-merchantable components, expressed in tons of dry-weight. Several methods may be used to derive forest biomass and its changes. Above-ground biomass and changes can be derived in two ways, namely:

(i) directly by measuring sample tree attributes in the field, such as diameters and heights, and applying, species-specific allometric equations or biomass tables based on these equations once or periodically.

(ii) indirectly by transforming available volume data from forest inventories, e.g., merchantable volume of growing stock, net annual increment or wood removals (Somogyi *et al.*, 2006).

The latter approach may achieve the transformation by applying biomass regression functions, which usually express biomass of species or species groups (t/ha) or its rate of change, directly as a function of growing stock density (m^3/ha), and age, eco-regions or other variables (Pan *et al.*, 2004).

More commonly than these biomass regression functions, a single, discrete transformation factors[2] is applied to merchantable volume to derive above-ground biomass and its changes:

(i) Biomass Expansion Factors (BEF) expand the dry weight[3] of the merchantable volume of growing stock, net annual increment, or wood removals, to account for non-merchantable components of the tree, stand, and forest. Before applying such BEFs, merchantable volume (m^3) must be converted to dry-weight (tonne) by multiplying with a conversion factor known as basic wood density (D) in (t/m^3). BEFs are dimensionless since they convert between units of weight.

This method gives best results, when the BEFs have actually been determined based on dry weights, and when locally applicable basic wood densities are well known.

(ii) Biomass Conversion and Expansion Factors (BCEF) combine conversion and expansion. They have the dimension (t/m^3) and transform in one single multiplication growing stock, net annual increment, or wood removals (m^3) directly into above-ground biomass, above-ground biomass growth, or biomass removals (t).

BCEFs are more convenient. They can be applied directly to volume-based forest inventory data and operational records without the need of having to resort to basic wood densities. They provide best results, when they have been derived locally, based directly on merchantable volume.

Mathematically, BCEF and BEF are related by:

$$\text{BCEF} = \text{BEF} \bullet \text{D}$$

Application of this equation requires caution because basic wood density and biomass expansion factors tend to be correlated. If the same sample of trees was used to determine D, BEF or BCEF, conversion will not introduce error. If, however, basic wood density is not known with certainty, transforming one into the other might introduce error, as BCEF implies a specific but unknown basic wood density. Ideally, all conversion and expansion factors would be derived or their applicability checked locally.

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[1] Please see glossary (Annex 4A.1) for definitions of terms.

[2] While these transformation factors are usually applied in discrete form, they can also be expressed and depicted as continuous functions of growing stock density, age, or other variables.

[3] In some applications, biomass expansion factors expand dry-weight of merchantable components to total biomass, including roots, or expand merchantable volume to above-ground or total biomass volume (Somogyi *et al.*, 2006). As used in this document, biomass expansion factors always transform dry-weight of merchantable volume including bark to above-ground biomass, excluding roots.

Both BEF and BCEF tend to decrease as a function of stand age, as growing stock density (volume of growing stock per ha) increases. This is because of the increasing ratio of merchantable volume to total volume. The decrease is rapid at low growing stock densities or for young stands and levels out for older stands and higher stand densities.

The *GPG-LULUCF* provided only average default BEF values, together with wide ranges, and general guidance on how to select applicable values for specific countries from these ranges. To facilitate selection of more reliable default values, this document provides default factors as a function of growing stock density in Table 4.5. Since more comprehensive and more recent data were found in the literature, Table 4.5 contains BCEF defaults only. Countries that possess country-specific basic wood densities and BEF on a consistent basis may apply them to calculate country-specific BCEF using the formula given above.

BCEF or BEF that apply to growing stock and net annual increment are different. In this document, the following symbols are used:

$BCEF_S$: biomass conversion and expansion factor applicable to growing stock; transforms merchantable volume of growing stock into above-ground biomass.

$BCEF_I$: biomass conversion and expansion factor applicable to net annual increment; transforms merchantable volume of net annual increment into above-ground biomass growth.

$BCEF_R$: biomass conversion and expansion factors applicable to wood removals; transforms merchantable biomass to total biomass (including bark). $BCEF_R$ and BEF_R for wood and fuelwood removal will be larger than that for growing stock due to harvest loss (see Annex 4A.1 Glossary). If a country specific value for harvest loss is not known, defaults are 10% for hardwoods and 8% for conifers (Kramer and Akca, 1982). Default conversion and expansion factors for wood removals can be derived by dividing $BCEF_S$ by (1– 0.08) for conifers and (1-0.1) for broadleaves.

It is *good practice* to estimate growing stock biomass, above-ground biomass growth and above-ground biomass removals by strata; to document these strata; and to aggregate results ex post. Methods described above will yield above-ground biomass and its changes. Results must be expanded to total biomass via applicable below-ground biomass to above-ground biomass ratios.

4.2.1.2 CHOICE OF EMISSION FACTORS

The Gain-Loss Method requires the above-ground biomass growth, biomass conversion and expansion factor (BCEF), BEF, and/or basic wood densities according to each forest type and climatic zone in the country, plus emission factors related to biomass loss, including losses due to wood removals, fuelwood removals and disturbances.

Annual biomass carbon gain, ΔC_G

Mean above-ground biomass growth (increment), G_W

Tier 1

Default values of the above-ground biomass growth (G_W) which are provided in Tables 4.9, 4.10 and 4.12 can be used at Tier 1. If available, it is *good practice* to use other regional default values for different forest types more relevant to the country.

Tier 2

Tier 2 method uses more country-specific data to calculate the above-ground biomass growth, G_W from country-specific net annual increment of growing stock (I_V). Tables 4.11a and 4.11b provide default values for I_V. Combined default biomass conversion and expansion factor ($BCEF_I$) of I_v are provided in Table 4.5. Separate data on biomass expansion factor for increment (BEF_I) and basic wood density (D) can also be used to convert the available data to G_W. Tables 4.13 and 4.14 provide default values for basic wood density.

Tier 3

Under Tier 3, process-based estimation will have access to detailed forest inventory or monitoring system with data on growing stock and past and projected net annual increment and functions relating to growing stock or net annual increment directly to biomass and biomass growth. It is also possible to derive net annual increment by process simulation. Specific carbon fraction and basic wood density should also be incorporated.

Forest inventories usually provide conditions of forest growing stock and net annual increment in the year of the inventory. When the year of inventory does not coincide with the year of reporting, interpolated or extrapolated net annual increment or increment estimated by models (i.e., model capable of simulating forest dynamics), should be used along with data on harvesting and disturbances to update inventory data to the year of interest.

Below-ground biomass growth (increment)

Tier 1

Below-ground carbon stock changes, as a default assumption consistent with the *1996 IPCC Guidelines*, can be zero. Alternatively, default values for below-ground biomass to above-ground biomass ratios (R) are to be used to estimate below-ground biomass growth. Default values are provided in Table 4.4. Strictly, these ratios of below-ground biomass to above-ground biomass are only valid for stocks, but no appreciable error is likely to obtain if they are applied to above-ground biomass growth over short periods.

Tier 2

Country-specific below-ground biomass to above-ground biomass ratios should be used to estimate below-ground biomass for different forest types.

Tier 3

For preference, below-ground biomass should be directly incorporated in models for calculating total biomass increment and losses. Alternatively, nationally or regionally determined below-ground biomass to above-ground biomass ratios or regression models (e.g., Li *et al.*, 2003) may be used.

Annual carbon loss in biomass, ΔC_L

Biomass loss due to wood removals, $L_{wood-removals}$ and $L_{fuelwood}$

When computing carbon loss through biomass removals, the following factors are needed: Wood removal (H), fuelwood removal as trees or parts of trees (FG), basic wood density (D), below-ground biomass to above-ground biomass ratio (R), carbon fraction (CF), BCEF for wood removals. While all wood removals represent a loss for the forest biomass pool, Chapter 12 provides guidance for estimating annual change in carbon stocks in harvested wood products.

Disturbances, $L_{disturbance}$

The estimate of other losses of carbon requires data on areas affected by disturbances ($A_{disturbance}$) and the biomass of these forest areas (B_W). Above ground biomass estimates of forest types affected by disturbance are required, along with below-ground biomass to above-ground biomass ratio and fraction of biomass lost in disturbance.

Chapter 2, Tables 2.4, 2.5 and 2.6 provide fuel biomass consumption values, emission factors, and combustion factors needed for estimating proportion of biomass lost in fires and proportion to be transferred to dead organic matter under higher tiers.

Tier 1

The average biomass varies with the forest types and management practices. The default values are given in Tables 4.9 and 4.10. In the case of fire, both CO_2 and non-CO_2 emissions occur from combusted fuels of above-ground biomass including understory. Fire may consume a high proportion of understory vegetation. In the case of other disturbances, a fraction of above ground biomass is transferred to dead organic matter and under Tier 1, all biomass in area subjected to disturbance is assumed to be emitted in the year of disturbance.

Tier 2

Under Tier 2, biomass changes due to disturbances will be taken into account by forest category, type of disturbance and intensity. Average values for biomass are obtained from country-specific data.

Tier 3

In addition to calculating losses similar to Tier 2, Tier 3 can also adopt models, which typically employ spatially referenced or spatially explicit information on the year and type of disturbance.

4.2.1.3 CHOICE OF ACTIVITY DATA

Area of managed Forest Land

All tiers require information on areas of managed Forest Land according to different forest types, climate, management systems, and regions.

Tier 1

Tier 1 uses data of forest area which can be obtained through national statistics, from forest agencies (which may have information on areas of different management practices), conservation agencies (especially for areas managed for natural regeneration), municipalities, survey and mapping agencies. Cross-checks should be made to ensure complete and consistent representation for avoiding omissions or double counting as specified in Chapter 3. If no country data are available, aggregate information can be obtained from international data sources (FAO, 1995; FAO, 2001; TBFRA, 2000). It is *good practice* to verify, validate, and update the FAO data using national sources.

Tier 2

Tier 2 uses country-defined national data sets, according to different forest types, climate, management systems, and regions, with a resolution sufficient to ensure appropriate representation of land areas in line with provisions of Chapter 3 of this volume. Approach 2 of Chapter 3 is relevant for Tier 2.

Tier 3

Tier 3 uses country-specific data on managed Forest Land from different sources, notably national forest inventories, registers of land use and land-use changes, or remote sensing. These data should give a full accounting of all land-use transitions to Forest Land and disaggregate along climate, soil, and vegetation types. Geo-referenced area under different forest types may be used to track changes in area under different land-use types, using Approach 3 of Chapter 3.

Wood removals

The inventory requires data on wood removals, including fuelwood removals and biomass losses due to disturbances, in order to calculate biomass stock changes and carbon pool transfers. In addition to wood removals for industrial purposes, there may also be wood removals for small scale processing or direct sales to consumers from land owners. This quantity may not be included in official statistics and may need to be estimated by survey. Fuelwood from branches and tops of felled trees must be subtracted from transfers to the dead wood pool. Salvage of wood from areas affected by disturbances must also be subtracted from biomass, to ensure that no double counting occurs in Tier 1 inventories in which the biomass in areas affected by disturbances is already assumed released to the atmosphere.

In using production statistics, users must pay careful attention to the units involved. It is important to check whether the information in the original data is reported in biomass, volumes underbark or overbark to ensure that expansion factors are used only where appropriate and in a consistent way.

Unless restricted to Approach 1 land representation without supplementary data, so that all forest land is counted under *Forest Land Remaining Forest Land*, wood removals from Forest Land being converted to another land use should not be included in losses reported for *Forest Land Remaining Forest Land* since these losses are reported in the new land-use category. If the statistics on wood removals do not provide stratification on lands, then an amount of biomass approximating the biomass loss from lands converted from Forest Land should be subtracted from the total wood removals.

Extraction of roundwood is published in the UNECE/FAO Timber Bulletin and by FAO Yearbook of Forest Products. The latter is based primarily on data provided by the countries. In the absence of official data, FAO provides an estimate based on the best information available. Usually, the FAO yearbook appears with a two-year time lag.

Tier 1

FAO data can be used as a Tier 1 default for H in Equation 2.12 in Chapter 2. The roundwood data include all wood removed from forests which are reported in cubic meters underbark. The underbark data need conversion to overbark before using $BCEF_R$. Conversion from underbark to overbark volumes is done by using bark percentages.

Tier 2

Country-specific data should be used.

Tier 3

Country-specific wood removals data from different forest categories should be used at the spatial resolution chosen for reporting

Fuelwood removal

Estimation of carbon losses due to fuelwood removal requires annual volume of fuelwood removed (FG) and basic wood density (D). Fuelwood is produced in different ways in countries and varies from ordinary timber harvesting, to using parts of trees, to gathering of dead wood. Fuelwood constitutes the largest component of biomass loss for many countries, thus reliable estimates are needed for such countries. . If possible, fuelwood removal from *Forest Land Remaining Forest Land* and that coming from Forest Land conversion to other uses should be separated.

Tier 1

FAO provides statistics on fuelwood and charcoal removals for all countries. FAO statistics are based on what is provided by the concerned ministries/ departments in the countries and in some cases may not account fully for the entire fuelwood and charcoal removal due to the limitations of national data collection and reporting systems. Thus, under Tier 1, FAO statistics can be used directly but should be checked for completeness by the national source of data for the FAO such as the Ministry of Forests or Agriculture or any statistical organization. FAO or any national estimates should be supplemented from regional surveys or local studies on fuelwood consumption, since fuelwood is collected from multiple sources; forests, timber processing residues, farms, homesteads, village commons, etc. If more complete information is available nationally, it should be used.

Tier 2

Country-specific data should be used, if available. Regional surveys of fuelwood removals can be used to verify and supplement the national or FAO data source. At the national level, aggregate fuelwood removals can be estimated by conducting regional level surveys of rural and urban households at different income levels, industries and establishments.

Tier 3

Fuelwood removals data from national level studies should be used at the resolution required for the Tier 3 model, including the non-commercial fuelwood removals. Fuelwood removal should be linked to forest types and regions.

Different methods of fuelwood removal from *Forest Land Remaining Forest Land* should be accounted at regional or disaggregated level through surveys. The source of fuelwood should be identified to ensure that no double counting occurs.

Disturbances

A database on rate and impact of natural disturbances by type, for all European countries (Schelhaas *et al.*, 2001), can be found at: http://www.efi.fi/

A UNEP database on global burnt area can be found at: http://www.grid.unep.ch/

However, one should note that the UNEP database is only valid for year 2000. In many countries inter-annual variability in burnt area is large, so these figures will not provide a representative average. Many countries maintain their own disturbance statistics e.g., Stocks *et al.* (2002) which can be employed in Tier 2 or Tier 3 approaches (Kurz and Apps, 2006).

The FRA2005 (FAO, 2005) should also be examined for data on disturbances.

4.2.1.4 CALCULATION STEPS FOR TIER 1

The following summarizes steps for estimating change in carbon stocks in biomass (ΔC_B) using the default methods:

Step 1: Using guidance from Chapter 3 (approaches in representing land areas), categorise the area (A) of *Forest Land Remaining Forest Land* into forest types of different climatic or ecological zones, as adopted by the country. As a point of reference, Annex 3A.1 of *GPG-LULUCF* (IPCC, 2003) provides national-level data of forest area and annual change in forest area by region and by country as a means of comparison. Alternatively FAO also periodically provides area data;

Step 2: Estimate the annual biomass gain in *Forest Land Remaining Forest Land* (ΔC_G) using estimates of area and biomass growth, for each forest type and climatic zone in the country available using Equations 2.9 and 2.10 in Chapter 2;

Step 3: Estimate the annual carbon loss due to wood removals ($L_{wood\text{-}removals}$) using Equation 2.12 in Chapter 2;

Step 4: Estimate annual carbon loss due to fuelwood removal ($L_{fuelwood}$) using Equation 2.13 in Chapter 2;

Step 5: Estimate annual carbon loss due to disturbance ($L_{disturbance}$) using Equation 2.14 in Chapter 2, avoid double counting of losses already covered in wood removals and fuelwood removals;

Step 6: From the estimated losses in Steps 3 to 5, estimate the annual decrease in carbon stocks due to biomass losses (ΔC_L) using Equation 2.11 in Chapter 2;

Step 7: Estimate the annual change in carbon stocks in biomass (ΔC_B) using Equation 2.7 in Chapter 2.

Example. The following example shows Gain-Loss Method (Tier 1) calculations of annual change in carbon stocks in biomass (ΔC_B), using Chapter 2, Equation 2.7 ($\Delta C_B = (\Delta C_G - \Delta C_L)$), for a hypothetical country in temperate continental forest zone of Europe (Table 4.1, Section 4.5):

- the area of *Forest Land Remaining Forest Land* (A) within the country is 100,000 ha (see Chapter 3 for area categorization);
- it is a 25-year-old pine forest, average above-ground growing stock volume is 40 m^3 ha^{-1};
- the merchantable round wood harvest over bark (H) is 1,000 m^3 yr^{-1};
- whole trees fuel wood removal (FG_{trees}) is 500 m^3 yr^{-1};
- area of insect disturbance is 2,000 ha yr^{-1} with above-ground biomass affected 4.0 tonne d.m. ha^{-1}.

Annual gain in biomass (ΔC_G) is a product of mean annual biomass increment (G_{TOTAL}), area of land (A) and carbon fraction of dry matter (CF); Equation 2.9 in Chapter 2 ($\Delta C_G = \sum_{ij} (A \bullet G_{TOTAL} \bullet CF$). G_{TOTAL} is calculated using Chapter 2, Equation 2.10 for given values of annual above-ground biomass growth (G_W), below-ground biomass to above-ground biomass ratio (R), and default data tables in Section 4.5.

For the hypothetical country,

G_W = 4.0 tonnes d.m. ha^{-1} yr^{-1} (Table 4.9);

R = 0.29 tonne d.m. (tonne d.m.)$^{-1}$ for above-ground biomass of 50 to 150 t ha^{-1} (Table 4.4 with reference to Table 4.7 for above ground biomass);

G_{TOTAL} = 4.0 tonnes d.m. ha^{-1} yr^{-1} $\bullet$ (1 + 0.29) = 5.16 tonnes d.m. ha^{-1} yr^{-1} (Equation 2.10); and

CF = 0.47 tonne C (tonne d.m.)$^{-1}$ (Table 4.3).

Consequently, (Equation 2.9): ΔC_G = 100,000 ha $\bullet$ 5.16 tonnes d.m. ha^{-1} yr^{-1} $\bullet$ 0.47 tonne C (tonne dm)$^{-1}$ = 242,520 tonnes C yr^{-1}.

Biomass loss (ΔC_L) is a sum of annual loss due to wood removals ($L_{wood\text{-}removals}$), fuel wood gathering ($L_{fuelwood}$) and disturbances ($L_{disturbance}$), Equation 2.11 in Chapter 2.

Wood removal ($L_{wood\text{-}removals}$) is calculated with Equation 2.12, Chapter 2, merchantable round wood over bark (H), biomass conversion expansion factor ($BCEF_R$), bark fraction in harvested wood (BF), below-ground biomass to above-ground biomass ratio (R), carbon fraction of dry matter (CF) and default tables, Section 4.5.

For the hypothetical country,

$BCEF_R$ = 1.11 tonnes d.m. m^{-3} (Table 4.5 with reference to growing stock volume 40 m^3 ha^{-1});

BF = 0.1 tonne d.m. (tonne d.m.)$^{-1}$. R = 0.29 tonne d.m. (tonne d.m.)$^{-1}$ for above-ground biomass 50 to 150 t ha^{-1} (Table 4.4, for above-ground biomass refer to Table 4.7); and

CF = 0.47 tonne C (tonne d.m.)$^{-1}$ (Table 4.3).

$L_{wood\text{-}removals}$ = 1,000 m^3 yr^{-1} $\bullet$ 1.11 tonnes d.m. m^{-3} (1 + 0.29 + 0.1) $\bullet$ 0.47 tonne C (tonne d.m.)$^{-1}$

= 725.16 tonnes C yr^{-1} (Equation 2.12).

Fuelwood removal ($L_{fuelwood}$) is calculated using Equation 2.13, Chapter 2, wood removals as whole trees (FG_{trees}), biomass conversion expansion factor ($BCEF_R$), below-ground biomass to above-ground biomass ratio (R), carbon fraction of dry matter (CF) and default tables in Section 4.5. For the hypothetical country,

$BCEF_R$ = 1.11 tonnes d.m. m^{-3} (Table 4.5 with reference to growing stock volume 40 m^3 ha^{-1});

R = 0.29 tonne d.m. (tonne dm)$^{-1}$ for above-ground biomass 50 to 150 t ha^{-1} (Table 4.4, for above-ground biomass refer to Table 4.7); and

CF = 0.47 tonne C (tonne dm)$^{-1}$ (Table 4.3).

$L_{fuelwood}$ = 500 m^3 yr^{-1} $\bullet$ 0.75 tonne d.m. m^{-3} (1 + 0.29) $\bullet$ 0.47 tonne C (tonne d.m.)$^{-1}$

= 336.50 tonne C yr^{-1} (Equation 2.13).

Annual carbon loss in biomass due to disturbances ($L_{disturbance}$) is calculated using Equation 2.14, Chapter 2, area of disturbances ($A_{disturbance}$), average above-ground biomass affected (B_W), below-ground biomass to above-ground biomass ratio (R), carbon fraction of dry matter (CF), fraction of biomass lost in disturbance (fd) and default tables in Section 4.5. For the hypothetical country,

R = 0.29 tonne d.m. $(\text{tonne dm})^{-1}$ for above-ground biomass 50 to 150 t ha^{-1} (Table 4.4, for above-ground biomass refer to Table 4.7);

CF = 0.47 tonne C $(\text{tonne dm})^{-1}$ (Table 4.3); and fd = 0.3

$L_{disturbance}$ = 2,000 ha yr^{-1} ● 4.0 tonnes d.m. ha^{-1} (1 + 0.29) ● 0.47 tonne C $(\text{tonne dm})^{-1}$ ● 0.3

= 1,455.12 tonnes C yr^{-1} (Equation 2.14)

Annual decrease in carbon stocks due to biomass losses (ΔC_L),

ΔC_L = 725.16 tonnes C yr^{-1} + 336.50 tonnes C yr^{-1} + 1,455.12 tonnes C yr^{-1}

= 2,516.78 tonnes C yr^{-1} (Equation 2.11)

Annual change in carbon stocks in biomass (ΔC_B)

Using Chapter 2, Equation 2.7 ($\Delta C_B = (\Delta C_G - \Delta C_L)$),

ΔC_B = 242,520 tonnes C yr^{-1} – 2,516.78 tonnes C yr^{-1} = 240,003.22 tonnes C yr^{-1}

4.2.1.5 UNCERTAINTY ASSESSMENT

This section considers source-specific uncertainties relevant to inventory estimates made for *Forest Land Remaining Forest Land*. Estimating country-specific and/or disaggregated values requires more accurate information on uncertainties than given below. Volume 1, Chapter 3 provides information on uncertainties associated with sample-based studies. The literature available on uncertainty estimates on emission factors and activity data is limited.

Emission and removal factors

FAO (2006) provides uncertainty estimates for forest carbon factors; basic wood density (10 to 40%); annual increment in managed forests of industrialized countries (6 %); growing stock (industrialized countries 8%, non-industrialized countries 30%); combined natural losses for industrialized countries (15%); wood and fuelwood removals (industrialized countries 20%).

In Finland, the uncertainty of basic wood density of pine, spruce and birch trees is under 20% in studies of Hakkila (1968, 1979). The variability between forest stands of the same species should be lower or at most the same as for individual trees of the same species. In Finland, the uncertainty of biomass expansion factors for pine, spruce, and birch was approximately 10% (Lehtonen *et al.*, 2003).

In eight Amazon tropical forest inventory plots, combined measurement errors led to errors of 10-30% in estimates of basal area change over periods of less than 10 years (Phillips *et al.*, 2002).

The major sources of uncertainty of wood density and biomass expansion factors are stand age, species composition, and structure. To reduce uncertainty, countries are encouraged to develop country- or region-specific biomass expansion factors and BCEFs that fit their conditions. In case country- or regional-specific values are unavailable, the sources of default parameters should be checked and their correspondence with specific conditions of a country should be examined.

The causes of variation of annual increment include climate, site growth conditions, and soil fertility. Artificially regenerated and managed stands are less variable than natural forests. The major ways to improve accuracy of estimates are associated with application of country-specific or regional increment stratified by forest type. If the default values of increment are used, the uncertainty of estimates should be clearly indicated and documented. Tier 3 approaches can use growth curves stratified by species, ecological zones, site productivity and management intensity. Similar approaches are routinely used in timber supply planning models and this information can be incorporated into carbon accounting models (e.g., Kurz *et al.*, 2002).

Data on commercial fellings are relatively accurate, although they may be incomplete or biased due to illegal fellings and underreporting due to tax regulations. Traditional wood that is gathered and used directly, without being sold, is not likely to be included in any statistics. Countries must carefully consider these issues. The amount of wood removed from forests after storm breaks and pest outbreaks varies both in time and volume. No default data can be provided on these types of losses. The uncertainties associated with these losses can be estimated from the amount of damaged wood directly withdrawn from the forest or using data on damaged wood subsequently used for commercial and other purposes. If fuelwood gathering is treated separately from fellings, the relevant uncertainties might be high, due to high uncertainty associated with traditional gathering.

Activity data
Area data should be obtained using the guidance in Chapter 3 or from FAO (2000). Industrialized countries estimated an uncertainty in forest area estimates of approximately 3% (FAO, 2000).

4.2.2 Dead organic matter

The general description of methods for estimating changes in carbon stocks in dead organic matter (DOM) pools (litter and dead wood) has been provided in Chapter 2.

This section focuses on methods for estimating carbon stock changes in dead organic matter pools for *Forest Land Remaining Forest Land*. Tier 1 methods assume that the net carbon stock changes in DOM pools are zero because the simple input and output equations used in Tier 1 methods are not suitable to capture the DOM pool dynamics. Countries that want to quantify DOM dynamics need to develop Tier 2 or 3 methodologies. The countries where DOM is a key category should adopt higher tiers and estimate DOM changes.

The dead wood (DW) pool contains carbon in coarse woody debris, dead coarse roots, standing dead trees, and other dead material not included in the litter or soil carbon pools. Estimating the size and dynamics of the dead wood pool poses many practical limitations, particularly related to field measurements. The uncertainties associated with estimates of the rate of transfer from the DW pool to the litter and soil pools, and emissions to the atmosphere are generally high. The amount of dead wood is highly variable between stands, both in managed (Duvall and Grigal, 1999; Chojnacky and Heath, 2002) and unmanaged lands (Spies *et al.*, 1988). Amounts of dead wood depend on the time since last disturbance, the type of the last disturbance, losses during disturbances, the amount of biomass input (mortality) at the time of the disturbance (Spies *et al.*, 1988), natural mortality rates, decay rates, and management (Harmon *et al.*, 1986).

Net litter accumulation rates can be estimated using the stock-difference method or the gain-loss method. The latter requires an estimate of the balance of the annual amount of litterfall (which includes all leaves, twigs and small branches, fruits, flowers, roots, and bark) minus the annual rate of litter decomposition. In addition, disturbances can add and remove carbon from the litter pool, influencing the size and composition of the litter pool. The litter dynamics during the early stages of stand development depend on the type and intensity of the last disturbance. Where disturbance has transferred biomass to DOM pools (e.g., wind-throw or insect kill), litter pools can be decreasing until losses are compensated by litter inputs. Where disturbance has removed litter (e.g., wildfire), litter pools can be increasing in the early stages of stand development if litter input exceeds decay. Management such as timber harvesting, slash burning, and site preparation alter litter properties (Fisher and Binkley, 2000), but there are few studies clearly documenting the effects of management on litter carbon (Smith and Heath, 2002).

4.2.2.1 CHOICE OF METHOD

The decision tree in Figure 2.3 in Chapter 2 provides guidance in the selection of the appropriate tier level for the implementation of estimation procedures. The choice of method is described jointly for dead wood and Litter since the equations are identical for both, but the estimates are calculated separately for each of the two pools.

The estimation of changes in carbon stocks in DOM pool requires estimates of changes in carbon stocks of dead wood and litter pools (refer to Equation 2.17 of Chapter 2).

Tier 1
The Tier 1 method assumes that the dead wood and litter carbon stocks are in equilibrium so that the changes in carbon stock in the DOM pools are assumed to be zero. Countries experiencing significant changes in forest types, disturbance or management regimes in their forests are encouraged to develop domestic data to quantify the impacts from these changes using Tier 2 or 3 methodologies and to report the resulting stock changes and non-CO_2 emissions.

Tiers 2 and 3
Two general methods are available for estimating the carbon stock changes in dead wood and litter. Similar methods exist for the estimation of biomass carbon stock changes, and the choice of method for estimating DOM changes may be affected by the choice of method for biomass carbon stock change estimation.

Gain-Loss Method: The Gain-Loss method uses a mass balance of inputs to and losses from the dead wood and litter pools to estimate stock changes over a specified period. This involves estimating the area of managed *Forest Land Remaining Forest Land* and the average annual transfer of carbon stock into and out of dead wood and litter pools (Equation 2.18 in Chapter 2). To reduce uncertainty, the area under *Forest Land Remaining*

Forest Land can be further stratified by climate or ecological zones, and classified by forest type, productivity, disturbance regime, management practice, or other factors that affect dead wood and litter carbon pool dynamics. Estimation of the net balance requires calculation on a per hectare basis of the annual transfers into the dead wood and litter pools from stem mortality, litterfall and turnover, and the losses from decomposition. In addition, in areas subject to management activities or natural disturbances, dead wood and litter will be added in the form of biomass residues, and transferred through harvest (salvage of standing dead trees), burning or other mechanisms.

It is *good practice* that the stratification of Forest Land adopted for DOM be identical to that used for the estimation of changes in biomass carbon stocks (Section 4.2.1).

Stock-Difference Method: This involves estimating the area of managed *Forest Land Remaining Forest Land*, determining the dead wood and litter carbon stocks at two points of time and the calculation of the difference between the two carbon stock estimates (Equation 2.19 in Chapter 2). The annual carbon stock change for the inventory year is obtained by dividing the change in carbon stock by the period (years) between the two measurements. Method 2 is only feasible for countries which have forest inventories based on sample plots. Calculating carbon stock changes as the difference of carbon stocks at two points in time requires that the area at time t1 and t2 is identical to ensure that reported carbon stocks are not the result of changes in area.

For Tiers 2 and 3 methods, both options, are data intensive and require field measurements and models for their implementation. Such models can build on the knowledge and information compiled for the simulation of forest dynamics as used in the timber supply planning process (e.g. Kurz *et al.*, 2002, and Kurz and Apps, 2006).

4.2.2.2 CHOICE OF EMISSION/REMOVAL FACTORS

Tier 1

By default, it is assumed that the carbon stocks in the DOM pools in *Forest Land Remaining Forest Land* are stable. Carbon-dioxide emissions originating from dead wood and litter pools during wildfire are assumed to be zero, and accumulation of carbon in dead wood and litter pools during regrowth is also not counted. Non- CO_2 emissions from wildfire, including CH_4 and CO are estimated in Tier 1.

Tiers 2 and 3

The parameter f_{BLol} is the fraction of total biomass left to decay on the ground, see Chapter 2, Equation 2.20. Resolution and accuracy of the transferred carbon will correspond to the expansion factors applied in calculating losses.

Tier 2 estimation of f_{Blol} requires national data on average proportions of carbon left after disturbances. When national data are incomplete, Chapter 2 provides two tables:

- Default values of combustion factor to be used as $(1- f_{BL})$ in case the country has good growing stock biomass data; in this case the proportion lost is used; see Table 2.6
- Default values of biomass removals to be used as $[M_B \bullet (1- f_{BL})]$ in case the growing stock biomass data are not reliable. M_B is the mass of fuel available for combustion (see Table 2.4 and Equation 2.27 in Chapter 2).

Country-specific values for transfer of carbon in live trees that are harvested to harvest residues can be derived from national expansion factors, taking into account the forest type (coniferous/broadleaved/ mixed), the rate of biomass utilization, harvesting practices and the amount of damaged trees during harvesting operations. Both harvest and natural disturbances add biomass to dead wood and litter pools. Other management practices (such as burning of harvest residues) and wildfire remove carbon from dead wood and litter pools. If the area under each management practice and type of forest affected by disturbance are known, then disturbance matrices (see Chapter 2, Table 2.1; Kurz *et al.*, 1992) can be used to define for each disturbance type the proportion of each biomass, dead organic matter, and soil carbon pool that is transferred to other pools, to the atmosphere, or removed from the forest during harvest.

Tier 3 estimation of f_{Blol}, will require more detailed knowledge of the proportion of rapid emissions from disturbances such as fires and windstorms. Data should be obtained by on-site measurements or from studies of similar disturbances. Disturbance matrices (see Chapter 2, Table 2.1) have been developed to define, for each disturbance type, the proportion of biomass (and all other carbon pools) that is transferred to other carbon pools, released to the atmosphere, or transferred to harvested wood products (Kurz *et al.*, 1992). Disturbance matrices ensure conservation of carbon when calculating the immediate impacts of harvest or disturbances on ecosystem carbon.

Tier 3 methods rely on more complex forest carbon accounting models that track the rates of input and losses from dead organic matter pools for each forest type, productivity, and age-class. Where comprehensive forest inventories exist, that include re-measurement of dead organic matter pools, estimates of carbon stock changes can also be derived using the stock-difference approach described in Equation 2.19 in Chapter 2. It is *good practice* that inventory-based approaches with periodic sampling follow the principles set out in Chapter 3, Annex 3A.3. Inventory-based approaches can be coupled with models to capture the dynamics of all forest carbon pools. Tier 3 methods provide estimates of greater certainty than lower tiers and feature a greater link between the dynamics of biomass and dead organic matter carbon pools. Other important parameters in modelling dead wood and litter carbon budgets are decay rates, which may vary with the forest type and climatic conditions, and forest management practices (e.g., controlled broadcast burning or thinning and other forms of partial harvest).

4.2.2.3 CHOICE OF ACTIVITY DATA

Countries using a Tier 1 method require no activity data for estimation of changes in carbon stock in DOM in *Forest Land Remaining Forest Land.*

Countries using higher tiers require activity data on the areas of *Forest Land Remaining Forest Land* classified by major forest types, management practices, and disturbance regimes. Total forest area and all other activity data should be consistent with that reported under other sections of this chapter, notably under biomass section of *Forest Land Remaining Forest Land* (Section 4.2.1). Country-specific activity data on the area annually affected by harvest and disturbances can be derived from national monitoring programs. The assessment of changes in carbon stock in DOM is greatly facilitated if this information can be used in conjunction with national soil and climate data, vegetation inventories, and other geophysical data.

Data sources will vary according to a country's forest management system. Data can be compiled from individual contractors or companies, regulation bodies and governmental agencies responsible for forest inventory and management, and from research institutions. Data formats vary widely, and include, among others, activity reports submitted regularly within incentive programs or as required by regulations, forest management inventories and from monitoring programs using remotely sensed imagery (Wulder *et al.*, 2004).

4.2.2.4 CALCULATION STEPS FOR TIER 1

Since Tier 1 assumes no change in DOM for *Forest Land Remaining Forest Land*, guidance on calculations steps is not relevant.

4.2.2.5 UNCERTAINTY ASSESSMENT

Tier 1 by definition assumes stable carbon stocks so formal uncertainty analysis is not appropriate. In fact the assumption is almost never true at the stand level and unlikely to be true in general, although the resulting error could be small for a forested landscape because increases in some stands could be off-set by decreases in others, but for the entire landscape or country, dead organic matter pools can be either increasing or decreasing. An understanding of the types of changes that are occurring in the forests of a country can provide some qualitative insight into the direction of change in dead organic matter pools. For example, in some countries biomass growing stocks are increasing because harvest and disturbance losses are smaller than growth increments. It is likely that dead organic matter pools are also increasing, even if the rate of increase cannot be known unless a Tier 2 or 3 estimation method is used.

Countries that use methods that assume all carbon losses occur in the year of disturbance are likely to overestimate disturbance losses in the years of above-average disturbances, and underestimate true emissions in years of below-average disturbances. Countries with fairly constant harvest or disturbance rates that rely on such methods are likely to be closer to the actual net carbon stock changes.

The uncertainty of estimates using higher Tier methods must be evaluated for each country using expert judgment. It is fair to assume that the uncertainty in the estimates of changes of carbon stock in dead organic matter is generally larger than that of the estimates of changes in carbon stock in biomass since, in most countries, considerably more data are available on biomass stocks than on dead organic matter stocks. Moreover, models that describe biomass dynamics are generally more advanced than models of dead organic matter dynamics.

Given the increased importance of understanding the non-timber components of forest ecosystems, many countries have revised their inventory procedures. More data on dead organic matter carbon stocks and their dynamics are becoming available, which will allow inventory agencies to better identify, quantify and reduce uncertainties in dead organic matter estimates in the years to come.

4.2.3 Soil carbon

This section elaborates on estimation procedures and *good practices* for estimating change in forest soil C stocks. It does not include forest litter, which is a dead organic matter pool. Separate guidance is provided for two types of forest soils: 1) mineral forest soils, and 2) organic forest soils.

The organic C content of mineral forest soils (to 1 m depth) typically varies between 20 to over 300 tonnes C ha^{-1} depending on the forest type and climatic conditions (Jobbagy and Jackson, 2000). Globally, mineral forest soils contain approximately 700 Pg C (Dixon *et al.*, 1994), but soil organic C pools are not static due to differences between C inputs and outputs over time. Inputs are largely determined by the forest productivity, the decomposition of litter and its incorporation into the mineral soil and subsequent loss through mineralization/respiration (Pregitzer, 2003). Other losses of soil organic C occur through erosion or the dissolution of organic C that is leached to groundwater or loss through overland flow. A large proportion of input is from above-ground litter in forest soils so soil organic matter tends to concentrate in the upper soil horizons, with roughly half of the soil organic C in the upper 30 cm layer. The C held in the upper profile is often the most chemically decomposable, and the most directly exposed to natural and anthropogenic disturbances. This section only deals with soil C and does not address decomposing litter (i.e., dead organic matter, see Section 4.2.2).

Human activities and other disturbances such as changes in forest type, productivity, decay rates and disturbances can alter the C dynamics of forest soils. Different forest management activities, such as rotation length; choice of tree species; drainage; harvest practices (whole tree or sawlog, regeneration, partial cut or thinning); site preparation activities (prescribed fires, soil scarification); and fertilization, affect soil organic C stocks (Harmon and Marks, 2002; Liski *et al.*, 2001; Johnson and Curtis, 2001). Changes in disturbance regimes, notably in the occurrence of severe forest fires, pest outbreaks, and other stand-replacing disturbances are also expected to alter the forest soil C pool (Li and Apps, 2002; de Groot *et al.,* 2002). In addition, drainage of forest stands on organic soils reduces soil C stocks.

General information and guidelines on estimating changes soil C stocks are found in Chapter 2, Section 2.3.3, and needs to be read before proceeding with the specific guidelines dealing with forest soil C stocks. Changes in soil C stocks associated with forests are computed using Equation 2.24 in Chapter 2, which combines the change in soil organic C stocks for mineral soils and organic soils; and stock change for soil inorganic C pools (Tier 3 only). This section elaborates on estimation procedures and *good practices* for estimating change in forest soil C organic stocks (Note: It does not include forest litter, i.e., dead organic matter). Separate guidance is provided for two types of forest soils: 1) mineral forest soils, and 2) organic forest soils. See Section 2.3.3.1 for general discussion on soil inorganic C (no additional information is provided in the Forest Land discussion below).

To account for changes in soil C stocks associated with *Forest Land Remaining Forest Land*, countries need to have, at a minimum, estimates of the total Forest Land area at the beginning and end of the inventory time period, stratified by climate region and soil type. If land-use and management activity data are limited, Approach 1 activity data (see Chapter 3) can be used as the basis for a Tier 1 approach, but higher Tiers are likely to need more detailed records or knowledge of country experts about the approximate distribution of forest management systems. Forest Land classes must be stratified according to climate regions and major soil types, which can be accomplished with overlays of suitable climate and soil maps.

4.2.3.1 CHOICE OF METHOD

Inventories can be developed using Tier 1, 2 or 3 approaches, and countries may choose to use different tiers for mineral and organic soils. Decision trees are provided for mineral soils (Figure 2.4) and organic soils (Figure 2.5) in Chapter 2 to assist inventory compilers with selection of the appropriate tier for their soil C inventory.

Mineral soils

In spite of a growing body of literature on the effect of forest types, management practices and other disturbances on soil organic C, the available evidence remains largely site- and study-specific, but eventually may be generalized based on the influence of climatic conditions, soil properties, the time scale of interest, taking into consideration sampling intensity and effects across different soil depth increments (Johnson and Curtis, 2001; Hoover, 2003; Page-Dumroese *et al.*, 2003). However, the current knowledge remains inconclusive on both the magnitude and direction of C stock changes in mineral forest soils associated with forest type, management and other disturbances, and cannot support broad generalizations.

Tier 1

Due to incomplete scientific basis and resulting uncertainty, it is assumed in the Tier 1 method that forest soil C stocks do not change with management. Furthermore, if using Approach 2 or 3 activity data (see Chapter 3), it is not necessary to compute C stock changes for mineral soils (i.e., change in SOC stocks is 0).

If using activity data collected via Approach 1 (see Chapter 3), and it is not possible to identify the amount of land converted *from* and *to* Forest Land, then the inventory compiler should estimate soil C stocks for Forest Land using the areas at and the end of the year for which the inventory is being estimated, and the difference estimates the uptake or less of forest soil. The changes in soil C stocks for Forest Land are summed with the changes in stocks for other land uses to estimate the influence of land-use change. If the compiler does not compute a stock for Forest Land, it is likely to create systematic errors in the inventory. For example, land converted from Forest Land to Cropland or Grassland will have a soil C stock estimated in the final year of the inventory, but will have no stock in the first year of the inventory (when it was forest). Consequently, conversion to Cropland or Grassland is estimated as a gain in soil C because the soil C stocks are assumed to be 0 in the Forest Land, but not in Cropland and Grassland. This would introduce a bias into the inventory estimates. SOC_0 and SOC_{0-T} are estimated for the top 30 cm of the soil profile using Equation 2.25 (Chapter 2). Note that areas of exposed bedrock in Forest Land are not included in the soil C stock calculation (assume a stock of 0).

Tier 2

Using Equation 2.25 (Chapter 2) soil organic C stocks are computed based on reference soil C stocks and country-specific stock change factors for forest type (F_I), management (F_{MG}) and natural disturbance regime (F_D). Note that the stock change factor for natural disturbance regime (F_D) is substituted for the land-use factor (F_{LU}) in Equation 2.25. In addition, country-specific information can be incorporated to better specify reference C stocks, climate regions, soil types, and/or the land management classification system.

Tier 3

Tier 3 approaches will require considerable knowledge and data allowing for the development of an accurate and comprehensive domestic estimation methodology, including evaluation of model results and implementation of a domestic monitoring scheme and/or modelling tool. The basic elements of a country-specific approach are (adapted from Webbnet Land Resource Services Pty ltd, 1999):

- Stratification by climatic zones, major forest types and management regimes coherent with those used for other C pools in the inventory, especially biomass;
- Determination of dominant soil types in each stratum;
- Characterization of corresponding soil C pools, identification of determinant processes in SOC input and output rates and the conditions under which these processes occur; and
- Determination and implementation of suitable methods to estimate carbon stock changes from forest soils for each stratum on an operational basis, including model evaluation procedures; methodological considerations are expected to include the combination of monitoring activities – such as repeated forest soil inventories - and modelling studies, and the establishment of benchmark sites. Further guidance on good soil monitoring practices is available in the scientific literature (Kimble *et al.*, 2003, Lal *et al.*, 2001, McKenzie *et al.*, 2000). It is *good practice* for models developed or adapted for this purpose to be peer-reviewed, and validated with observations representative of the ecosystems under study and independent from the calibration data.

Organic soils

Tier 1

Currently, only C emissions due to drainage of forest organic soils are addressed in the Tier 1 method due to data limitations and lack of sufficient knowledge that constrain the development of a more refined default methodology. Using Equation 2.26 (Chapter 2), drained forest organic soils are stratified by climate type, and then multiplied by a climate-specific emission factor to derive an estimate of annual C emissions. Areas converted to Forest Land can be included in the total area estimate, in using Approach 1 land representation, without supplementary data, to be able to identify land-use changes.

Tier 2

For Tier 2, the same basic equation is used as in Tier 1 (Equation 2.26), but country-specific information is incorporated to better specify emission factors, climate regions, and/or develop a forest classification scheme, relevant for organic soils.

Tier 3

Tier 3 methodology involves the estimation of CO_2 emissions associated with management of forested organic soils, including all anthropogenic activities likely to alter the hydrological regime, surface temperature, and vegetation composition of forested organic soils; and major disturbances such as fires.

4.2.3.2 CHOICE OF STOCK CHANGE AND EMISSION FACTORS

Mineral soils

Tier 1

It is not necessary to compute the stock estimates for *Forest Land Remaining Forest Land* with Approach 2 or 3 activity data (see Chapter 3). If using Approach 1 activity data, stock change factors, including input, management and disturbance regime, are equal to 1 using the Tier 1 approach. Consequently, only reference C stocks are needed to apply the method, and those are provided in Table 2.3 of Chapter 2.

Tier 2

In a Tier 2 approach, stock change factors are derived based on a country-specific classification scheme for management, forest types, and natural disturbance regimes. A Tier 2 approach should also include the derivation of country-specific reference C stocks, and a more detailed classification of climate and soils than the default categories provided with the Tier 1 method.

It is *good practice* to focus on the factors that have the largest overall effect, taking into account the impact on forest SOC and the extent of affected forests. Management practices can be coarsely labeled as intensive (e.g., plantation forestry) or extensive (e.g., natural forest); these categories can also be redefined according to national circumstances. The development of stock change factors is likely to be based on intensive studies at experimental sites and sampling plots involving replicated, paired site comparisons (Johnson *et al.*, 2002; Olsson *et al.*, 1996; see also the reviews by Johnson and Curtis, 2001; and Hoover, 2003). In practice, it may not be possible to separate the effects of a different forest types, management practices and disturbance regimes, in which case some stock change factors can be combined into a single modifier. If a country has well-documented data for different forest types under different management regimes, it might be possible to derive soil organic C estimates directly without using reference C stocks and adjustment factors. However, a relationship to the reference C stocks must be established so that the impact of land-use change can be computed without artificial increases or decreases in the C stocks due to a lack of consistency in the methods across the various land-use categories (i.e., Forest Land, Cropland, Grassland, Settlements, and Other Land).

Inventories can also be improved by deriving country-specific reference C stocks (SOC_{ref}), compiled from published studies or surveys. Such values are typically obtained through the development and/or compilation of large soil profile databases (Scott *et al.*, 2002; Siltanen *et al.*, 1997). Additional guidance for deriving stock change factors and reference C stocks is provided in Section 2.3.3.1 (Chapter 2).

Tier 3

Constant stock change rate factors *per se* are less likely to be estimated in favor of variable rates that more accurately capture land-use and management effects. See Section 2.3.3.1 (Chapter 2) for further discussion.

Organic soils

Tier 1

Default emission factors are provided in Table 4.6 of Section 4.5, to estimate the loss of C associated with drainage of organic soils.

Tier 2

Tier 2 approaches involve the derivation of emission factors from country-specific data. The main consideration is whether forests types or management in addition to climate regions will be subdivided into finer classes. These decisions will depend on experimental data that demonstrate significant differences in C loss rates. For example, drainage classes can be developed for various forest management systems. In addition, management activities may disrupt the C dynamics of the underlying organic soils. Harvest, for example, may cause a rise in the water table due to reduced interception, evaporation and transpiration (Dubé *et al.*, 1995).

Tier 3

Constant emission rate factors *per se* are less likely to be estimated in favor of variable rates that more accurately capture land-use and management effects. See Section 2.3.3.1 (Chapter 2) for further discussion.

4.2.3.3 CHOICE OF ACTIVITY DATA

Mineral soils

Tier 1

For the Tier 1 approach, it is assumed that forest soil C stocks do not change with management, and therefore it is not necessary to classify forest into various types, management classes or natural disturbance regimes. However, if using Approach 1 activity data (see Chapter 3), environmental data will be needed to classify the country into climate regions and soil types in order to apply the appropriate reference C stocks to Forest Land. A detailed description of the default climate classification scheme is given in Chapter 3, Annex 3A.5. If the information needed to classify climate types is not available from national databases, there are international sources of climate data such as United Nations Environmental Program. Data will also be needed to classify soils into the default categories provided in Chapter 3, and if national data are not available to map the soil types, international soils data provide a reasonable alternative, such as the FAO Soils Map of the World.

Tier 2
Activity data for the Tier 2 approach consist of the major forest types, management practices, disturbance regimes and the areas to which they apply. It is preferable for the data to be linked with the national forest inventory, where one exists, and/or with national soil and climate databases. Typical changes include: conversion of unmanaged to managed forest; conversion of native forest into a new forest type; intensification of forest management activities, such as site preparation, tree planting and rotation length changes; changes in harvesting practices (bole vs. whole-tree harvesting; amount of residues left on-site); frequency of disturbances (pest and disease outbreaks, flooding, fires, etc). Data sources will vary according to a country's forest management system, but could include individual contractors or companies, statutory forest authorities, research institutions and agencies responsible for forest inventories. Data formats vary widely, and include, among others, activity reports, forest management inventories and remote sensing imagery.

In addition, Tier 2 should involve a finer stratification of environmental data than the Tier 1 approach, including climate regions and soil types, which would likely be based on national climate and soils data. If a finer classification scheme is utilized in a Tier 2 inventory, reference C stocks will also need to be derived for the more detailed set of climate regions and soil types, and the land management data will need to be stratified based on the country-specific classification.

Tier 3
For application of dynamic models and/or a direct measurement-based inventory in Tier 3, similar or more detailed data on the combinations of climate, soil, topographic and management data are needed, relative to the Tiers 1 and 2 methods, but the exact requirements will be dependent on the model or measurement design.

Organic soils

Tier 1
Forests are not stratified into various systems using Tier 1 methods. However, land areas do need to be stratified by climate region and soil type (see Chapter 3 for guidance on soil and climate classification) so that organic soils may be identified and the appropriate default emission factor applied.

Tier 2
Tier 2 approaches may involve a finer stratification of management, forest type or disturbance regime, in a manner consistent with the country-specific emission factors for organic soils. For example, forest systems will need to be stratified by drainage if management factors are derived by drainage class. However it is *good practice* for the classification to be based on empirical data that demonstrates significant differences in rates of C change for the proposed categories. In addition, Tier 2 approaches should involve a finer stratification of climate regions.

Tier 3
For application of dynamic models and/or a direct measurement-based inventory in Tier 3, similar or more detailed data on the combinations of climate, soil, topographic and management data are needed, relative to the Tiers 1 and 2 methods, but the exact requirements will be dependent on the model or measurement design.

4.2.3.4 CALCULATION STEPS FOR TIER 1

Mineral soils
Since Tier 1 assumes no change in mineral soil C stocks for *Forest Land Remaining Forest Land*, guidance on calculations steps are not provided.

Organic soils
Step 1: Estimate the area of drained organic soils under managed forest in each climatic region of the country for each year or for the last year in each time period of the inventory (e.g., emissions over an inventory time period between 1990 and 2000 would be based on the land-use in 2000, assuming land-use and management are only known for these two years during the inventory time period).

Step 2: Select the appropriate emission factor (EF) for annual losses of CO_2 (from Table 4.6).

Step 3: Estimate total emissions by summing the product of area (A) multiplied by the emission factor (EF) for all climate zones.

4.2.3.5 UNCERTAINTY ASSESSMENT

Three broad sources of uncertainty exists in soil C inventories: 1) uncertainties in land-use and management activity and environmental data; 2) uncertainties in reference soil C stocks if using Tier 1 or 2 approaches (mineral soils only); and 3) uncertainties in the stock change/emission factors for Tier 1 or 2 approaches, model structure/parameter error for Tier 3 model-based approaches, or measurement error/sampling variability associated with Tier 3 measurement-based inventories. In general, precision of an inventory is increased (i.e., smaller confidence ranges) with more sampling to estimate values for the three broad categories. In addition, reducing bias (i.e., improve accuracy) is more likely through the development of a higher Tier inventory that incorporates country-specific information.

For Tier 1, uncertainties are provided with the reference C stocks in the first footnote of Table 2.3 (Chapter 2), and emission factor uncertainties for organic soils are provided in Table 4.6, Section 4.5. Uncertainties in land-use and management data will need to be addressed by the inventory compiler, and then combined with uncertainties for the default factors and reference C stocks (mineral soils only) using an appropriate method, such as simple error propagation equations. Refer to Section 4.2.1.5 for uncertainty estimate for land area estimates. However, it is *good practice* for the inventory compiler to derive uncertainties from country-specific activity data instead of using a default level.

Default reference C stocks for mineral soils and emission factors for organic soils can have inherently high uncertainties, particularly bias, when applied to specific countries. Defaults represent globally averaged values of land-use and management impacts or reference C stocks that may vary from region-specific values (Powers *et al.*, 2004; Ogle *et al.*, 2006). Bias can be reduced by deriving country-specific factors using Tier 2 method or by developing a Tier 3 country-specific estimation system. The underlying basis for higher Tier approaches will be research in the country or neighbouring regions that address the effect of land use and management on soil C. In addition, it is *good practice* to further minimize bias by accounting for significant within-country differences in land-use and management impacts, such as variation among climate regions and/or soil types, even at the expense of reduced precision in the factor estimates (Ogle *et al.*, 2006). Bias is considered more problematic for reporting stock changes because it is not necessarily captured in the uncertainty range (i.e., the true stock change may be outside of the reported uncertainty range if there is significant bias in the factors).

Uncertainties in land-use activity statistics may be improved through a better national system, such as developing or extending a ground-based survey with additional sample locations and/or incorporating remote sensing to provide additional coverage. It is *good practice* to design a classification that captures the majority of land-use and management activity with a sufficient sample size to minimize uncertainty at the national scale.

For Tier 2 methods, country-specific information is incorporated into the inventory analysis for purposes of reducing bias. For example, Ogle *et al.* (2003) utilized country-specific data to construct probability distribution functions for US specific factors, activity data and reference C stocks for agricultural soils. It is *good practice* to evaluate dependencies among the factors, reference C stocks or land-use and management activity data. In particular, strong dependencies are common in land-use and management activity data because management practices tend to be correlated in time and space. Combining uncertainties in stock change/emission factors, reference C stocks and activity data can be done using methods such as simple error propagation equations or Monte-Carlo procedures.

Tier 3 models are more complex and simple error propagation equations may not be effective at quantifying the associated uncertainty in resulting estimates. Monte Carlo analyses are possible (Smith and Heath, 2001), but can be difficult to implement if the model has many parameters (some models can have several hundred parameters) because joint probability distribution functions must be constructed quantifying the variance as well as covariance among the parameters. Other methods are also available such as empirically-based approaches (Monte *et al.*, 1996), which use measurements from a monitoring network to statistically evaluate the relationship between measured and modelled results (Falloon and Smith, 2003). In contrast to modelling, uncertainties in measurement-based Tier 3 inventories can be determined from the sample variance, measurement error and other relevant sources of uncertainty.

4.2.4 Non-CO_2 greenhouse gas emissions from biomass burning

Both uncontrolled (wildfires) and managed (prescribed) fires can have a major impact on the non-CO_2 greenhouse gas emissions from forests. In *Forest Land Remaining Forest Land*, emissions of CO_2 from biomass burning also need to be accounted for because they are generally not synchronous with rates of CO_2 uptake. This is especially important after stand replacing wildfire, and during cycles of shifting cultivation in tropical regions.

Where the type of forest changes (e.g., conversion of natural forests to plantation forests), there may be net emissions of CO_2 from biomass burning during the initial years, in particular if significant woody biomass is burnt during the conversion. Over time, however, the impacts are not as great as those that result from *Forest Land Converted to Cropland or Grassland.* Fire emissions during land-use conversion are reported in the new land-use category unless restricted Approach 1 land area representation is being used without supplementary data to enable land use conversions to be identified explicitly, in which case fire emissions from Forest Land should all be included in the *Forest Land Remaining Forest Land* category.

The general method for estimating greenhouse gas emissions in *Forest Land Remaining Forest Land*, and in *Land Converted to Forest Land* is described in Equation 2.27 in Chapter 2. Default tables for Tier 1 approach or components of a Tier 2 approach are provided in that Section 2.4 of Chapter 2.

4.2.4.1 CHOICE OF METHOD

It is *good practice* that countries choose the appropriate Tier for reporting greenhouse gas emissions from fire, based on the decision tree in Figure 2.6 in Chapter 2. Where fire is a key category, emphasis should be on using a Tier 2 or Tier 3 approach. For prescribed fires, country-specific data are required to generate reliable estimates of emissions, since activity data, in general, are poorly reflected in global data sets. In Forest Land, both the CO_2 emissions due to biomass burning and the CO_2 removals resulting from vegetation regrowth need to be accounted for when estimating the net carbon flux.

4.2.4.2 CHOICE OF EMISSIONS FACTORS

The mass of fuel available for combustion (M_B of Equation 2.27) is critical for estimating the non-CO_2 emissions. Default data to support estimation of emissions under a Tier 1 approach are given in Tables 2.4 to 2.6 in Chapter 2. Countries need to judge how their vegetation types correspond with the broad vegetation categories described in the default tables. Guidance for this is provided in Chapter 3 (*Consistent Representation of Lands*). Countries using Tier 2 are likely to have national data at disaggregated level on M_B, according to forest types and management systems. Tier 3 estimation requires spatial estimates of M_B according to different forest types, regions and management systems. Tier 3 estimation methods can also distinguish fires burning at different intensities, resulting in different amounts of fuel consumption.

4.2.4.3 CHOICE OF ACTIVITY DATA

Estimates of area burnt in *Forest Land Remaining Forest Land* are needed. A global database exists that covers the area burnt annually by fires but this will not provide reliable data for the area burnt annually by prescribed fires in individual countries. It is *good practice* to develop national estimates of the area burnt and the nature of the fires especially how they affect forest carbon dynamics (e.g., effects on tree mortality) to improve the reliability of national inventories. Countries using Tier 2 are likely to have access to national estimates. Tier 3 estimation requires regional and forest type specific estimates of area subjected to fire and fire intensity.

Summary of steps for calculating greenhouse gas emissions from biomass burning using Equation 2.27 in Chapter 2:

Step 1: Using guidance from Chapter 3 (approaches in representing land-use areas), categorise the area of *Forest Land Remaining Forest Land* into forest types of different climatic or ecological zones, as adopted by the country for Equation 2.27. Obtain estimates of A (area burnt) from global database or from national sources.

Step 2: Estimate the mass of fuel (M_B) available for combustion, in tonnes/ha, which includes biomass, litter and dead wood.

Step 3: Select combustion factor C_f (default values are in Table 2.6, Chapter 2).

Step 4: Multiply M_B and C_f to provide an estimate of the amount of fuel combusted. If M_B or C_f is unknown, defaults for the product of M_B and C_f are given in Table 2.4.

Step 5: Select emission factors G_{ef} (default factors are in Table 2.5, Chapter 2).

Step 6: Multiply parameters A, M_B, C_f, (or M_B and C_f, Table 2.4) and G_{ef} to obtain the quantity of greenhouse gas emission from biomass burning. Repeat the steps for each greenhouse gas.

4.2.4.4 UNCERTAINTY ASSESSMENT

Country-specific uncertainty estimates are to be estimated for *Forest Land Remaining Forest Land*. These result from the product of the uncertainties associated with activity data (area burnt) and the emission factors. It is *good practice* to provide error estimates (e.g., ranges, standard errors) and not to use country-specific data (for example, if it is of a limited nature) or approaches, unless this leads to a reduction in uncertainties compared with a Tier 1 approach.

4.3 LAND CONVERTED TO FOREST LAND

This section provides methodological guidance on annual estimation of emissions and removals of greenhouse gases, which occur on lands converted to Forest Land from different land-uses, including Cropland, Grassland, Wetlands, Settlements, and Other land, through afforestation and reforestation, either by natural or artificial regeneration (including plantations). The emissions and removals on abandoned lands, which are regenerating to forest due to human activities, should be also estimated under this section. It substitutes the method described under categories 5A, 5C, and 5D of the *IPCC Guidelines*. Land is converted to Forest Land by afforestation and reforestation, either by natural or artificial regeneration (including plantations). The anthropogenic conversion includes promotion of natural re-growth (e.g., by improving the water balance of soil by drainage), establishment of plantations on non-forest lands or previously unmanaged Forest land, lands of settlements and industrial sites, abandonment of croplands, pastures or other managed lands, which re-grow to forest. Unmanaged forests are not considered as anthropogenic greenhouse gas sources or sinks, and are excluded from inventory calculations. Where these unmanaged forests are affected by human activities such as planting, thinning, promotion of natural regeneration or others, they change status and become managed forests, reported under the category *Land Converted to Forest Land*, whose greenhouse gas emissions and removals should be included in the inventory and estimated with the use of the guidance in this section. Land conversion may result in an initial loss of carbon due to changes in biomass, dead organic matter, and soil carbon. But natural regeneration or plantation practices lead to carbon accumulation and that is related to changes in the area of plantations and their biomass stocks.

Converted areas are considered Forest Land, if, following conversion, they correspond to definition of forest adopted by the country. *Land Converted to Forest Land* is covered in this section of the national greenhouse gas inventory until the time the soil carbon in new forests reach a stable level. A default period of 20 years[4] is suggested. Forest ecosystems may require a certain time to return to the level of biomass, stable soil and litter pools of undisturbed state. With this in mind and as a practical matter, the default 20-year time interval is suggested. Countries also have an option to extend the length of transition period. After 20 years or other time interval chosen, the converted lands become forest, i.e., the land areas are transferred from the *Land Converted to Forest Land* category to *Forest Land Remaining Forest Land* (Section 4.2), where areas still becoming established can be treated as a separate stratum if necessary. Logging followed by regeneration or re-growth should be considered under *Forest Land Remaining Forest Land* category, since no land-use change is involved.

Some abandoned lands may be too infertile, saline, or eroded for forest re-growth to occur. In this case, either the land remains in its current state or it may further degrade and lose organic matter. Those lands that remain constant with respect to carbon flux can be ignored. However, in some countries, the degradation of abandoned lands may be a significant problem and could be an important source of CO_2. Where lands continue to degrade, both above-ground biomass and soil carbon may decline rapidly, e.g., due to erosion. The carbon in eroded soil could be re-deposited in rivers, lakes or other lands downstream. For countries with significant areas of such lands, this issue should be considered in a more refined calculation.

Classification of land: *Land Converted to Forest Land* can be classified based on climate domain and ecological zones and forest crown cover classes. The carbon stock varies with climate, biome or forest type, species mix, management practices, etc. It is *good practice* to stratify lands into homogenous sub-categories (see Chapter 3) to reduce uncertainty in estimates of greenhouse gas emissions.

The estimation of emissions and removals of carbon from land-use conversion to Forest Land is divided into three sub-sections: Change in Carbon Stocks in Biomass (Section 4.3.1), Change in Carbon Stocks in Dead Organic Matter (Section 4.3.2) and Change in Carbon Stocks in Soils (Section 4.3.3). The annual changes in carbon stocks on *Land Converted to Forest Land* are calculated using Equations 2.2 and 2.3 of Chapter 2 on the

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[4] It is clear that most forest ecosystems will take longer than 100 years to return to the level of biomass, soil and litter pools in undisturbed state; however human-induced activities can enhance the rate of return to stable state of carbon stocks. With this in mind and as a practical matter, the default 20-year time interval is suggested to capture the establishment of the forest ecosystems. Countries also have the option to extend the length of the transition period, though a consistent transition period will be required for the land use matrix system of land area representation to work properly.

basis of annual changes in carbon stocks in biomass, dead organic matter (including dead wood and litter) and soil. Changes in carbon stock in *Land Converted to Forest Land* are estimated using:

- annual change in carbon stocks in above- and below-ground biomass
- annual change in carbon stocks in dead organic matter that includes dead wood and litter
- annual change in carbon stocks in soils

The approach for calculation of non-CO_2 emissions is described in Section 4.3.4 based on methods given in Chapter 2.

Application of these methods will only be possible if using Approach 2 or 3 land area representation as set out in Chapter 3, or Approach 1 data with supplementary data to enable land-use conversions to be identified. The actions to be taken in this case have already been identified in Section 4.2 above (*Forest Land Remaining Forest Land*).

4.3.1 Biomass

This section presents methodological guidance for calculation of emissions and removals of CO_2 by changes in biomass on *Land Converted to Forest Land*. It substitutes the methodology provided for reporting on "Changes in Forest and Other Woody Biomass Stocks" and "Abandonment of Managed Lands" categories of the *IPCC Guidelines* as applied to newly established forests.

4.3.1.1 CHOICE OF METHOD

This section presents methodological guidance for calculation of emissions and removals of CO_2 by changes in above-ground and below-ground biomass on *Land Converted to Forest Land*. Based on key category analysis, activity data and resources available, three tier methods are suggested to estimate changes in biomass stocks. The decision tree in Figure 1.3 in Chapter 1 illustrates *good practice* approach for choosing the method to calculate CO_2 emissions and removals in biomass on *Land Converted to Forest Land*.

Tier 1

Annual change in carbon stocks in biomass is estimated with the use of Equation 2.7 in Chapter 2. Tier 1 follows the default approach. It implies the use of default parameters provided in Section 4.5. This approach can be also applied, if the data on previous land uses are not available, which may be the case, when areas are estimated using Approach 1 from Chapter 3. It implies the use of default parameters in Tables 4.1 through 4.14.

Annual increase in carbon stocks in biomass, ΔC_G. The calculations of ΔC_G should be made according to Equation 2.9 in Chapter 2. As the growth rate of trees strongly depends on management regime, a distinction should be made between intensively (e.g., plantation forestry) and extensively (naturally re-growing stands with reduced or minimum human intervention) managed forests. The intensively and extensively managed forests can be further stratified based on climate, species, management practices, etc. Hence, the annual increase in carbon stocks can be estimated separately for intensively and extensively managed forests, using Equation 2.9 twice. First, for intensively managed forests using relevant area (A_I) and the relevant mean annual biomass growth (G_{Total}) for intensively managed forests and second, for extensively managed forests by using appropriate area (A_E) and mean annual biomass growth (G_{Total}) data for extensively managed forests. G_{TOTAL} is calculated using Equation 2.10, Chapter 2, and default data tables in Section 4.5. The intensively managed and extensively managed forests can be further stratified based on climate, species, forest management practices, etc. The default data for extensively and intensively managed forests from the tables should be chosen with regard to tree species composition and climatic region. The default data for extensively and intensively managed forests should be taken from Section 4.5, correspondingly.

Annual decrease in carbon stocks in biomass due to losses, ΔC_L. Biomass loss due to wood removal ($L_{wood\text{-}removals}$), fuelwood removal ($L_{fuelwood}$) and disturbances ($L_{disturbance}$) attributed to *Land Converted to Forest Land*, is estimated using Equation 2.11 in Chapter 2.

The loss of biomass due to wood removal ($L_{wood\text{-}removals}$) is estimated with the use of Equation 2.12, of Chapter 2, and default values of basic wood density and the data on round wood logging, biomass conversion expansion factor, below-ground biomass to above-ground biomass ratio (R) and carbon fraction of dry matter (CF), provided in Section 4.5 tables. The biomass loss due to fuelwood removal ($L_{fuelwood}$) is estimated using Equation 2.13, fuelwood collecting data and relevant $BCEF_R$ for growing stock, R and CF from default tables in Section 4.5. The ($L_{disturbance}$) could be estimated using Equation 2.14, in Chapter 2, area of disturbance, average growing stock biomass of land areas affected by disturbances and appropriate R and CF from default tables in Section 4.5.

The ΔC_L should be assumed 0, if no data on losses are available (for Equation 2.11). To prevent double accounting or omission, consistent reporting of biomass loss should be maintained in Sections 4.2.1 and 4.3.1.

Tier 2

The Tier 2 method is similar to Tier 1, but it uses nationally derived data and more disaggregated activity data and allows for more precise estimates of changes in carbon stocks in biomass. The net annual CO_2 removals are calculated as a sum of increase in biomass due to biomass growth on converted lands, changes due to actual conversion (difference between biomass stocks before and after conversion) and losses on converted lands (Equations 15 and 16, Chapter 2).

In addition to default values, the application of Tier 2 (Equation 2.15) requires national data on: i) area annually converted to forest; ii) average annual growth in carbon stocks in biomass per ha on converted lands, obtained e.g., from forest inventories (no default data can be provided); iii) change in biomass carbon when non-forest land becomes Forest Land; and iv) emissions due to loss of biomass on converted land. The approach may require data on previous land uses as well as knowledge of land-use change matrix (see Table 3.4 in Chapter 3) and carbon stocks on those lands.

$\boldsymbol{\Delta C_G}$ should be estimated using Equation 2.9, where the area (A) of *Land Converted to Forest Land* should be considered separately along with respective mean annual increments for intensively and extensively managed forests (further categorized based on species, climate, etc.) and summed up. Average annual increment in biomass for managed forests is calculated in accordance with Tier 2 method as in Section 4.2.1, *Forest Land Remaining Forest Land* and Equation 2.10, Chapter 2, based on country-specific data on average annual biomass growth in merchantable volume per ha on land converted to forests (obtained e.g., from forest inventories) and on basic wood density, biomass conversion and expansion factors and below-ground to above-ground biomass ratio.

$\boldsymbol{\Delta C_{CONVERSION}}$ accounts for the initial change in biomass stocks resulting from the land-use conversion, e.g., part of biomass may be withdrawn through land clearing, restocking or other human-induced activities applied on land prior to artificial or natural regeneration. These changes in carbon stocks in biomass are calculated with the use of Equation 2.16 in Chapter 2. This requires estimates of biomass stocks on land type *i* before (B_{BEFORE_i}) and after (B_{AFTER_i}) the conversion in tonnes d.m. ha^{-1}, area of land-use *i* converted to Forest Land ($\Delta A_{TO\_FOREST_i}$) in a certain year, and the carbon fraction of dry matter (CF).

The calculation of $\Delta C_{CONVERSION}$ may be applied separately to account for different carbon stocks occurring on specific types of land (ecosystems, site types, etc.) before the transition. The $\Delta A_{TO\_FOREST_i}$ refers to the particular inventory year for which the calculations are made.

$\boldsymbol{\Delta C_L}$ is estimated using Equation 2.11 in Chapter 2. Biomass loss due to wood removal ($L_{wood-removals}$), fuelwood removal ($L_{fuelwood}$), and disturbances ($L_{disturbance}$) should be estimated with the use of Equations 2.12 to 2.14, in Chapter 2. Inventory compilers are encouraged to develop country-specific wood density and BEF or BCEF values for growing stock increment and harvests to apply them in Equation 2.12 (for Tier 2 calculations). Chapter 2 describes the method for calculation of biomass losses from fuelwood gathering ($L_{fuelwood}$) and disturbances ($L_{disturbance}$). The ΔC_L should be assumed 0, if no data on losses are available. It is *good practice* to ensure consistent reporting on biomass losses between Sections 4.2.2 and 4.2.3 to avoid over- and underestimates due to double counting or omissions.

Tier 3

Tier 3 should be used when land conversion to Forest Land is a key category and leading to a significant change of carbon stocks. It can follow the same equations and steps as Tier 2 or can use more complex methods and models, but in either case, it can make use of substantial national methods and country-specific data. The Equations 2.15 and 2.16 can be expanded on the basis of finer geographical scale and sub-division to forest type, species, and land type before conversion. Country-defined methodologies may be based on regular forest inventory or geo-referenced data and (or) models for accounting for changes in biomass. National activity data can have high resolution and be available for all categories of converted lands and forest types established on them. It is *good practice* to describe and document the methodology in accordance with Volume 1, Chapter 8 (Reporting Guidance and Tables).

Transfer of biomass to dead organic matter

During the process of conversion of land to Forest Land as well as during the process of extraction of biomass through felling, the non-commercial component of the biomass is left on the forest floor or transferred to dead organic matter. Refer to Section 4.3.2 for description of the method and the assumptions about the fate of dead organic matter.

4.3.1.2 CHOICE OF EMISSION FACTORS

Annual increase in carbon stocks in biomass, ΔC_G

The calculations distinguish between two broad management practices: intensive (e.g., plantation forestry with site preparation, planting of selected species and fertilization) and extensive (natural regeneration with minimum human intervention). These categories can also be refined according to national circumstances, for example based on stand origin (e.g., natural or artificial regeneration, restocking, promotion of natural re-growth, etc.), climate, species, management practice, etc.

Tier 1

The methods for calculation of total biomass require above-ground and below-ground biomass pools (for pool descriptions, refer to Chapter 1). The tables in Section 4.5 represent default values of average annual growth in above-ground biomass for intensively (plantations) and extensively (naturally regenerated) managed forests, biomass conversion and expansion factors, below-ground biomass to above-ground biomass ratio and carbon fraction of dry matter (CF). The below-ground biomass to above-ground biomass ratio should be used to account for below-ground biomass in total biomass estimations. Basic wood density and biomass expansion factors, which allow for calculation of ΔC_G as described in Section 4.2.1 *Forest Land Remaining Forest Land*. It is *good practice* to explore any regional or otherwise relevant default values to the country.

Tier 2

It is *good practice* to determine, wherever possible, annual increment values, below-ground biomass to above-ground biomass, basic wood density, and biomass conversion and expansion factors appropriate for national conditions and use them in calculations under Tier 2. These categories can also be refined according to national circumstances, for example based on stand origin (natural or artificial regeneration, restocking, promotion of natural re-growth, etc.), climate, species composition, and management regime. The further stratifications may refer to tree species composition, management regime, stand age, climatic region and soil type, etc. Countries are encouraged to obtain specific biomass increment and expansion factors through research efforts. Additional guidance is provided in Section 4.2.1.

Tier 3

The increment in biomass carbon stocks can be estimated based on country-specific annual biomass growth and carbon fraction in biomass data that come from forest inventories, sample plots, research and (or) models. The inventory compilers should ensure that the models and forest inventory data have been appropriately documented and described in line with the requirements highlighted in Volume 1, Chapter 8.

Change in biomass stocks on land before and after conversion, $\Delta C_{CONVERSION}$

The calculations of biomass stocks before and after conversion should be made with the use of values consistent with other land uses. For example, comparable values of carbon stock should be used to estimate initial carbon stock for Grassland converted to Forest Land and for changes in biomass for *Grassland Remaining Grassland*.

Tier 1

No estimate of $\Delta C_{CONVERSION}$ is required for Tier 1 calculations.

Tier 2

It is *good practice* to obtain and use, wherever possible, country-specific data on biomass stocks on land before and after conversion. The estimates should be consistent with those used in calculations of carbon stock changes in Cropland, Grassland, Wetlands, Settlements and Other Land, and should be obtained from national agencies or surveys. Tier 2 may imply the use of a combination of country-specific and default data. For default biomass stock values on land before the conversion, refer to other sections of this Volume.

Tier 3

Estimates and calculations should be performed based on forest inventory and or model data. Forest inventory, models and data should be documented in line with procedures outlined in Volume 1, Chapter 8.

Change in carbon stocks in biomass due to losses, ΔC_L

Wood removal, fuelwood removal, and natural disturbances such as windfall, fires, and insect outbreaks result in loss of carbon on *Land Converted to Forest Land* that should be reported in accordance with *good practice* approach provided in Section 4.2.1. The *good practice* approach provided in Section 4.2.1 for estimating losses of carbon is fully applicable and should be used for appropriate calculations under Section 4.2.2. If changes in carbon stocks are derived from regular forest inventories, the losses from wood removal and disturbances will be covered without a need to report on them separately. It is *good practice* to ensure consistent reporting on losses of biomass between Sections 4.2.1 and 4.2.2 to avoid double counting or omissions.

The data on logging of round wood should be taken from national sources or FAO. It should be noted that FAO data on logging is in merchantable round wood over bark. Bark fraction in harvested wood (BF) should be applied to account for bark in wood removals with harvest. If logging is significant in the country, the inventory compilers are encouraged to use national harvest data or derive country-specific BF values.

In most countries, information on area disturbed is not likely to be available by the two sub-categories, *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* sub-categories. Given that the latter is, in most cases, much smaller than the former, all disturbances can be applied to *Forest Land Remaining Forest Land*, or the disturbed area can be pro-rated in proportion to the two land sub-categories.

Fuelwood consumption data are not normally reported separately for *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*. Then it is likely that the default fuelwood data is likely to be reported in *Forest Land Remaining Forest Land*. The reporting of fuelwood should be cross-checked between the two land sub-categories to avoid double counting by checking with reporting of fuelwood in *Forest Land Remaining Forest Land*.

4.3.1.3 CHOICE OF ACTIVITY DATA

Area of land converted to forest, ΔA_{TO_FOREST}

All tiers require information on areas converted to Forest Land over the 20 years prior to the inventory year. After 20 years or other time interval chosen, the lands converted to Forest Land, as defined in the country, should be transferred to and accounted for under Section 4.2 (*Forest Land Remaining Forest Land*). The same area data should be used for Sections 4.3.2 (Change in Carbon Stocks in Dead Organic Matter), Section 4.3.3 (Change in Carbon Stocks in Soils), and Section 4.3.4 (Non-CO_2 Greenhouse Gas Emissions). If possible, these areas should be further disaggregated to take into consideration major soil types and biomass densities on land before and after conversion. Box 4.3 gives examples of a *good practice* approach in identification of lands converted to Forest Land. Subject to national data availability, the inventory compilers can also choose *good practice* approach on the basis of approaches provided in Chapter 3.

Different biomass growth rates should be used for calculations of biomass stocks for forests naturally re-growing on abandoned lands and for forest plantations. To undertake calculations under Tiers 2 and 3, inventory compilers are encouraged to obtain information on types of previous land uses for lands converted to Forest Land.

Tier 1

Activity data can be obtained through national statistics, from forestry agencies (information on areas of different management practices), conservation agencies (naturally regenerated areas), municipalities, survey and mapping agencies. Expert judgment may be used to assess whether new forests are predominantly intensively or extensively managed, if no recorded data are available. If the data on intensively and extensively managed areas of forests become available, these should be used for further partitioning areas to obtain more accurate estimates. Cross-checks should be applied to ensure complete and consistent representation of data to avoid omissions or double counting. If no country data are available, aggregate information can be obtained from international data sources (FAO, 2001; TBFRA, 2000).

Tier 2

Areas under different land uses subjected to conversion during a given year or over a period of years should be available. They can come from national data sources and a land-use change matrix or its equivalent that covers all possible transitions to Forest Land. Country-defined national data sets should have a resolution sufficient to ensure appropriate representation of land areas in line with provisions of Chapter 3 of this Volume. It is important to estimate area converted to forest through natural regeneration and plantation approach.

Tier 3

National activity data on land conversion to Forest Land through natural and artificial regeneration should be available from different sources, notably national forest inventories, registers of land use and land-use changes and remote sensing, as described in Chapter 3 of this Volume. These data should give a full accounting of all land-use transitions to Forest Land and can be further disaggregated along climate, soil, and vegetation types. Area under plantations is usually available according to species and age of the stand.

BOX 4.3
EXAMPLES OF *GOOD PRACTICE* APPROACH IN IDENTIFICATION OF LANDS CONVERTED TO FOREST LAND

National land management systems can allow for identification of land-use changes, and the land census systems implemented in many countries also enables consistent representation and timely tracking changes in land use. The national inventory compilers should take the data from land management systems or censuses and use them as the basis for identification of converted lands. The land conversion data may be obtained directly from companies, private owners, ministries and agencies, which undertake particular activities over converted lands.

In some countries, special accounting systems have been designed to estimate emissions and removals over converted lands. The Australia National Carbon Accounting System (NCAS) <http://www.greenhouse.gov.au/> is an example of a *good practice* approach in identification of land conversion. The NCAS is a sophisticated model-based tool that comprises data from resource census, field studies, and remote sensing. It operates at high spatial and temporal scales. The NCAS addresses all sectors of activity in land systems, including carbon pools and all greenhouse gases as affected by human-induced activities. It allows for tracking afforestation and reforestation activities within the territory of the country along with estimating emissions and removals relevant to them. As soon as the new data enter the NCAS, the inventory data are updated continuously. Design and implementation of the NCAS and its components has been subjected to extensive peer review and Quality Assurance/Quality Control regime (AGO, 2002).

Similar systems are being developed in New Zealand (Stephens *et al.,* 2005; Trotter *et al.,* 2005), Canada (Kurz and Apps, 2006), and other countries. The use of such land management systems contributes to development of high quality inventories and reduces the levels of uncertainty within the sector.

4.3.1.4 CALCULATION STEPS FOR TIER 1

The following summarizes steps for estimating change in carbon stocks in biomass (ΔC_B) using the default methods

Step 1: Estimate area converted to Forest Land (during the period 20 years before the year of the inventory) from other land-use categories such as Cropland, Grassland, and Settlements. Refer to Chapter 3 for detailed approaches for estimating *Land Converted to Forest Land*.

Step 2: Disaggregate the area converted to Forest Land according to intensively managed forest (through plantation forestry) and extensively managed forest (through natural regeneration) based on the approach used for conversion.

Step 3: Calculate the initial biomass loss associated with the land conversion, $\Delta C_{CONVERSION}$ (Equation 2.16). This can be stratified by land conversion methods.

Step 4: Estimate the annual increase in carbon stocks in biomass due to growth on *Land Converted to Forest Land* (ΔC_G), for intensively managed forests at species and other sub-category level, using Equations 2.9 and 2.10 in Chapter 2. Estimate annual increment of biomass at species and other sub-category level.

Step 5: Estimate the annual increase in carbon stocks in biomass growing on *Land Converted to Forest Land* (ΔC_G), for extensively managed forests at species and other sub-category level, using Equations 2.9 and 2.10 in Chapter 2.

Step 6: Estimate annual loss or decrease in biomass ($L_{wood\text{-}removals}$) due to commercial fellings (industrial wood and sawn logs) using Equation 2.12 in Chapter 2.

Step 7: Estimate biomass loss due to fuelwood removal ($L_{fuelwood}$) on *Land Converted to Forest Land* using Equation 2.13 in Chapter 2.

Step 8: Estimate annual carbon loss due to disturbance or other losses ($L_{disturbance}$) using Equation 2.14 in Chapter 2.

Step 9: Estimate the total loss of biomass carbon due to wood removal, fuelwood removal, and disturbance (ΔC_L) using Equation 2.11 in Chapter 2.

Step 10: Estimate the annual change in carbon stock in biomass (ΔC_B) on *Land Converted to Forest Land* using Equation 2.15 in Chapter 2.

Example. The following example shows Gain-Loss method (Tier 1) calculations of annual change in carbon stocks in biomass (ΔC_B in Equation 2.7, Chapter 2) for a hypothetical country in temperate continental forest zone of Europe (Table 4.1, Section 4.5). The area of non-forest land converted to Forest Land (A) within the country is 1,000 ha (see Chapter 3 for area categorization). The new forest is intensively managed 9-year-old pine plantation, average above-ground growing stock volume is 10 m^3 ha^{-1}. Thinning removed 100 m^3 yr^{-1} of merchantable round wood over bark (H); 50 m^3 yr^{-1} of whole trees (FG_{trees}) were removed as fuel wood. The area of insect disturbance ($A_{disturbance}$) is 50 ha yr^{-1} with 1.0 tonne d.m. ha^{-1} of above-ground biomass affected (B_W).

Annual gain in biomass (ΔC_G) is a product of mean annual biomass increment (G_{TOTAL}), area of land converted to Forest Land (A) and carbon fraction of dry matter (CF), Equation 2.9, Chapter 2.

G_{TOTAL} is calculated using annual above-ground biomass increment (G_W), below-ground biomass to above-ground biomass ratio (R), (Equation 2.10, Chapter 2) and default data tables, Section 4.5.

For the hypothetical country,

G_W = 4.0 tonnes d.m. ha^{-1} yr^{-1} (Table 4.12); and

R = 0.40 tonne d.m. $(\text{tonne d.m.})^{-1}$ for above-ground biomass <50 t ha^{-1} (Table 4.4, with reference to Table 4.8 for above-ground biomass).

G_{TOTAL} = 4.0 tonnes d.m. ha^{-1} yr^{-1} ● (1 + 0.40) = 5.6 tonnes d.m. ha^{-1} yr^{-1} (Equation 2.10)

CF = 0.47 tonne C $(\text{tonne d.m.})^{-1}$ (Table 4.3)

ΔC_G (Equation 2.9): = 1,000 ha ● 5.6 tonnes d.m. ha^{-1} yr^{-1} ● 0.47 tonne C $(\text{tonne d.m.})^{-1}$

= 2,632 tonnes C yr^{-1}

Biomass loss (ΔC_L) is a sum of annual loss due to wood removals ($L_{wood\text{-}removals}$), fuelwood removal ($L_{fuelwood}$) and disturbances ($L_{disturbance}$), Equation 2.11, Chapter 2.

Wood removals ($L_{wood\text{-}removals}$) is calculated using Equation 2.12 in Chapter 2 with merchantable round wood over bark (H), biomass conversion expansion factor ($BCEF_R$), bark fraction in harvested wood (BF), below-ground biomass to above-ground biomass ratio (R), carbon fraction of dry matter (CF), and default tables in Section 4.5. For the hypothetical country,

$BCEF_R$ = 2.0 tonnes d.m. m^{-3} (Table 4.5, with reference to volume of growing stock 10 m^3 ha^{-1});

Default BEF = 0.1 tonne d.m. $(\text{tonne d.m.})^{-1}$;

R = 0.40 tonne d.m. $(\text{tonne d.m.})^{-1}$ for above-ground biomass <50 t ha^{-1} (Table 4.4, for above-ground biomass refer to Table 4.8); and

CF = 0.47 tonne C $(\text{tonne d.m.})^{-1}$ (Table 4.3).

$L_{wood\text{-}removals}$ = 100 m^3 yr^{-1} ● 2 tonnes d.m. m^{-3} (1 + 0.40 + 0.1) ● 0.47 tonne C $(\text{tonne d.m.})^{-1}$

= 141 tonnes C yr^{-1} (Equation 2.12)

Fuelwood removal ($L_{fuelwood}$) is calculated using Equation 2.13, Chapter 2 with wood removals as whole trees (FG_{trees}), biomass conversion expansion factor ($BCEF_R$), below-ground biomass to above-ground biomass ratio (R), carbon fraction of dry matter (CF), and default tables in Section 4.5. For the hypothetical country,

$BCEF_R$ = 2.0 tonnes d.m. m^{-3} (Table 4.5, with reference to growing stock volume 10 m^3 ha^{-1});

R = 0.40 tonne d.m. $(\text{tonne d.m.})^{-1}$ for above-ground biomass <50 t ha^{-1} (Table 4.4, with reference to Table 4.8 for above-ground biomass); and

CF = 0.47 tonne C $(\text{tonne d.m.})^{-1}$ (Table 4.3).

$L_{fuelwood}$ = 50 m^3 yr^{-1} ● 2.0 tonnes d.m. m^{-3} (1 + 0.40) ● 0.47 tonne C $(\text{tonne d.m.})^{-1}$

= 65.80 tonnes C yr^{-1} (Equation 2.13)

Annual carbon loss in biomass due to disturbances ($L_{disturbance}$) is calculated using Equation 2.14, Chapter 2 with area of disturbances ($A_{disturbance}$), average above-ground biomass affected (B_W), below-ground biomass to above-ground biomass ratio (R), carbon fraction of dry matter (CF), fraction of biomass lost in disturbance (fd), and default tables in Section 4.5. For the hypothetical country,

fd = 0.3;

R = 0.40 tonne d.m. (tonne d.m.)$^{-1}$ for above-ground biomass <50 t ha^{-1} (Table 4.4, with reference to Table 4.8 for above-ground biomass); and

CF = 0.47 tonne C (tonne d.m.)$^{-1}$ (Table 4.3).

$L_{disturbance}$ = 50 ha yr^{-1} ● 1.0 tonne d.m. ha^{-1} (1 + 0.40) ● 0.47 tonne C (tonne d.m.)$^{-1}$ ● 0.3
= 9.87 tonnes C yr^{-1} (Equation 2.14)

Annual decrease in carbon stocks due to biomass losses (ΔC_L),

ΔC_L = 141.00 tonnes C yr^{-1} + 65.80 tonnes C yr^{-1} + 9.87 tonnes C yr^{-1}
= 216.67 tonnes C yr^{-1} (Equation 2.11)

Annual change in carbon stocks in biomass (ΔC_B)

Using Chapter 2, Equation 2.7 ($\Delta C_B = (\Delta C_G - \Delta C_L)$),

ΔC_B = 2,632 tonnes C yr^{-1} – 216.67 tonnes C yr^{-1} = 2,415.33 tonnes C yr^{-1} (Equation 2.7)

4.3.1.5 UNCERTAINTY ASSESSMENT

The emission factors required for estimating carbon stock changes for *Land Converted to Forest Land* are nearly identical to those required for *Forest Land Remaining Forest Land*, but refer to lands converted to forests within 20 years of the inventory year (default period of conversion). The discussion on uncertainty for *Forest Land Remaining Forest Land* also applies here. The uncertainty involved in the estimation of biomass stocks on land before and after conversion is likely to be high. This uncertainty can be reduced by conducting sample field studies in dominant land-use categories subjected to conversion to Forest Land. The uncertainty is likely to be low for the wood removal (industrial round wood), since national statistics are likely to be maintained on commercial harvests, although sometimes it may be difficult to separate commercial harvests due to deforestation from those that come from *Forest Land Remaining Forest Land*. However, the uncertainty is likely to be high for fuelwood removal and gathering and biomass loss due to disturbance. The uncertainty involved for commercial and traditional methods should be reduced by conducting sample surveys in different socio-economic and climatic regions.

The critical activity data required for estimating carbon stock changes include the area of land converted and loss rates of biomass during the initial conversion and thereafter. The level of uncertainty for area under intensive and extensive plantations is likely to be low since most countries maintain records of the area afforested and reforested. The uncertainty should be reduced by developing a land-use change matrix of *Forest Land Remaining Forest Land* and for different categories of *Land Converted to Forest Land*, based on remote sensing or other monitoring techniques. A combination of remote sensing and ground surveys could have an uncertainty as low as 10-15%.

4.3.2 Dead organic matter

In this section, changes in carbon stock in dead organic matter pools are discussed for the land-use category *Land Converted to Forest Land*. Cropland, Grassland, Settlements, and other land-use categories can be potentially converted to Forest Land through planting or natural regeneration. It is likely that most non-forest land will not have significant dead wood or litter carbon pools. Accordingly, the Tier 1 assumption is that carbon stocks in dead wood and litter pools in non-forest land are zero, and that carbon in dead organic matter pools increases linearly to the value of mature forests over a specified time period (default = 20 years). The Tier 1 assumption for the conversion of unmanaged to managed Forest Land is that the dead organic matter carbon stocks in unmanaged forests are similar to those of managed forests and that no carbon stock changes need to be reported. In reality, other things being equal, dead organic matter carbon stocks in unmanaged forests are higher than those in managed forests because harvest removes woody biomass that would otherwise contribute to long-term dynamics of DOM pools (Kurz *et al.*, 1998) and it is *good practice* that countries with high rates of conversion of unmanaged to managed forests use higher Tier methods to estimate the resulting changes in DOM carbon stocks.

Methods to estimate emissions and removals of carbon in dead organic matter pools following conversion of land to Forest Land require estimates of the carbon stocks just prior to and just following the conversion, and estimates of the areas of lands converted during the inventory period. Some of the non-forest land-use categories, such as Wetlands, Settlements, Cropland and Grassland can have significant carbon stock in the DOM pools. It is *good practice* to assess whether the assumption of zero DOM pool sizes is justified for lands converted to Forest Land. Higher Tier methods can specify the initial DOM pool sizes (e.g., in some land-use categories dead wood and litter pools are non-zero) and quantify the length of the transition period (default = 20 years) during which DOM pools are changing as a result of a transition to Forest Land.

4.3.2.1 CHOICE OF METHOD

The general methods for estimating changes in carbon stock in dead organic matter pools have been described in Chapter 2, Section 2.3.2. The decision tree in Figure 1.3 in Chapter 1 provides guidance in the selection of the appropriate tier level for the implementation of estimation procedures. Dead wood and litter carbon stock estimates often differ significantly depending on previous land use, forest type, and regeneration type.

Tier 1

For *Land Converted to Forest Land*, the Tier 1 assumption is that dead wood and litter pools increase linearly from zero (in the non-forest land-use category) to the default values for the climate region over a period of T years (the current default is 20 years for both litter and dead wood carbon pools). Human activities such as fuelwood collection and some silvicultural practices such as frequent thinnings can greatly affect the rate of carbon accumulation in dead wood and litter pools. It is *good practice* to assess whether the default pool sizes and the assumed transitions periods are reasonable given a country's climatic and management regimes. The 20-year default period is appropriate for litter pools but likely too short for dead wood pools, particularly in colder regions with slow growing vegetation. If the time required to accumulate DOM pools is longer than the default period, then the Tier 1 assumptions may overestimate the rates of carbon accumulation. Where the area involved in land-use conversion to forests is large, it is *good practice* to develop national estimates of the rates of litter and dead wood carbon accumulation in lands converted to Forest Land.

Tiers 2 and 3

Changes in carbon stock in dead wood and litter pools under a Tier 2 or Tier 3 can be estimated using the two methods outlined in Chapter 2 (Equations 2.18 and 2.19 in Chapter 2). It is *good practice* to stratify areas converted to Forest Land according to the prior land use, the methods used during the conversion (e.g., site preparation, treatment of residual biomass), and the productivity and characteristics of the forest that is regrowing. All of these factors influence the magnitude and rate of change of carbon stock in the DOM pools on *Land Converted to Forest Land*.

Countries using higher Tier methods are also encouraged to select more appropriate transition periods for litter and dead wood carbon stocks. Litter pools can stabilize relatively quickly as inputs balance outputs. Dead wood pools generally require much longer transition periods from non-forest to forest conditions. Moreover, both litter and dead wood carbon stock sizes are affected by many factors and countries using higher Tiers are encouraged to select DOM stock values at maturity that adequately reflect national circumstances. Countries using Tier 3 modeling approaches will obtain estimates of dead organic matter stocks based on the simulated balance of input and losses.

4.3.2.2 CHOICE OF EMISSION/REMOVAL FACTORS

Tier 1

Countries using a Tier 1 method require data on the default dead wood and litter carbon stocks in the six land-use categories in different climatic regions, as defined in Table 3.1, Chapter 3. The Tier 1 assumption is that carbon stocks in litter and dead wood pools in all non-forest land-use categories are zero. For lands converted to Forest Land, the carbon stocks in dead wood and litter pools are assumed to increase linearly over the transition period T (default is 20 years for both litter and dead wood C stocks). Thus, the annual rate of increase is estimated as the ratio between the difference in carbon stocks in the DOM pools in the non-forest and forest categories, and the number of years in the transition period T.

Tiers 2 and 3

The higher Tier methods described in Chapter 4, Section 4.2 *Forest Land Remaining Forest Land* are equally applicable to *Land Converted to Forest Land*. Additional emission and removal factors are required where the impacts of the land-use conversion practices (e.g., site preparation and slash burning) are to be estimated. Additional requirements may arise if the assumption that carbon stocks in dead wood and litter pools of non-forest land-use categories are zero cannot be justified, such as in some agro-forestry systems, in settlements with substantial forest cover, and in other circumstances. This may pose special challenges because forest inventories typically do not include such areas and other data sources need to be identified or measurement programs implemented.

4.3.2.3 CHOICE OF ACTIVITY DATA

The Tier 1 method requires activity data on the annual rate of conversion to Forest Land. Activity data should be consistent with those used for estimating changes in carbon stock in biomass on *Land Converted to Forest Land*, according to the general principles set out in Chapter 3. Activity data can be obtained from national statistics, from forest management agencies, conservation agencies, municipalities, survey and mapping agencies. Where reporting programs are used, it is *good practice* to implement verification procedures and cross-checks to ensure complete and consistent representation of *Land Converted to Forest Land*, to avoid omissions or double counting. Data should be disaggregated according to the general climatic categories and forest types.

Inventories using higher Tiers will require more comprehensive information on the establishment of new forests, with refined soil classes, climate, and spatial and temporal resolution.

All changes in dead organic matter pools occurring over the number of years (T) selected as the transition period should be included. Lands where the transitions occurred more than T years ago are transferred to and reported under the category *Forest Land Remaining Forest Land*.

4.3.2.4 CALCULATION STEPS FOR TIER 1

The following summarizes steps for estimating change in carbon stocks in dead organic matter using the default methods

Step 1: Estimate area converted to Forest Land (during the period 20 years prior to the year of inventory) from other land-use categories such as Cropland, Grassland and Settlements. Refer to Chapter 3 for detailed approaches for estimating *Land Converted to Forest Land*.

Step 2: The Tier 1 assumption is that dead organic matter (dead wood and litter) carbon stocks on non-forest land are zero. If national data on dead wood and litter carbon stocks in non-forest land are available, disaggregate the area converted to Forest Land according to the land-use category of origin, e.g., Grassland, Cropland, etc., using the same categories for which dead organic matter estimates are available. Default values for litter carbon stocks in Forest Land are provided in Table 2.2. Statistically valid, regional default estimates for dead wood carbon stocks in forests are not available.

Step 3: Estimate the average annual increment of dead organic matter stocks, separately for dead wood and litter, by dividing the difference in pre- and post-conversion carbon stocks by the time period of transition (Equation 2.23 in Chapter 2). The default Tier 1 assumption is that non-forest dead organic matter carbon stocks are zero and that the period of transition is 20 years.

Step 4: Estimate the annual change in carbon stock in dead organic matter on *Land Converted to Forest Land* by multiplying the average annual increment (Step 3) by the area of lands converted to Forest Land over the past 20 (default) years.

4.3.2.5 UNCERTAINTY ASSESSMENT

In general, the magnitude of uncertainty in dead organic matter pools is larger than the uncertainty in biomass estimates because much less data are typically available for DOM pools compared to biomass pools. Uncertainties in area estimates made using the approaches suggested in Chapter 3 are indicated in Table 3.7 and uncertainties in assessing dead organic matter carbon stock changes may be several times larger than the uncertainty of biomass stock change estimates using default coefficients.

Although relatively few estimates of uncertainty, in changes in carbon stock in DOM pools, are available in the literature or elsewhere, several sources of uncertainty can be identified for the estimates of changes in carbon stock in dead organic matter pools on *Land Converted to Forest Land*. First, the assumption that carbon stocks in DOM are zero in non-forest land is not always justified. Underestimating the true initial DOM stock size will lead to overestimates of the true accumulation rates. Second, the default values for litter and dead wood carbon stock sizes are likely to be biased by being based upon estimates from land that was Forest Land for a long period of time. Thus the stock sizes at the end of the transition period may be overestimated, again, leading to overestimates of the accumulation rates. Third, the default transition period may be too long for litter carbon stocks, leading to underestimates of the true accumulation rates. For the dead wood pool, however, the current default assumption of a 20-year transition period is likely to be too short. Thus, the rate of carbon accumulation in the dead wood pool may be overestimated.

4.3.3 Soil carbon

Land conversions on mineral soils generally either maintain similar levels of C storage or create conditions that increase soil C stocks, particularly if the land was previously managed for annual crop production (Post and Kwon, 2000). However, under certain circumstances, Grassland conversion to Forest Land has been shown to cause small C losses in mineral soils for several decades following conversion (Davis and Condron, 2002; Paul *et al.*, 2002). Emissions of C from organic soils will vary depending on the previous use and level of drainage. Specifically, conversion from Cropland will tend to decrease emissions; conversions from Grassland will likely maintain similar emission rates; while conversion from Wetlands often increases C emissions.

General information and guidelines on estimating changes soil C stocks are found in Section 2.3.3 in Chapter 2 (including equations), and need to be read before proceeding with guidelines dealing with forest soil C stocks. The total change in soil C stocks for *Land Converted to Forest Land* is computed using Equation 2.24 (Chapter 2), which combines the change in soil organic C stocks for mineral soils and organic soils; and carbon stock changes for inorganic soil C pools (Tier 3 only). This section provides specific guidance for estimating soil organic C stock changes; see Section 2.3.3.1 (Chapter 2) for general discussion on soil inorganic C (no additional information is provided in the Forest Land discussion below).

To account for changes in soil C stocks associated with *Land Converted to Forest Land*, countries need to have, at a minimum, estimates of the areas of *Land Converted to Forest Land* during the inventory time period, stratified by climate region and soil type. If land-use and management data are limited, Approach 1 activity data can be used as a starting point, along with knowledge of country experts of the approximate distribution of land-use types being converted. If previous lands uses and conversions for *Land Converted to Forest Land* are unknown, SOC stocks changes can still be computed using the methods provided in *Forest Land Remaining Forest Land*, but the land base will likely be different for forests in the current year relative to the initial year in the inventory. It is critical, however, that the total land area across all land-use sectors be equal over the inventory time period (e.g., if 5 Million ha is converted from Cropland and Grassland to Forest Land during the inventory time period, then Forest Land will have an additional 5 Million ha in the last year of the inventory, while Cropland and Grassland will have a corresponding loss of 5 Million ha in the last year), and the total change will be estimated when summing SOC stocks across all land uses. *Land Converted to Forest Land* is stratified according to climate regions and major soil types, which could either be based on default or country-specific classifications. This can be accomplished with overlays of climate and soil maps, coupled with spatially-explicit data on the location of land conversions.

Inventories can be developed using Tier 1, 2 or 3 approaches, with each successive Tier requiring more detail and resources than the previous. It is possible that countries will use different tiers to prepare estimates for the separate components in this source category (i.e., soil organic C stocks changes in mineral soils and organic soils; and stock changes associated with soil inorganic C pools).

4.3.3.1 CHOICE OF METHOD

Inventories can be developed using Tier 1, 2 or 3 approaches and countries may choose different tiers for mineral and organic soils. Decision trees are provided for mineral (Figure 2.4) and organic soils (Figure 2.5) in Section 2.3.3.1 (Chapter 2) to assist inventory compilers with selection of the appropriate tier for their soil C inventory.

Mineral soils

Tier 1

Change in soil organic C stocks can be estimated for mineral soils with land-use conversion to Forest Land using Equation 2.25 (Chapter 2). For Tier 1, the initial (pre-conversion) soil organic C stock ($SOC_{(0-T)}$) and C stock in the last year of the inventory time period (SOC_0) are determined from the common set of reference soil organic C stocks (SOC_{REF}) and default stock change factors (F_{LU}, F_{MG}, F_I) as appropriate for describing land use and management both pre- and post-conversion. Note that area of exposed bedrock in Forest Land or the previous land use are not included in the soil C stock calculation (assume a stock of 0). Annual rates of stock changes are calculated as the difference in stocks (over time) divided by the time dependence (D) of the stock change factors (default is 20 years).

Tier 2

The Tier 2 approach for mineral soils also uses Equation 2.25 (Chapter 2), but involves country or region-specific reference C stocks and/or stock change factors and possibly more disaggregated land-use activity and environmental data.

Tier 3

Tier 3 approaches will involve more detailed and country-specific models and/or measurement-based approaches along with highly disaggregated land-use and management data. It is *good practice* that Tier 3 approaches estimating soil C change from land-use conversions to Forest Land, employ models, monitoring networks and/or data sets that are capable of representing transitions over time from other land uses, including Grassland, Cropland, and possibly Settlements or other land uses. It is important that models be evaluated with independent observations from country or region-specific field locations that are representative of the interactions of climate, soil and forest type/management on post-conversion change in soil C stocks.

Organic soils

Tier 1 and Tier 2

Land Converted to Forest Land on organic soils within the inventory time period is treated the same as *Forest Land Remaining Forest Land* on organic soils. C losses for the newly converted Forest Land are computed using Equation 2.26 (Chapter 2) if the soils are drained. Additional guidance on the Tiers 1 and 2 approaches are given in Section 4.3.3.1.

Tier 3

Similar to mineral soils, a Tier 3 approach will involve country-specific models and/or measurement-based approaches along with highly disaggregated land-use and management data (see mineral soils above for additional discussion).

4.3.3.2 CHOICE OF STOCK CHANGE AND EMISSION FACTORS

Mineral soils

Tier 1

For native unmanaged land, as well as for managed Forest Land, Settlements and nominally managed Grassland with low disturbance regimes, soil C stocks are assumed equal to the reference values (i.e., land use, disturbance (forests only), management and input factors equal 1), but it will be necessary to apply the appropriate stock change factors to represent other systems which may be converted to Forest Land, such as improved and degraded Grassland, as well as all Cropland systems. See the appropriate land-use section for default stock change factors (Forest Land in 4.2.3.2, Cropland in Section 5.2.3.2, Grassland in 6.2.3.2, Settlements in 8.2.3.2, and Other Land in 9.3.3.2). Default reference C stocks are found in Table 2.3 (Chapter 2).

Tier 2

Estimation of country-specific stock change factors is probably the most important development associated with the Tier 2 approach. Differences in soil organic C stocks among land uses are computed relative to a reference condition. If default reference C stocks are used, the reference condition is native vegetation that is neither degraded nor improved through land-use and management practices. Stock change factors for land-use conversion to native forests will be equal to 1 if the forest represents the reference condition. However, stock change factors will need to be derived for *Land Converted to Forest Land* that do not represent the reference condition, accounting for the influence of disturbance (F_D), input (F_I) and management (F_{MG}), which are then used to further refine the C stocks of the new forest system. See the appropriate section for specific information regarding the derivation of stock change factors for other land-use sectors (Cropland in 5.2.3.2, Grassland in Section 6.2.3.2, Settlements in 8.2.3.2, and Other Land in 9.3.3.2).

Reference C stocks can also be derived from country-specific data in a Tier 2 approach. However, reference values should be consistent across the land uses (i.e., Forest Land, Cropland, Grassland, Settlements, Other Land), and thus must be coordinated among the various teams conducting soil C inventories for AFOLU.

Tier 3

Constant stock change rate factors *per se* are less likely to be estimated in favor of variable rates that more accurately capture land-use and management effects. See Section 2.3.3.1 (Chapter 2) for further discussion.

Organic soils

Tier 1 and Tier 2

Land Converted to Forest Land on organic soils within the inventory time period is treated the same as *Forest Land Remaining Forest Land* on organic soils, i.e., they have a constant emission factor applied to them, based on climate regime. Tier 1 emission factors are given in Table 4.6 (Section 4.5), while Tier 2 emission factors are derived from country or region-specific data.

Tier 3

Constant emission rate factors *per se* are less likely to be estimated in favor of variable rates that more accurately capture land-use and management effects. See Section 2.3.3.1 in Chapter 2 for further discussion.

4.3.3.3 CHOICE OF ACTIVITY DATA

Mineral soils

Tier 1 and Tier 2

For purposes of estimating soil carbon stock change, area estimates of *Land Converted to Forest Land* should be stratified according to major climate regions and soil types. This can be based on overlays with suitable climate and soil maps and spatially-explicit data of the location of land conversions. Detailed descriptions of the default climate and soil classification schemes are provided in Chapter 3. Specific information is provided in the each of the land-use sections regarding treatment of land-use/management activity data (Forest Land in Section 4.2.3.3, Cropland in 5.2.3.3, Grassland in 6.2.3.3, Settlements in 8.2.3.3, and Other Land in 9.3.3.3).

One critical issue in evaluating the impact of *Land Converted to Forest Land* on soil organic C stocks is the type of land-use and management activity data. Activity data gathered using Approach 2 or 3 (see Chapter 3 for discussion about Approaches) provide the underlying basis for determining the previous land use for *Land Converted to Forest Land*. In contrast, aggregate data (Approach 1, Chapter 3) only provide the total amount of area in each land use and do not form a basis for determining specific transitions. Therefore, the previous land use before conversion to Forest Land will be unknown. This is not problematic using Tier 1 or 2 methods because the calculation is not dynamic and assumes a step change from one equilibrium state to another. With aggregate data (Approach 1), changes in soil organic C stocks may be computed separately for each land-use sector and then combined to obtain the total stock change. Some of the stock changes will result from less or more land area in a particular sector, but such changes in the land base will be counter-balanced by a concomitant increase or decrease in land area for another sector. Using this approach, it will be necessary for coordination among each sector to ensure the total land base is remaining constant over time, given that some land area will be lost and gained within individual sectors during each inventory year due to land-use change.

Tier 3

For application of dynamic models and/or a direct measurement-based inventory in Tier 3, similar or more detailed data on the combinations of climate, soil, topographic and management data are needed, relative to Tier 1 or 2 method, but the exact requirements will be dependent on the model or measurement design.

Organic soils

Tier 1 and Tier 2

Land Converted to Forest Land on organic soils within the inventory time period is treated the same as *Forest Land Remaining Forest Land* on organic soils; see Section 4.2.3.3.

Tier 3

Similar to mineral soils, Tier 3 approaches will likely require more detailed data on the combinations of climate, soil, topographic and management data, relative to Tier 1 or 2 methods, but the exact requirements will be dependent on the model or measurement design.

4.3.3.4 CALCULATION STEPS FOR TIER 1

Mineral soils

The steps for estimating SOC_0 and $SOC_{(0-T)}$ and net soil C stock change per ha of *Land Converted to Forest Land* are as follows:

Step 1: Determine the land-use and management by mineral soil types and climate regions for land at the beginning of the inventory period, which can vary depending on the time step of the activity data (0-T; e.g., 5, 10 or 20 years ago).

Step 2: Select the native reference C stock value (SOC_{REF}), based on climate and soil type from Table 2.3, for each area of land being inventoried. The reference C stocks are the same for all land-use categories to ensure that erroneous changes in the C stocks are not computed due to differences in reference stock values among sectors.

Step 3: Select the land-use factor (F_{LU}), management factor (F_{MG}) and C input levels (F_I) representing the land-use and management system present before conversion to forest. Values for F_{LU}, F_{MG} and F_I are given in the respective section for the land-use sector (Cropland in Chapter 5, and Grassland in Chapter 6).

Step 4: Multiply these values by the reference soil C stock to estimate of 'initial' soil organic C stock ($SOC_{(0-T)}$) for the inventory time period.

Step 5: Estimate SOC_0 by repeating step 1 to 4 using the same native reference C stock (SOC_{REF}), but with land-use, management and input factors that represent conditions in the last (year 0) inventory year. For Tier 1, all stock change factors are assumed equal to 1 for Forest Land (although for Tier 2, different values for these factors under newly converted Forest Land should be used, based on country-specific data).

Step 6: Estimate the average annual change in soil C stock for the area over the inventory time period, $\Delta C_{CC_{Mineral}}$, (see Equation 2.25 in Chapter 2).

Step 7: Repeat Steps 1 to 6 if there are additional inventory time periods (e.g., 1990 to 2000, 2001 to 2010, etc.).

A numerical example is given below for afforestation of cropland soil.

Example: An area of 100,000 ha of cropland was planted to forest. The soil type is an Ultisol in a tropical moist climate, which has a native reference stock, SOC_{Ref} (0-30 cm), of 47 tonnes C ha^{-1} (Table 2.3). The previous land use was annual row crops, with conventional tillage, no fertilization and where crop residues are removed, so that the soil carbon stock at the beginning of the inventory time period (in this example, 5 yrs earlier in 1995) was ($SOC_{Ref} \bullet F_{LU} \bullet F_{MG} \bullet F_I$) = 47 tonnes C ha^{-1} ● 0.48 ● 1 ● 0.92 = 20.8 tonnes C ha^{-1} (see Table 5.5, Chapter 5, for stock change factor for cropland). Under Tier 1, managed forest is assumed to have the same soil C stock as the reference condition (i.e. all stock change factors are equal to 1). Thus, the average annual change in soil C stock for the area over the inventory time period is estimated as (47 tonnes C ha^{-1} – 20.8 tonnes C ha^{-1}) / 20 yrs = 1.3 tonnes C ha^{-1} yr^{-1}. For the area reforested there is an increase of 131,000 tonnes C yr^{-1}. (Note: 20 years is the time dependence of the stock change factor, i.e., factor represents annual rate of change over 20 years)

Organic soils

Calculation steps are the same as described in Section 4.2.3.4 above.

4.3.3.5 UNCERTAINTY ASSESSMENT

Uncertainty analyses for *Land Converted to Forest Land* are fundamentally the same as *Forest Land Remaining Forest Land*. Three broad sources of uncertainty exists: 1) uncertainties in land-use and management activity and environmental data; 2) uncertainties in reference soil C stocks if using Tier 1 or 2 approaches (mineral soils only); and 3) uncertainties in the stock change/emission factors for Tier 1 or 2 approaches, model structure/parameter error for Tier 3 model-based approaches, or measurement error/sampling variability associated with a Tier 3 measurement-based inventories. See the uncertainty section in *Forest Land Remaining Forest Land* for additional discussion (Section 4.2.3.5).

4.3.4 Non-CO_2 greenhouse gas emissions from biomass burning

The guidance to estimate non-CO_2 greenhouse gas emissions from biomass burning or fire on *Land Converted to Forest Land* is discussed in Section 4.2.4. General guidance is also provided in Chapter 2, Section 2.4.

Guidance for estimating N_2O emissions from forest soils is provided in Chapter 11.

4.4 COMPLETENESS, TIME SERIES, QA/QC, AND REPORTING AND DOCUMENTATION

4.4.1 Completeness

Completeness is a requirement for greenhouse gas inventories, and it is *good practice* to address all forest carbon gains and losses including harvested wood products. Greenhouse gas inventory for Forest Land should include all land under Forest Land and all land-use categories converted to Forest Land. For completeness, it is *good practice* to include all the carbon pools and non-CO_2 greenhouse gases. Chapter 11, Section 11.2 provides advice on N_2O emission from drained organic soils. The forest area used for calculation for different carbon pools should be the same. Emissions from organic soils and emissions or removals attributed to land-use change on mineral soils should be estimated. Higher tiers include additional impacts of management and natural disturbance regimes on mineral soil C stocks or emissions from organic soils, by incorporating country-specific information. A complete accounting of emissions and removals of CO_2 associated with *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*, or from the effects of biomass burning in managed (and unmanaged, when applicable) Forest Land is necessary. It is *good practice* that all losses from biomass carbon pools that result in transfers to dead organic matter pools are first accounted as changes to biomass carbon stocks. It is *good practice* that countries using Tier 1 estimation methods do not account for carbon emissions from DOM pools during fire or other disturbances because all DOM pool additions are assumed to have been released in the year of addition. Consequently, Tier 1 methods also preclude the accounting of DOM pool increases following natural disturbances.

4.4.2 Developing a consistent times series

It is *good practice* to develop a consistent time series of inventories of anthropogenic emissions and removals of greenhouse gases for all AFOLU categories using the guidance in Volume 1, Chapter 5. Because activity data may only be available every few years, achieving time series consistency may require interpolation or extrapolation from longer time series or trends, possibly using information on changes in forest policies and incentive schemes where drivers are needed.

Consistent accounting over time of land areas included in biomass and soil C emissions and removals inventory requires that activity data for all land-use categories be stratified by a common definition of climate and soil types. Thus, areas subject to land-use change will not be lost or double-counted due to accounting errors resulting from inconsistent definitions for climate and forest types and soil strata within other land-use categories. To estimate emissions and removals of greenhouse gases, whether by Tier 1, 2 or 3, ideally the same protocol (sampling strategy, method, etc.) should be applied consistently every year in the time series, at the same level of disaggregation, and, where country-specific data are used, it is *good practice* to use the same coefficients and methods for equivalent calculations at all points in the time series.

However, as inventory capacity and information and data sources availability improve over time, new sources and sink categories should be included, or moving to higher tier, the methods and data used to calculate estimates can be updated and refined. In these circumstances, consistent recalculation of historical emissions and removals is a *good practice*. In some cases, if some historical data are missing, then they may need to be estimated from other data sources. For example, the *2006 IPCC Guidelines* now require estimation of emissions of CO_2 and non-CO_2 from forests, which were not included under the 1966 Guidelines (refer to Chapter 1). The level of knowledge and detail of emission estimates for soils will also improve over time, necessitating recalculation of historic inventories to take account of new data and/or methods. Often, changes in forest soils cannot be detected at time scale finer than a decade; it will be necessary to interpolate between measurements in order to obtain annual estimates of emissions and removals. Changes in forest types, practices and disturbances need to be tracked for long time periods determined for example by soil carbon dynamics or forest rotation periods where these are specifically tracked in detailed model calculations.

Where countries use Tier 1 methods, estimates of DOM stock changes are only provided in the case of land-use change to or from Forest Land. It is *good practice* to recalculate the entire time series of data if either the default values for litter and dead wood carbon pools or the lengths of the transition periods are changed. It is also *good practice* to recalculate the entire time series of estimates if revisions to activity data, such as the rate of land-use change, have occurred. As more ground plot and other sample data on dead wood and litter carbon stocks become available in the future, countries are likely to improve the models used in higher Tier estimation procedures. It is *good practice* to use the same model parameter values (such as litterfall rates, decay rates, disturbance impacts) for the entire time series and to recalculate the entire time series if one or more of the model parameters have changed. Failure to do so may result in artificial sources or sinks, for example as a result of decay rate modifications.

4.4.3 Quality Assurance and Quality Control

The characteristics of the greenhouse gas inventory estimate of Forest Land can have different level of precision, accuracy and levels of bias. Moreover, the estimates are influenced by the quality and consistency of data and information available in a country, as well as gaps in knowledge. In addition, depending on the tier level used by a country, estimates can be affected by different sources of errors, such as sampling errors, assessment errors, classification errors in remote sensing imagery, and modeling errors that can propagate to the total estimation.

It is *good practice* to execute quality control checks through Quality Assurance (QA) and Quality Control (QC) procedures, and expert review of the emission estimation procedures. Additional quality control checks as outlined in Tier 2 procedures in Volume 1, Chapter 6, and quality assurance procedures may also be applicable, particularly if higher Tier methods are used to estimate emissions. It is *good practice* to supplement the general QA/QC related to data processing, handling, and reporting and documenting, with source-specific category procedures. QA/QC procedures should be documented separately for *Forest Land Remaining Forest Land* and for *Land Converted to Forest Land*.

Agencies which collect data are responsible for reviewing the data collection methods, checking the data to ensure that they are collected and aggregated or disaggregated correctly, and cross-checking the data with other data sources and with previous years to ensure that the data are realistic, complete and consistent over time. FAO data needs to cross checked with other national sources for accuracy and consistency. The basis for the estimates (e.g., statistical surveys or ′desk estimates′) must be reviewed and described as part of the QC process. Documentation is a crucial component of the review process because it enables reviewers to identify inaccuracy, gaps and suggest improvements. Documentation and transparency in reporting is most important for highly uncertain source categories and to give reasons for divergences between country-specific factors and default or factors used by other countries. Countries with similar (ecological) conditions are encouraged to collaborate in the refinements of methods, emissions factors and uncertainty assessment.

Activity data check: The inventory agency should, where possible, check data comprising of all managed land areas, using independent sources and compare them. For many countries, FAO database could be the main source and in such a case the data must be cross-checked with other sources. Any differences in area records should be documented for the purposes of review. Activity data area totals should be summed across all land-use categories to ensure that total area involved in the inventory and its stratification across climate and soil types remains constant over time. This ensures that Forest Land areas are neither ‘created’ nor ‘lost’ over time, which would result in major errors in the inventory. When using country-specific data (such as data on standing biomass and biomass growth rates, carbon fraction in above-ground biomass and biomass expansion factors, and synthetic fertilizer consumption estimates), the inventory agency should compare them to the IPCC default values or the Emission Factor Database (EFDB) and note the differences.

The country-specific parameters should be of high quality, preferably peer-reviewed experimental data, adequately described, and documented. The agencies performing the inventory are encouraged to ensure that *good practice* methods have been used and the results peer-reviewed. Assessments on test areas can be used to validate the reliability of figures reported.

Internal and external review: The review processes as set out in Volume 1, Chapter 8 should be undertaken by experts preferably not directly involved in the inventory development. The inventory agency should utilize experts in greenhouse gas removals and emissions in AFOLU to conduct expert peer-review of the methods and data used. Given the complexity and uniqueness of the parameters used in calculating country-specific factors for some categories, selected specialists in the field should be involved in such reviews. If soil factors are based on direct measurements, the inventory agency should review the measurements to ensure that they are representative of the actual range of environmental and soil management conditions, and inter-annual climatic variability, and were developed according to recognized standards. The QA/QC protocol in effect at the sites should also be reviewed and the resulting estimates compared between sites and with default-based estimates.

It is *good practice* that countries using Tier 1 methods review and, if necessary, revise the default assumptions for carbon stocks in litter and dead wood pools which are required for estimation of carbon losses following deforestation. Countries that use higher tier methods are encouraged to calculate intermediate indicators of the models used to develop estimates of DOM stock changes. For example, QA/QC procedures could compare estimates of stock sizes, litterfall inputs, decay losses, etc., against literature values and other peer-reviewed publications. Where possible, it is also *good practice* to compare model estimates against field measurements and other data sources. One QA/QC check that is easily implemented in modelling systems is to calculate an internal mass balance to ensure that the model neither produces nor loses carbon that is not reported as a source or a sink. For example, conservation of mass requirements include that losses from biomass pools are either accounted as input to the DOM pools, are transferred outside of the forest ecosystem or released to the atmosphere (in case of fire). Further, harvest data can be used to check transfer (stop loss) estimates produced by models. A second QA/QC procedure that can be implemented in countries that use higher Tier estimation methods is to establish upper and lower bounds for DOM pools stratified by regions, forest type, and soil type (organic vs. mineral soils). Any values, reported in inventories or estimated by models that fall outside these bounds can be investigated further.

4.4.4 Reporting and Documentation

General requirements for reporting and documentation are set out in Volume 1, Chapter 8. In general it is *good practice* to archive and document all data and information (such as figures, statistics, sources of assumptions, modeling approaches, uncertainty analyses, validation studies, inventory methods, research experiments, measurements arising from field site studies, associated protocols, and other basic data) applied to produce the national emissions/removals inventory. Elaborations on carbon pool definitions should be reported, and definitions relevant to determining the extent of the managed land included in the inventory, together with evidence that these definitions have been applied consistently over time provided.

Documentation is needed for demonstrating completeness, consistency of time series data and methods for interpolating between samples, methods and years, and for recalculating and avoidance of double counting as well as for performing QA/QC. As inventory compilers decide to progress through higher tier levels, whose calculation methods and data are not described in the present volume or characterized by more disaggregated approaches, additional documentation is required to support the use of more advanced and accurate methodologies, country-defined parameters, and high resolution maps and data sets. However, at all tier levels, explanation is needed for decisions regarding choice of methodology, coefficients, and activity data. The aim is to facilitate reconstruction of estimates by independent third parties, but it may prove impractical to include all documentation necessary in national inventory report. The inventory should therefore include summaries of approaches and methods used, and references to source of data such that the reported emissions estimates are transparent and steps adopted in their calculation may be retraced.

Emission factors: Sources of the emission or removal factors that were used (specific IPCC default values or otherwise) have to be quoted. If country- or region- or forest type-specific emission factors were used, and if new methods (other than the default IPCC methods) were used, the scientific basis of these emission factors and methods should be completely described and documented. This includes defining the input parameters and describing the process by which these emission factors and methods are derived, as well as describing sources and magnitudes of uncertainties. Inventory agencies using country-specific emission factors should provide information on the basis of selection of a different factor, describe how it was derived, compare it to other published emission factors, explain any significant differences, and attempt to place bounds on uncertainty.

Activity data: Sources of all activity data, such as areas, soil types and characteristics and vegetation covers, used in the calculations should be provided (i.e., complete citations for statistical databases from which data were drawn). Reference to the metadata for the databases are useful, including information on dates and frequency of data collection, sampling procedures, analytical procedures used to obtain soil characteristics and minimum detectable change in organic carbon, and estimates of accuracy and precision. When activity data were not obtained directly from databases, the information and assumptions that were used to derive the activity data should be provided, as well as estimates of the uncertainty associated to the derived activity data. This applies in particular when scaling up procedures are used to derive large-scale estimates; in these cases the statistical procedures should be described along with the associated uncertainty.

Results of model simulations: If inventory agencies used data output from models in their estimation procedures, the rationale for model selection and use should be provided. It is a *good practice* to provide complete citations of peer-reviewed publications in which the model is described, and modelling results are interpreted and validated. Detailed information should be provided to enable reviewers to assess the model's validity, including the general modeling approach, key model assumptions, input and output data, parameter values and parameterization procedures, confidence intervals of model outputs, and the outcome of any sensitivity analysis conducted on the output. In addition, computer source code for models should be permanently archived for future reference, along with all the input and output files.

Analysis of emissions: Significant fluctuations in emissions between years should be explained. A distinction should be made between changes in activity levels and changes in emission coefficients from year to year, and the reasons for these changes documented. If different emission factors are used for different years, the reasons for this should be explained and documented.

4.5 TABLES

TABLE 4.1
CLIMATE DOMAINS (FAO, 2001), CLIMATE REGIONS (CHAPTER 3), AND ECOLOGICAL ZONES (FAO, 2001)

Climate domain		Climate region	Ecological zone		
Domain	**Domain criteria**		**Zone**	**Code**	**Zone criteria**
Tropical	all months without frost; in marine areas, temperature >18°C	Tropical wet	Tropical rain forest	TAr	wet: ≤ 3 months dry, during winter
		Tropical moist	Tropical moist deciduous forest	TAwa	mainly wet: 3-5 months dry, during winter
		Tropical dry	Tropical dry forest	TAWb	mainly dry: 5-8 months dry, during winter
			Tropical shrubland	TBSh	semi-arid: evaporation > precipitation
			Tropical desert	TBWh	arid: all months dry
		Tropical montane	Tropical mountain systems	TM	altitudes approximately >1000 m, with local variations
Sub-tropical	≥ 8 months at a temperature >10°C	Warm temperate moist	Subtropical humid forest	SCf	humid: no dry season
		Warm temperate dry	Subtropical dry forest	SCs	seasonally dry: winter rains, dry summer
			Subtropical steppe	SBSh	semi-arid: evaporation >precipitation
			Subtropical desert	SBWh	arid: all months dry
		Warm temperate moist or dry	Subtropical mountain systems	SM	altitudes approximately 800 m-1000 m
Temp-erate	4-8 months at a temperature >10°C	Cool temperate moist	Temperate oceanic forest	TeDo	oceanic climate: coldest month >0°C
			Temperate continental forest	TeDc	continental climate: coldest month <0°C
		Cool temperate dry	Temperate steppe	TeBSk	semi-arid: evaporation > precipitation
			Temperate desert	TeBWk	arid: all months dry
		Cool temperate moist or dry	Temperate mountain systems	TeM	altitudes approximately >800 m
Boreal	≤ 3 months at a temperature >10°C	Boreal moist	Boreal coniferous forest	Ba	coniferous dense forest dominant
		Boreal dry	Boreal tundra woodland	Bb	woodland and sparse forest dominant
		Boreal moist or dry	Boreal mountain systems	BM	altitudes approximately >600 m
Polar	all months <10°C	Polar moist or dry	Polar	P	all months <10°C

Climate domain: Area of relatively homogenous temperature regime, equivalent to the Köppen-Trewartha climate groups (Köppen, 1931).

Climate region: Areas of similar climate defined in Chapter 3 for reporting across different carbon pools.

Ecological zone: Area with broad, yet relatively homogeneous natural vegetation formations that are similar, but not necessarily identical, in physiognomy.

Dry month: A month in which Total Precipitation (mm) ≤ 2 x Mean Temperature (ºC).

TABLE 4.2
FOREST AND LAND COVER CLASSES

Forest or land cover class	**Definition**
Forest	Land spanning more than 0.5 hectare with trees higher than 5 meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds *in situ*. It does not include land that is predominantly under agricultural or urban land use. Forest is determined both by the presence of trees and the absence of other predominant land uses. The trees should be able to reach a minimum height of 5 meters *in situ*. Areas under reforestation that have not yet reached but are expected to reach a canopy cover of 10 percent and tree height of 5 meters are included, as are temporarily unstocked areas, resulting from human intervention or natural causes, which are expected to regenerate. Includes: areas with bamboo and palms provided that height and canopy cover criteria are met; forest roads, firebreaks and other small open areas; forest in national parks, nature reserves and other protected areas such as those of specific scientific, historical, cultural or spiritual interest; windbreaks, shelterbelts and corridors of trees with an area of more than 0.5 hectare and width of more than 20 meters; plantations primarily used for forestry or protective purposes, such as rubber-wood plantations and cork oak stands. Excludes: tree stands in agricultural production systems, for example in fruit plantations and agroforestry systems. The term also excludes trees in urban parks and gardens.
Other wooded land	Land not classified as "Forest", spanning more than 0.5 hectare; with trees higher than 5 meters and a canopy cover of 5-10 percent, or trees able to reach these thresholds *in situ*; or with a combined cover of shrubs, bushes and trees above 10 percent. It does not include land that is predominantly under agricultural or urban land use.
Other land	All land that is not classified as Forest or Other Wooded Land. Includes: agricultural land, meadows and pastures, built-up areas, barren land, etc; areas classified under the subcategory 'Other Land with tree cover'.
Other land with tree cover	Land classified as Other Land, spanning more than 0.5 hectare with a canopy cover of more than 10 percent of trees able to reach a height of 5 meters at maturity. Includes: groups of trees and scattered trees in agricultural landscapes, parks, gardens, and around buildings (provided that the area, height and canopy cover criteria are met); tree plantations established mainly for other purposes than wood, such as fruit orchards and palm plantations.

Source: FAO, 2006. Global Forest Resources Assessment 2005 – progress towards sustainable forest management. FAO Forestry Paper No. 147. Rome.

TABLE 4.3
CARBON FRACTION OF ABOVEGROUND FOREST BIOMASS

Domain	Part of tree	Carbon fraction, (CF) [tonne C (tonne d.m.)$^{-1}$]	References
Default value	All	0.47	McGroddy *et al.*, 2004
Tropical and Subtropical	All	0.47 (0.44 - 0.49)	Andreae and Merlet, 2001; Chambers *et al.*, 2001; McGroddy *et al.*, 2004; Lasco and Pulhin, 2003
	wood	0.49	Feldpausch *et al.*, 2004
	wood, tree d < 10 cm	0.46	Hughes *et al.*, 2000
	wood, tree d ≥ 10 cm	0.49	Hughes *et al.*, 2000
	foliage	0.47	Feldpausch *et al.*, 2004
	foliage, tree d < 10 cm	0.43	Hughes *et al.*, 2000
	foliage, tree d ≥ 10 cm	0.46	Hughes *et al.*, 2000
Temperate and Boreal	All	0.47 (0.47 - 0.49)	Andreae and Merlet, 2001; Gayoso *et al.*, 2002; Matthews, 1993; McGroddy *et al.*, 2004
	broad-leaved	0.48 (0.46 - 0.50)	Lamlom and Savidge, 2003
	conifers	0.51 (0.47 - 0.55)	Lamlom and Savidge, 2003

TABLE 4.4
RATIO OF BELOW-GROUND BIOMASS TO ABOVE-GROUND BIOMASS (R)

Domain	Ecological zone	Above-ground biomass	R [tonne root d.m. (tonne shoot d.m.)$^{-1}$]	References
Tropical	Tropical rainforest		0.37	Fittkau and Klinge, 1973
	Tropical moist deciduous forest	above-ground biomass <125 tonnes ha^{-1}	0.20 (0.09 - 0.25)	Mokany *et al.*, 2006
		above-ground biomass >125 tonnes ha^{-1}	0.24 (0.22 - 0.33)	Mokany *et al.*, 2006
	Tropical dry forest	above-ground biomass <20 tonnes ha^{-1}	0.56 (0.28 - 0.68)	Mokany *et al.*, 2006
		above-ground biomass >20 tonnes ha^{-1}	0.28 (0.27 - 0.28)	Mokany *et al.*, 2006
	Tropical shrubland		0.40	Poupon, 1980
	Tropical mountain systems		0.27 (0.27 - 0.28)	Singh *et al.*, 1994
Subtropical	Subtropical humid forest	above-ground biomass <125 tonnes ha^{-1}	0.20 (0.09 - 0.25)	Mokany *et al.*, 2006
		above-ground biomass >125 tonnes ha^{-1}	0.24 (0.22 - 0.33)	Mokany *et al.*, 2006
	Subtropical dry forest	above-ground biomass <20 tonnes ha^{-1}	0.56 (0.28 - 0.68)	Mokany *et al.*, 2006
		above-ground biomass >20 tonnes ha^{-1}	0.28 (0.27 - 0.28)	Mokany *et al.*, 2006
	Subtropical steppe		0.32 (0.26 - 0.71)	Mokany *et al.*, 2006
	Subtropical mountain systems		no estimate available	
Temperate	Temperate oceanic forest, Temperate continental forest, Temperate mountain systems	conifers above-ground biomass < 50 tonnes ha^{-1}	0.40 (0.21 - 1.06)	Mokany *et al.*, 2006
		conifers above-ground biomass 50-150 tonnes ha^{-1}	0.29 (0.24 - 0.50)	Mokany *et al.*, 2006
		conifers above-ground biomass > 150 tonnes ha^{-1}	0.20 (0.12 - 0.49)	Mokany *et al.*, 2006
		Quercus spp. above-ground biomass >70 tonnes ha^{-1}	0.30 (0.20 - 1.16)	Mokany *et al.*, 2006
		Eucalyptus spp. above-ground biomass < 50 tonnes ha^{-1}	0.44 (0.29 - 0.81)	Mokany *et al.*, 2006
		Eucalyptus spp. above-ground biomass 50-150 tonnes ha^{-1}	0.28 (0.15 - 0.81)	Mokany *et al.*, 2006
		Eucalyptus spp. above-ground biomass > 150 tonnes ha^{-1}	0.20 (0.10 - 0.33)	Mokany *et al.*, 2006
		other broadleaf above-ground biomass < 75 tonnes ha^{-1}	0.46 (0.12 - 0.93)	Mokany *et al.*, 2006
		other broadleaf above-ground biomass 75-150 tonnes ha^{-1}	0.23 (0.13 - 0.37)	Mokany *et al.*, 2006
		other broadleaf above-ground biomass >150 tonnes ha^{-1}	0.24 (0.17 - 0.44)	Mokany *et al.*, 2006
Boreal	Boreal coniferous forest, Boreal tundra woodland, Boreal mountain systems	above-ground biomass <75 tonnes ha^{-1}	0.39 (0.23 - 0.96)	Li *et al.*, 2003; Mokany *et al.*, 2006
		above-ground biomass >75 tonnes ha^{-1}	0.24 (0.15 - 0.37)	Li *et al.*, 2003; Mokany *et al.*, 2006

TABLE 4.5
DEFAULT BIOMASS CONVERSION AND EXPANSION FACTORS (BCEF), TONNES BIOMASS (M^3 OF WOOD VOLUME)$^{-1}$

BCEF for expansion of merchantable growing stock volume to above-ground biomass ($BCEF_S$), for conversion of net annual increment ($BCEF_I$) and for conversion of wood and fuelwood removal volume to above-ground biomass removal ($BCEF_R$)

Climatic zone	**Forest type**	**BCEF**	**Growing stock level (m^3)**			
			<20	21-50	51-100	>100
Boreal	pines	$BCEF_S$	**1.2** (0.85-1.3)	**0.68** (0.5-0.72)	**0.57** (0.52-0.65)	**0.5** (0.45-0.58)
		$BCEF_I$	0.47	0.46	0.46	0.463
		$BCEF_R$	1.33	0.75	0.63	0.55
	larch	$BCEF_S$	**1.22** (0.9-1.5)	**0.78** (0.7-0.8)	**0.77** (0.7-0.85)	**0.77** (0.7-0.85)
		$BCEF_I$	0.9	0.75	0.77	0.77
		$BCEF_R$	1.35	0.87	0.85	0.85
	firs and spruces	$BCEF_S$	**1.16** (0.8-1.5)	**0.66** (0.55-0.75)	**0.58** (0.5-0.65)	**0.53** (0.45-0.605)
		$BCEF_I$	0.55	0.47	0.47	0.464
		$BCEF_R$	1.29	0.73	0.64	0.59
	hardwoods	$BCEF_S$	**0.9** (0.7-1.2)	**0.7** (0.6-0.75)	**0.62** (0.53-0.7)	**0.55** (0.5-0.65)
		$BCEF_I$	0.65	0.54	0.52	0.505
		$BCEF_R$	1.0	0.77	0.69	0.61

TABLE 4.5 (CONTINUED)
DEFAULT BIOMASS CONVERSION AND EXPANSION FACTORS (BCEF), TONNES BIOMASS (M^3 OF WOOD VOLUME)$^{-1}$

BCEF for expansion of merchantable growing stock volume to above-ground biomass (BCEF$_S$), for conversion of net annual increment (BCEF$_I$) and for conversion of wood and fuelwood removal volume to above-ground biomass removal (BCEF$_R$)

Climatic zone	**Forest type**	**BCEF**	**Growing stock level (m^3)**				
Temperate			<20	21-40	41-100	100 -200	>200
	hardwoods	BCEF$_S$	**3.0** (0.8-4.5)	**1.7** (0.8-2.6)	**1.4** (0.7-1.9)	**1.05** (0.6-1.4)	**0.8** (0.55-1.1)
		BCEF$_I$	1.5	1.3	0.9	0.6	0.48
		BCEF$_R$	3.33	1.89	1.55	1.17	0.89
	pines	BCEF$_S$	**1.8** (0.6 -2.4)	**1.0** (0.65 -1.5)	**0.75** (0.6-1.0)	**0.7** (0.4-1.0)	**0.7** (0.4-1.0)
		BCEF$_I$	1.5	0.75	0.6	0.67	0.69
		BCEF$_R$	2.0	1.11	0.83	0.77	0.77
	other conifers	BCEF$_S$	**3.0 (**0.7-4.0)	**1.4** (0.5-2.5)	**1.0** (0.5-1.4)	**0.75** (0.4-1.2)	**0.7** (0.35-0.9)
		BCEF$_I$	1.0	0.83	0.57	0.53	0.60
		BCEF$_R$	3.33	1.55	1.11	0.83	0.77
Mediterranean, dry tropical, subtropical			<20	21-40	41-80	>80	
	hardwoods	BCEF$_S$	**5.0** (2.0-8.0)	**1.9** (1.0-2.6)	**0.8** (0.6-1.4)	**0.66** (0.4-0.9)	
		BCEF$_I$	1.5	0.5	0.55	0.66	
		BCEF$_R$	5.55	2.11	0.89	0.73	
	conifers	BCEF$_S$	**6.0** (3.0-8.0)	**1.2** (0.5-2.0)	**0.6** (0.4-0.9)	**0.55** (0.4-0.7)	
		BCEF$_I$	1.5	0.4	0.45	0.54	
		BCEF$_R$	6.67	1.33	0.67	0.61	

Table 4.5 (continued)
Default biomass conversion and expansion factors (BCEF), tonnes biomass (m^3 of wood volume)$^{-1}$

BCEF for expansion of merchantable growing stock volume to above-ground biomass ($BCEF_S$), for conversion of net annual increment ($BCEF_I$) and for conversion of wood and fuelwood removal volume to above-ground biomass removal ($BCEF_R$)

Climatic zone	Forest type	BCEF	Growing stock level (m^3)							
			<10	11-20	21-40	41-60	61-80	80-120	120-200	>200
Humid tropical	conifers	$BCEF_S$	**4.0** (3.0-6.0)	**1.75** (1.4-2.4)	**1.25** (1.0-1.5)	**1.0** (0.8-1.2)	**0.8** (0.7-1.2)	**0.76** (0.6-1.0)	**0.7** (0.6-0.9)	**0.7** (0.6-0.9)
		$BCEF_I$	2.5	0.95	0.65	0.55	0.53	0.58	0.66	0.70
		$BCEF_R$	4.44	1.94	1.39	1.11	0.89	0.84	0.77	0.77
	natural forests	$BCEF_S$	**9.0** (4.0-12.0)	**4.0** (2.5-4.5)	**2.8** (1.4-3.4)	**2.05** (1.2-2.5)	**1.7** (1.2-2.2)	**1.5** (1.0-1.8)	**1.3**(0.9-1.6)	**0.95** (0.7-1.1)
		$BCEF_I$	4.5	1.6	1.1	0.93	0.9	0.87	0.86	0.85
		$BCEF_R$	10.0	4.44	3.11	2.28	1.89	1.67	1.44	1.05

Note: Lower values of the ranges for $BCEF_S$ apply if growing stock definition includes branches, stem tops and cull trees; upper values apply if branches and tops are not part of growing stock, minimum top diameters in the definition of growing stock are large, inventoried volume falls near the lower category limit or basic wood densities are relatively high. Continuous graphs, functional forms and updates with new studies can be found at the forest- and climate- change website at: http://www.fao.org/forestry/

Average BCEF for inhomogeneous forests should be derived as far as possible as weighted averages. It is good practice to justify the factors chosen. To apply $BCEF_I$, an estimate of the current average growing stock is necessary. It can be derived from FRA 2005 at http://www.fao.org/forestry/

$BCEF_R$ values are derived by dividing $BCEF_S$ by 0.9

Sources*:* *Boreal forests*: Alexeyev V.A. and R.A. Birdseye, 1998; Fang J. and Z.M. Wang, 2001; *temperate forests*: Fang J. *et al.*, 2001; Fukuda M. *et al*., 2003; Schroeder P. *et al*., 1997; Snowdon P. *et.al*., 2000; Smith J. *et. al*., 2002; Brown S., 1999; Schoene D. and A. Schulte, 1999; Smith J. *et al.*, 2004; *Mediterranean forests*: Vayreda *et al*., 2002; Gracia *et al*., 2002; *tropical forests*: Brown S. *et al*., 1989; Brown S. and A. Lugo, 1992; Brown S., 2002; Fang J.Y., 2001.

TABLE 4.6
EMISSION FACTORS FOR DRAINED ORGANIC SOILS IN MANAGED FORESTS

Climate	Emission factors (tonnes C ha^{-1} yr^{-1})	
	Values	Ranges
Tropical	1.36	0.82 – 3.82
Temperate	0.68	0.41 – 1.91
Boreal	0.16	0.08 – 1.09

Source: *GPG-LULUCF*, Table 3.2.3

TABLE 4.7
ABOVE-GROUND BIOMASS IN FORESTS

Domain	Ecological zone	Continent	Above-ground biomass (tonnes d.m. ha^{-1})	References
Tropical	Tropical rain forest	Africa	310 (130-510)	IPCC, 2003
		North and South America	300 (120-400)	Baker *et al.*, 2004a; Hughes *et al.*, 1999
		Asia (continental)	280 (120-680)	IPCC, 2003
		Asia (insular)	350 (280-520)	IPCC, 2003
	Tropical moist deciduous forest	Africa	260 (160-430)	IPCC, 2003
		North and South America	220 (210-280)	IPCC, 2003
		Asia (continental)	180 (10-560)	IPCC, 2003
		Asia (insular)	290	IPCC, 2003
	Tropical dry forest	Africa	120 (120-130)	IPCC, 2003
		North and South America	210 (200-410)	IPCC, 2003
		Asia (continental)	130 (100-160)	IPCC, 2003
		Asia (insular)	160	IPCC, 2003
	Tropical shrubland	Africa	70 (20-200)	IPCC, 2003
		North and South America	80 (40-90)	IPCC, 2003
		Asia (continental)	60	IPCC, 2003
		Asia (insular)	70	IPCC, 2003
	Tropical mountain systems	Africa	40-190	IPCC, 2003
		North and South America	60-230	IPCC, 2003
		Asia (continental)	50-220	IPCC, 2003
		Asia (insular)	50-360	IPCC, 2003
Subtropical	Subtropical humid forest	North and South America	220 (210-280)	IPCC, 2003
		Asia (continental)	180 (10-560)	IPCC, 2003
		Asia (insular)	290	IPCC, 2003
	Subtropical dry forest	Africa	140	Sebei *et al.*, 2001
		North and South America	210 (200-410)	IPCC, 2003
		Asia (continental)	130 (100-160)	IPCC, 2003
		Asia (insular)	160	IPCC, 2003
	Subtropical steppe	Africa	70 (20-200)	IPCC, 2003
		North and South America	80 (40-90)	IPCC, 2003
		Asia (continental)	60	IPCC, 2003
		Asia (insular)	70	IPCC, 2003
	Subtropical mountain systems	Africa	50	Montès *et al.*, 2002
		North and South America	60-230	IPCC, 2003
		Asia (continental)	50-220	IPCC, 2003
		Asia (insular)	50-360	IPCC, 2003

TABLE 4.7 (CONTINUED)
ABOVE-GROUND BIOMASS IN FORESTS

Domain	Ecological zone	Continent	Above-ground biomass (tonnes d.m. ha^{-1})	References
Temperate	Temperate oceanic forest	Europe	120	-
		North America	660 (80-1200)	Hessl *et al*., 2004; Smithwick *et al*., 2002
		New Zealand	360 (210-430)	Hall *et al*., 2001
		South America	180 (90-310)	Gayoso and Schlegel, 2003; Battles *et al*., 2002
	Temperate continental forest	Asia, Europe (≤20 y)	20	IPCC, 2003
		Asia, Europe (>20 y)	120 (20-320)	IPCC, 2003
		North and South America (≤20 y)	60 (10-130)	IPCC, 2003
		North and South America (>20 y)	130 (50-200)	IPCC, 2003
	Temperate mountain systems	Asia, Europe (≤20 y)	100 (20-180)	IPCC, 2003
		Asia, Europe (>20 y)	130 (20-600)	IPCC, 2003
		North and South America (≤20 y)	50 (20-110)	IPCC, 2003
		North and South America (>20 y)	130 (40-280)	IPCC, 2003
Boreal	Boreal coniferous forest	Asia, Europe, North America	10-90	Gower *et al*., 2001
	Boreal tundra woodland	Asia, Europe, North America (≤20 y)	3-4	IPCC, 2003
		Asia, Europe, North America (>20 y)	15-20	IPCC, 2003
	Boreal mountain systems	Asia, Europe, North America (≤20 y)	12-15	IPCC, 2003
		Asia, Europe, North America (>20 y)	40-50	IPCC, 2003

TABLE 4.8
ABOVE-GROUND BIOMASS IN FOREST PLANTATIONS

Domain	Ecological zone	Continent	Above-ground biomass (tonnes d.m. ha^{-1})	References
Tropical	Tropical rain forest	Africa broadleaf > 20 y	300	IPCC, 2003
		Africa broadleaf ≤ 20 y	100	IPCC, 2003
		Africa Pinus sp. > 20 y	200	IPCC, 2003
		Africa Pinus sp. ≤ 20 y	60	IPCC, 2003
		Americas Eucalyptus sp.	200	IPCC, 2003
		Americas Pinus sp.	300	IPCC, 2003
		Americas Tectona grandis	240	Kraenzel *et al*., 2003
		Americas other broadleaf	150	IPCC, 2003
		Asia broadleaf	220	IPCC, 2003
		Asia other	130	IPCC, 2003
	Tropical moist deciduous forest	Africa broadleaf > 20 y	150	IPCC, 2003
		Africa broadleaf ≤ 20 y	80	IPCC, 2003
		Africa Pinus sp. > 20 y	120	IPCC, 2003
		Africa Pinus sp. ≤ 20 y	40	IPCC, 2003
		Americas Eucalyptus sp.	90	Stape *et al*., 2004
		Americas Pinus sp.	270	IPCC, 2003
		Americas Tectona grandis	120	IPCC, 2003
		Americas other broadleaf	100	IPCC, 2003
		Asia broadleaf	180	IPCC, 2003
		Asia other	100	IPCC, 2003

TABLE 4.8 (CONTINUED)
ABOVE-GROUND BIOMASS IN FOREST PLANTATIONS

Domain	Ecological zone	Continent	Above-ground biomass (tonnes d.m. ha^{-1})	References
	Tropical dry forest	Africa broadleaf > 20 y	70	IPCC, 2003
		Africa broadleaf ≤ 20 y	30	IPCC, 2003
		Africa Pinus sp. > 20 y	60	IPCC, 2003
		Africa Pinus sp. ≤ 20 y	20	IPCC, 2003
		Americas Eucalyptus sp.	90	Stape *et al.*, 2004
		Americas Pinus sp.	110	IPCC, 2003
		Americas Tectona grandis	90	IPCC, 2003
		Americas other broadleaf	60	IPCC, 2003
		Asia broadleaf	90	IPCC, 2003
		Asia other	60	IPCC, 2003
	Tropical shrubland	Africa broadleaf	20	IPCC, 2003
		Africa Pinus sp. > 20 y	20	IPCC, 2003
		Africa Pinus sp. ≤ 20 y	15	IPCC, 2003
		Americas Eucalyptus sp.	60	IPCC, 2003
		Americas Pinus sp.	60	IPCC, 2003
		Americas Tectona grandis	50	IPCC, 2003
		Americas other broadleaf	30	IPCC, 2003
		Asia broadleaf	40	IPCC, 2003
		Asia other	30	IPCC, 2003
	Tropical mountain systems	Africa broadleaf > 20 y	60-150	IPCC, 2003
		Africa broadleaf ≤ 20 y	40-100	IPCC, 2003
		Africa Pinus sp. > 20 y	30-100	IPCC, 2003
		Africa Pinus sp. ≤ 20 y	10-40	IPCC, 2003
		Americas Eucalyptus sp.	30-120	IPCC, 2003
		Americas Pinus sp.	60-170	IPCC, 2003
		Americas Tectona grandis	30-130	IPCC, 2003
		Americas other broadleaf	30-80	IPCC, 2003
		Asia broadleaf	40-150	IPCC, 2003
		Asia other	25-80	IPCC, 2003
Subtropical	Subtropical humid forest	Americas Eucalyptus sp.	140	IPCC, 2003
		Americas Pinus sp.	270	IPCC, 2003
		Americas Tectona grandis	120	IPCC, 2003
		Americas other broadleaf	100	IPCC, 2003
		Asia broadleaf	180	IPCC, 2003
		Asia other	100	IPCC, 2003
	Subtropical dry forest	Africa broadleaf > 20 y	70	IPCC, 2003
		Africa broadleaf ≤ 20 y	30	IPCC, 2003
		Africa Pinus sp. > 20 y	60	IPCC, 2003
		Africa Pinus sp. ≤ 20 y	20	IPCC, 2003
		Americas Eucalyptus sp.	110	IPCC, 2003
		Americas Pinus sp.	110	IPCC, 2003
		Americas Tectona grandis	90	IPCC, 2003
		Americas other broadleaf	60	IPCC, 2003
		Asia broadleaf	90	IPCC, 2003
		Asia other	60	IPCC, 2003

TABLE 4.8 (CONTINUED)
ABOVE-GROUND BIOMASS IN FOREST PLANTATIONS

Domain	Ecological zone	Continent	Above-ground biomass (tonnes d.m. ha^{-1})	References
	Subtropical steppe	Africa broadleaf	20	IPCC, 2003
		Africa Pinus sp. > 20 y	20	IPCC, 2003
		Africa Pinus sp. ≤ 20 y	15	IPCC, 2003
		Americas Eucalyptus sp.	60	IPCC, 2003
		Americas Pinus sp.	60	IPCC, 2003
		Americas Tectona grandis	50	IPCC, 2003
		Americas other broadleaf	30	IPCC, 2003
		Asia broadleaf > 20 y	80	IPCC, 2003
		Asia broadleaf ≤ 20 y	10	IPCC, 2003
		Asia coniferous > 20 y	20	IPCC, 2003
		Asia coniferous ≤ 20 y	100-120	IPCC, 2003
	Subtropical mountain systems	Africa broadleaf > 20 y	60-150	IPCC, 2003
		Africa broadleaf ≤ 20 y	40-100	IPCC, 2003
		Africa Pinus sp. > 20 y	30-100	IPCC, 2003
		Africa Pinus sp. ≤ 20 y	10-40	IPCC, 2003
		Americas Eucalyptus sp.	30-120	IPCC, 2003
		Americas Pinus sp.	60-170	IPCC, 2003
		Americas Tectona grandis	30-130	IPCC, 2003
		Americas other broadleaf	30-80	IPCC, 2003
		Asia broadleaf	40-150	IPCC, 2003
		Asia other	25-80	IPCC, 2003
Temperate	Temperate oceanic forest	Asia, Europe, broadleaf > 20 y	200	IPCC, 2003
		Asia, Europe, broadleaf ≤ 20 y	30	IPCC, 2003
		Asia, Europe, coniferous > 20 y	150-250	IPCC, 2003
		Asia, Europe, coniferous ≤ 20 y	40	IPCC, 2003
		North America	50-300	IPCC, 2003
		New Zealand	150-350	Hinds and Reid, 1957; Hall and Hollinger, 1997; Hall, 2001
		South America	90-120	IPCC, 2003
	Temperate continental forest and mountain systems	Asia, Europe, broadleaf > 20 y	200	IPCC, 2003
		Asia, Europe, broadleaf ≤ 20 y	15	IPCC, 2003
		Asia, Europe, coniferous > 20 y	150-200	IPCC, 2003
		Asia, Europe, coniferous ≤ 20 y	25-30	IPCC, 2003
		North America	50-300	IPCC, 2003
		South America	90-120	IPCC, 2003
Boreal	Boreal coniferous forest and mountain systems	Asia, Europe > 20 y	40	IPCC, 2003
		Asia, Europe ≤ 20 y	5	IPCC, 2003
		North America	40-50	IPCC, 2003
	Boreal tundra woodland	Asia, Europe > 20 y	25	IPCC, 2003
		Asia, Europe ≤ 20 y	5	IPCC, 2003
		North America	25	IPCC, 2003

TABLE 4.9
ABOVE-GROUND NET BIOMASS GROWTH IN NATURAL FORESTS

Domain	Ecological zone	Continent	Above-ground biomass growth (tonnes d.m. ha^{-1} yr^{-1})	Reference
Tropical	Tropical rain forest	Africa (≤20 y)	10	IPCC, 2003
		Africa (>20 y)	3.1 (2.3-3.8)	IPCC, 2003
		North America	0.9-18	Clark *et al*., 2003 ; Hughes *et al*., 1999
		South America (≤20 y)	11	Feldpausch *et al*., 2004
		South America (>20 y)	3.1 (1.5-5.5)	Malhi *et al*., 2004
		Asia (continental ≤20 y)	7.0 (3.0-11.0)	IPCC, 2003
		Asia (continental >20 y)	2.2 (1.3-3.0)	IPCC, 2003
		Asia (insular ≤20 y)	13	IPCC, 2003
		Asia (insular >20 y)	3.4	IPCC, 2003
	Tropical moist deciduous forest	Africa (≤20 y)	5	Harmand *et al*., 2004
		Africa (>20 y)	1.3	IPCC, 2003
		North and South America (≤20 y)	7.0	IPCC, 2003
		North and South America (>20 y)	2.0	IPCC, 2003
		Asia (continental ≤20 y)	9.0	IPCC, 2003
		Asia (continental >20 y)	2.0	IPCC, 2003
		Asia (insular ≤20 y)	11	IPCC, 2003
		Asia (insular >20 y)	3.0	IPCC, 2003
	Tropical dry forest	Africa (≤20 y)	2.4 (2.3-2.5)	IPCC, 2003
		Africa (>20 y)	1.8 (0.6-3.0)	IPCC, 2003
		North and South America (≤20 y)	4.0	IPCC, 2003
		North and South America (>20 y)	1.0	IPCC, 2003
		Asia (continental ≤20 y)	6.0	IPCC, 2003
		Asia (continental >20 y)	1.5	IPCC, 2003
		Asia (insular ≤20 y)	7.0	IPCC, 2003
		Asia (insular >20 y)	2.0	IPCC, 2003
	Tropical shrubland	Africa (≤20 y)	0.2-0.7	Nygård *et al*., 2004
		Africa (>20 y)	0.9 (0.2-1.6)	IPCC, 2003
		North and South America (≤20 y)	4.0	IPCC, 2003
		North and South America (>20 y)	1.0	IPCC, 2003
		Asia (continental ≤20 y)	5.0	IPCC, 2003
		Asia (continental >20 y)	1.3 (1.0-2.2)	IPCC, 2003
		Asia (insular ≤20 y)	2.0	IPCC, 2003
		Asia (insular >20 y)	1.0	IPCC, 2003
	Tropical mountain systems	Africa (≤20 y)	2.0-5.0	IPCC, 2003
		Africa (>20 y)	1.0-1.5	IPCC, 2003
		North and South America (≤20 y)	1.8-5.0	IPCC, 2003
		North and South America (>20 y)	0.4-1.4	IPCC, 2003
		Asia (continental ≤20 y)	1.0-5.0	IPCC, 2003
		Asia (continental >20 y)	0.5-1.0	IPCC, 2003
		Asia (insular ≤20 y)	3.0-12	IPCC, 2003
		Asia (insular >20 y)	1.0-3.0	IPCC, 2003
Subtropical	Subtropical humid forest	North and South America (≤20 y)	7.0	IPCC, 2003
		North and South America (>20 y)	2.0	IPCC, 2003
		Asia (continental ≤20 y)	9.0	IPCC, 2003
		Asia (continental >20 y)	2.0	IPCC, 2003
		Asia (insular ≤20 y)	11	IPCC, 2003
		Asia (insular >20 y)	3.0	IPCC, 2003
	Subtropical dry forest	Africa (≤20 y)	2.4 (2.3-2.5)	IPCC, 2003
		Africa (>20 y)	1.8 (0.6-3.0)	IPCC, 2003
		North and South America (≤20 y)	4.0	IPCC, 2003

TABLE 4.9 (CONTINUED)
ABOVE-GROUND NET BIOMASS GROWTH IN NATURAL FORESTS

Domain	Ecological zone	Continent	Above-ground biomass growth (tonnes d.m. ha^{-1} yr^{-1})	Reference
		North and South America (>20 y)	1.0	IPCC, 2003
		Asia (continental ≤20 y)	6.0	IPCC, 2003
		Asia (continental >20 y)	1.5	IPCC, 2003
		Asia (insular ≤20 y)	7.0	IPCC, 2003
		Asia (insular >20 y)	2.0	IPCC, 2003
	Subtropical steppe	Africa (≤20 y)	1.2 (0.8-1.5)	IPCC, 2003
		Africa (>20 y)	0.9 (0.2-1.6)	IPCC, 2003
		North and South America (≤20 y)	4.0	IPCC, 2003
		North and South America (>20 y)	1.0	IPCC, 2003
		Asia (continental ≤20 y)	5.0	IPCC, 2003
		Asia (continental >20 y)	1.3 (1.0-2.2)	IPCC, 2003
		Asia (insular ≤20 y)	2.0	IPCC, 2003
		Asia (insular >20 y)	1.0	IPCC, 2003
	Subtropical mountain systems	Africa (≤20 y)	2.0-5.0	IPCC, 2003
		Africa (>20 y)	1.0-1.5	IPCC, 2003
		North and South America (≤20 y)	1.8-5.0	IPCC, 2003
		North and South America (>20 y)	0.4-1.4	IPCC, 2003
		Asia (continental ≤20 y)	1.0-5.0	IPCC, 2003
		Asia (continental >20 y)	0.5-1.0	IPCC, 2003
		Asia (insular ≤20 y)	3.0-12	IPCC, 2003
		Asia (insular >20 y)	1.0-3.0	IPCC, 2003
Temperate	Temperate oceanic forest	Europe	2.3	
		North America	15 (1.2-105)	Hessl *et al*., 2004
		New Zealand	3.5 (3.2-3.8)	Coomes *et al*., 2002
		South America	2.4-8.9	Echevarria and Lara, 2004
	Temperate continental forest	Asia, Europe, North America (≤20 y)	4.0 (0.5-8.0)	IPCC, 2003
		Asia, Europe, North America (>20 y)	4.0 (0.5-7.5)	IPCC, 2003
	Temperate mountain systems	Asia, Europe, North America	3.0 (0.5-6.0)	IPCC, 2003
Boreal	Boreal coniferous forest	Asia, Europe, North America	0.1-2.1	Gower *et al*., 2001
	Boreal tundra woodland	Asia, Europe, North America	0.4 (0.2-0.5)	IPCC, 2003
	Boreal mountain systems	Asia, Europe, North America (≤20 y)	1.0-1.1	IPCC, 2003
		Asia, Europe, North America (>20 y)	1.1-1.5	IPCC, 2003

TABLE 4.10
ABOVE-GROUND NET BIOMASS GROWTH IN TROPICAL AND SUB-TROPICAL FOREST PLANTATIONS

Domain	Ecological zone	Continent	Above-ground biomass growth (tonnes d.m. ha^{-1} yr^{-1})	References
Tropical	Tropical rain forest	Africa Pinus sp. ≤ 20 y	20	IPCC, 2003
		Africa other ≤ 20 y	6 (5-8)	IPCC, 2003
		Americas Eucalyptus sp.	20 (6-40)	IPCC, 2003
		Americas Pinus sp.	20	IPCC, 2003
		Americas Tectona grandis	15	IPCC, 2003
		Americas other broadleaf	20 (5-35)	IPCC, 2003
		Asia Eucalyptus sp.	5 (4-8)	IPCC, 2003
		Asia other	5 (2-8)	IPCC, 2003
	Tropical moist deciduous forest	Africa Eucalyptus sp. >20 y	25	IPCC, 2003
		Africa Eucalyptus sp. ≤20 y	20	IPCC, 2003
		Africa Pinus sp. > 20 y	15	IPCC, 2003
		Africa Pinus sp. ≤ 20 y	10	IPCC, 2003
		Africa other ≤ 20 y	9 (3-15)	IPCC, 2003
		Americas Eucalyptus sp.	16	Stape *et al*., 2004
		Americas Pinus sp.	7 (4-10)	IPCC, 2003
		Americas Tectona grandis	8 (4-12)	IPCC, 2003
		Americas other broadleaf	6-20	Lugo *et al*., 1990
		Asia	8	IPCC, 2003
	Tropical dry forest	Africa Eucalyptus sp. ≤20 y	13	IPCC, 2003
		Africa Pinus sp. > 20 y	10	IPCC, 2003
		Africa Pinus sp. ≤ 20 y	8	IPCC, 2003
		Africa other ≤ 20 y	10 (4-20)	IPCC, 2003
		Americas Eucalyptus sp.	20 (6-30)	IPCC, 2003
		Americas Pinus sp.	7 (4-10)	IPCC, 2003
		Americas Tectona grandis	8 (4-12)	IPCC, 2003
		Americas other broadleaf	10 (3-12)	IPCC, 2003
		Asia Eucalyptus sp.	15 (5-25)	IPCC, 2003
		Asia other	7 (2-13)	IPCC, 2003
	Tropical shrubland	Africa Eucalyptus sp. >20 y	8 (5-14)	IPCC, 2003
		Africa Eucalyptus sp. ≤20 y	5 (3-7)	IPCC, 2003
		Africa Pinus sp. > 20 y	2.5	IPCC, 2003
		Africa Pinus sp. ≤ 20 y	3 (0.5-6)	IPCC, 2003
		Africa other > 20 y	10	IPCC, 2003
		Africa other ≤ 20 y	15	IPCC, 2003
		Americas Eucalyptus sp.	20	IPCC, 2003
		Americas Pinus sp.	5	IPCC, 2003
		Asia	6 (1-12)	IPCC, 2003
	Tropical mountain systems	Africa	10	IPCC, 2003
		Americas Eucalyptus sp.	10 (8-18)	IPCC, 2003
		Americas Pinus sp.	10	IPCC, 2003
		Americas Tectona grandis	2	IPCC, 2003
		Americas other broadleaf	4	IPCC, 2003
		Asia Eucalyptus sp.	3	IPCC, 2003
		Asia other	5 (1-10)	IPCC, 2003
Subtropical	Subtropical humid forest	Americas Eucalyptus sp.	20 (6-32)	IPCC, 2003
		Americas Pinus sp.	7 (4-10)	IPCC, 2003
		Americas Tectona grandis	8 (4-12)	IPCC, 2003
		Americas other broadleaf	10 (3-12)	IPCC, 2003
		Asia	8	IPCC, 2003
	Subtropical dry forest	Africa Eucalyptus sp. ≤20 y	13	IPCC, 2003
		Africa Pinus sp. > 20 y	10	IPCC, 2003
		Africa Pinus sp. ≤ 20 y	8	IPCC, 2003
		Africa other ≤ 20 y	10 (4-20)	IPCC, 2003
		Americas Eucalyptus sp.	20 (6-30)	IPCC, 2003
		Americas Pinus sp.	7 (4-10)	IPCC, 2003
		Americas Tectona grandis	8 (4-12)	IPCC, 2003
		Americas other broadleaf	10 (3-12)	IPCC, 2003
		Asia Eucalyptus sp.	15 (5-25)	IPCC, 2003
		Asia other	7 (2-13)	IPCC, 2003

TABLE 4.10 (CONTINUED)
ABOVE-GROUND NET BIOMASS GROWTH IN TROPICAL AND SUB-TROPICAL FOREST PLANTATIONS

Domain	Ecological zone	Continent	Above-ground biomass growth (tonnes d.m. ha^{-1} yr^{-1})	References
	Subtropical steppe	Africa Eucalyptus sp. >20 y	8 (5-14)	IPCC, 2003
		Africa Eucalyptus sp. ≤20 y	5 (3-7)	IPCC, 2003
		Africa Pinus sp. > 20 y	2.5	IPCC, 2003
		Africa Pinus sp. ≤ 20 y	3 (0.5-6)	IPCC, 2003
		Africa other > 20 y	10	IPCC, 2003
		Africa other ≤ 20 y	15	IPCC, 2003
		Americas Eucalyptus sp.	20	IPCC, 2003
		Americas Pinus sp.	5	IPCC, 2003
		Asia	6 (1-12)	IPCC, 2003
	Subtropical mountain systems	Africa	10	IPCC, 2003
		Americas Eucalyptus sp.	10 (8-18)	IPCC, 2003
		Americas Pinus sp.	10	IPCC, 2003
		Americas Tectona grandis	2	IPCC, 2003
		Americas other broadleaf	4	IPCC, 2003
		Asia Eucalyptus sp.	3	IPCC, 2003
		Asia other	5 (1-10)	IPCC, 2003
Temperate	Temperate oceanic forest	Asia, Europe, broadleaf > 20 y	-	-
		Asia, Europe, broadleaf ≤ 20 y	-	-
		Asia, Europe, coniferous > 20 y	-	-
		Asia, Europe, coniferous ≤ 20 y	-	-
		North America	-	-
		New Zealand	-	-
		South America	-	-
	Temperate continental forest and mountain systems	Asia, Europe, broadleaf > 20 y	-	-
		Asia, Europe, broadleaf ≤ 20 y	-	-
		Asia, Europe, coniferous > 20 y	-	-
		Asia, Europe, coniferous ≤ 20 y	-	-
		North America	-	-
		South America	-	-
Boreal	Boreal coniferous forest and mountain systems	Asia, Europe > 20 y	-	-
		Asia, Europe ≤ 20 y	-	-
		North America	-	-
	Boreal tundra woodland	Asia, Europe > 20 y	-	-
		Asia, Europe ≤ 20 y	-	-
		North America	-	-

TABLE 4.11A
ABOVE-GROUND NET VOLUME GROWTH OF SELECTED FOREST PLANTATION SPECIES

Tree species	**Above-ground net volume growth (m^3 ha^{-1} y^{-1})**
Acacia auriculiformis	6 - 20
Acacia mearnsii	14 - 25
Araucaria angustifolia	8 - 24
Araucaria cunninghamii	10 - 18
Casuarina equisetifolia	6 - 20
Casuarina junghuhniana	7 - 11
Cordia alliadora	10 - 20
Cupressus lusitanica	8 - 40
Dalbergia sissoo	5 - 8
Eucalyptus camaldulensis	15 - 30
Eucalyptus deglupta	14 - 50
Eucalyptus globulus	10 - 40
Eucalyptus grandis	15 - 50
Eucalyptus robusta	10 - 40
Eucalyptus saligna	10 - 55
Eucalyptus urophylla	20 - 60
Gmelina arborea	12 - 50
Leucaena leucocephala	30 - 55
Pinus caribaea v. caribaea	10 - 28
Pinus caribaea v. hondurensis	20 - 50
Pinus oocarpa	10 - 40
Pinus patula	8 - 40
Pinus radiata	10 - 50
Swietenia macrophylla	7 - 30
Tectona grandis	6 - 18
Terminalia ivorensis	8 - 17
Terminalia superba	10 - 14

Source: Ugalde and Perez, 2001

TABLE 4.11B
MEAN ANNUAL INCREMENT (GROWTH OF MERCHANTABLE VOLUME) FOR SOME FOREST PLANTATION SPECIES

Planted forest type/ region	Tree species	Mean annual increment (MAI) over rotation (m^3 ha^{-1} yr^{-1})	
		MAI min	MAI max
Productive plantations			
Africa	Acacia mellifera	2.2	4.0
	Acacia nilotica	15.0	20.0
	Acacia senegal	1.4	2.6
	Acacia seyal	2.0	6.0
	Ailanthus excelsa	6.6	9.4
	Bamboo bamboo	5.0	7.5
	Cupressus spp.	15.0	24.0
	Eucalyptus spp.	12.0	14.0
	Khaya spp.	8.5	12.0
	Tectona grandis	2.5	3.5
Asia	Eucalyptus camaldulensis	21.0	43.0
	Pinus spp.	4.0	15.0
South America	Tectona grandis	7.3	17.3
	Xylia xylocapa	3.0	8.8
	Acacia spp.	15.0	30.0
	Araucaria angustifolia	15.0	30.0
	Eucalyptus spp.	20.0	70.0
	Hevea brasiliensis	10.0	20.0
	Mimosa scabrella	10.0	25.0
	Pinus spp.	25.0	40.0
	Populus spp.	10.0	30.0
	Tectona grandis	15.0	35.0
Productive, semi-natural forests			
Africa	Acacia albida	4.0	6.1
	Acacia mellifera	1.9	3.5
	Acacia nilotica	12.5	20.0
	Acacia senegal	1.1	2.4
	Acacia seyal	1.8	3.2
	Acacia tortilis	1.2	3.7
	Acacia tortilis var siprocarpa	1.5	2.4
	Balanites aegyptiaca	1.2	1.5
	Sclerocarya birrea	1.5	1.7
	Ziziphus mauritiana	0.9	1.0
Protective plantations			
Africa	Acacia mellifera	2.0	6.0
	Acacia nilotica	13.0	21.0
	Acacia senegal	1.4	2.8
	Acacia seyal	1.9	4.3
	Ailanthus spp.	6.0	12.0
	Bamboo bamboo	4.0	8.0
	Cupressus spp.	14.0	20.0
	Eucalyptus spp.	10.0	14.0
	Khaya spp.	7.0	16.0
	Tectona grandis	5.0	8.0

TABLE 4.11B (CONTINUED)
MEAN ANNUAL INCREMENT (GROWTH OF MERCHANTABLE VOLUME) FOR SOME FOREST PLANTATION SPECIES

Planted forest type/ region	Tree species	Mean annual increment (MAI) over rotation (m^3 ha^{-1} yr^{-1})	
		MAI min	MAI max
Protective Semi-natural plantations			
Africa	Acacia albida	4.0	6.2
	Acacia mellifera	1.7	3.2
	Acacia nilotica	12.0	15.0
	Acacia senegal	1.1	2.4
	Acacia seyal	1.8	3.3
	Acacia tortilis	1.3	3.5
	Acacia tortilis var siprocarpa	1.6	2.4
	Balanites aegyptiaca	1.2	1.5
	Sclerocarya birrea	1.5	1.7
	Ziziphus mauritiana	0.9	1.0

Source: FAO at http://www.fao.org/forestry/

TABLE 4.12
TIER 1 ESTIMATED BIOMASS VALUES FROM TABLES 4.7–4.11 (EXCEPT TABLE 4.11B)
(VALUES ARE APPROXIMATE; USE ONLY FOR TIER 1)

Climate domain	Ecological zone	Above-ground biomass in natural forests (tonnes d.m. ha^{-1})	Above-ground biomass in forest plantations (tonnes d.m. ha^{-1})	Above-ground net biomass growth in natural forests (tonnes d.m. ha^{-1} yr^{-1})	Above-ground net biomass growth in forest plantations (tonnes d.m. ha^{-1} yr^{-1})
Tropical	Tropical rain forest	300	150	7.0	15.0
	Tropical moist deciduous forest	180	120	5.0	10.0
	Tropical dry forest	130	60	2.4	8.0
	Tropical shrubland	70	30	1.0	5.0
	Tropical mountain systems	140	90	1.0	5.0
Sub-tropical	Subtropical humid forest	220	140	5.0	10.0
	Subtropical dry forest	130	60	2.4	8.0
	Subtropical steppe	70	30	1.0	5.0
	Subtropical mountain systems	140	90	1.0	5.0
Temperate	Temperate oceanic forest	180	160	4.4	4.4
	Temperate continental forest	120	100	4.0	4.0
	Temperate mountain systems	100	100	3.0	3.0
Boreal	Boreal coniferous forest	50	40	1.0	1.0
	Boreal tundra woodland	15	15	0.4	0.4
	Boreal mountain systems	30	30	1.0	1.0

TABLE 4.13 BASIC WOOD DENSITY (D) OF TROPICAL TREE SPECIES (OVEN-DRY TONNES (MOIST M^{-3}))

1 = Baker *et al.*, 2004b; 2 = Barbosa and Fearnside, 2004;
3 = CTFT, 1989; 4 = Fearnside, 1997; 5 = Reyes *et al.*, 1992

TABLE 4.13 BASIC WOOD DENSITY (D) OF TROPICAL TREE SPECIES (OVEN-DRY TONNES (MOIST M^{-3}))
1 = Baker *et al.*, 2004b; 2 = Barbosa and Fearnside, 2004;
3 = CTFT, 1989; 4 = Fearnside, 1997; 5 = Reyes *et al.*, 1992

Species	Density	Continent	Reference
Adina cordifolia	0.58-0.59	Asia	5
Aegle marmelo	0.75	Asia	5
Afzelia bipidensis	0.67-0.79	Africa	3
Agathis sp.	0.44	Asia	5
Aglaia llanosiana	0.89	Asia	5
Agonandra brasiliensis	0.74	Americas	4
Aidia ochroleuca	0.78	Africa	5
Alangium longiflorum	0.65	Asia	5
Albizia sp.	0.52	Americas	5
Albizzia amara	0.70	Asia	5
Albizzia falcataria	0.25	Asia	5
Alcornea sp.	0.34	Americas	5
Aldina heterophylla	0.73	Americas	4
Aleurites trisperma	0.43	Asia	5
Alexa grandiflora	0.59	Americas	4
Alexa imperatricis	0.52	Americas	4
Allophyllus africanus	0.45	Africa	5
Alnus ferruginea	0.38	Americas	5
Alnus japonica	0.43	Asia	5
Alphitonia zizyphoides	0.50	Asia	5
Alphonsea arborea	0.69	Asia	5
Alseodaphne longipes	0.49	Asia	5
Alstonia congensis	0.33	Africa	5
Amburana cearensis	0.43	Americas	1
Amoora sp.	0.60	Asia	5
Amphimas pterocarpoides	0.63	Africa	5
Anacardium excelsum	0.41	Americas	4
Anacardium giganteum	0.44	Americas	4
Anadenanthera macrocarpa	0.86	Americas	4
Andira inermis	0.64	Americas	4
Andira parviflora	0.69	Americas	4
Andira retusa	0.67	Americas	5
Aniba amazonica	0.52-0.56	Americas	1
Aniba canelilla	0.92	Americas	4
Aningeria robusta	0.44-0.53	Africa	3
Anisophyllea obtusifolia	0.63	Africa	5
Anisophyllea zeylanica	0.46	Asia	5
Anisoptera sp.	0.54	Asia	5
Annonidium mannii	0.29	Africa	5
Anogeissus latifolia	0.78-0.79	Asia	5
Anopyxis klaineana	0.74	Africa	5
Anthocephalus chinensis	0.33-0.36	Asia	5
Anthocleista keniensis	0.50	Africa	5
Anthonotha macrophylla	0.78	Africa	5
Anthostemma aubryanum	0.32	Africa	5
Antiaris africana	0.38	Americas	5
Antiaris sp.	0.38	Africa	5
Antidesma pleuricum	0.59	Asia	5
Antrocaryon klaineanum	0.50	Africa	5
Apeiba aspera	0.28	Americas	1
Apeiba echinata	0.36	Americas	5
Apeiba peiouma	0.20	Americas	4
Aphanamiris perrottetiana	0.52	Asia	5
Apuleia leiocarpa	0.70	Americas	1
Apuleia molaris	0.76	Americas	4
Araucaria bidwillii	0.43	Asia	5
Ardisia cubana	0.62	Americas	1
Artocarpus comunis	0.70	Americas	5
Artocarpus sp.	0.58	Asia	5
Aspidosperma album	0.76	Americas	4
Aspidosperma macrocarpon	0.67	Americas	1
Aspidosperma obscurinervium	0.86	Americas	4
Astronium gracile	0.73	Americas	4
Astronium graveolens	0.75	Americas	4
Astronium lecointei	0.73	Americas	5
Astronium ulei	0.71	Americas	4
Astronium urundeuva	1.21	Americas	4
Aucoumea klaineana	0.31-0.48	Africa	3
Autranella congolensis	0.78	Africa	5
Azadirachta sp.	0.52	Asia	5
Bagassa guianensis	0.69	Americas	4
Baillonella toxisperma	0.70	Africa	3
Balanites aegyptiaca	0.63	Africa	5
Balanocarpus sp.	0.76	Asia	5
Banara guianensis	0.61	Americas	5
Baphia kirkii	0.93	Africa	5
Barringtonia edulis	0.48	Asia	5
Basiloxylon exelsum	0.58	Americas	5
Bauhinia sp.	0.67	Asia	5
Beilschmiedia louisii	0.70	Africa	5
Beilschmiedia nitida	0.50	Africa	5
Beilschmiedia sp.	0.61	Americas	5
Beilschmiedia tawa	0.58	Asia	5
Berlinia sp.	0.58	Africa	5
Berrya cordifolia	0.78	Asia	5
Bertholletia excelsa	0.62	Americas	4
Bischofia javanica	0.54-0.62	Asia	5
Bixa arborea	0.32	Americas	4
Bleasdalea vitiensis	0.43	Asia	5
Blighia welwitschii	0.74	Africa	5
Bocoa sp.	0.42	Americas	1
Bombacopsis quinata	0.39	Americas	1
Bombacopsis sepium	0.39	Americas	5
Bombax costatum	0.35	Africa	3
Bombax paraense	0.39	Americas	1
Borojoa patinoi	0.52	Americas	5
Boswellia serrata	0.50	Asia	5
Bowdichia coccolobifolia	0.39	Americas	2
Bowdichia crassifolia	0.39	Americas	2
Bowdichia nitida	0.79	Americas	4
Bowdichia virgilioides	0.52	Americas	2
Brachystegia sp.	0.52	Africa	5
Bridelia micrantha	0.47	Africa	5
Bridelia squamosa	0.50	Asia	5
Brosimum acutifolium	0.55	Americas	4
Brosimum alicastrum	0.69	Americas	4
Brosimum guianense	0.96	Americas	4
Brosimum lactescens	0.70	Americas	1
Brosimum parinarioides	0.58	Americas	4
Brosimum potabile	0.53	Americas	4
Brosimum rubescens	0.87	Americas	4
Brosimum utile	0.40-0.49	Americas	1
Brysenia adenophylla	0.54	Americas	5
Buchenavia capitata	0.63	Americas	4
Buchenavia huberi	0.79	Americas	4
Buchenavia latifolia	0.45	Asia	5
Buchenavia oxycarpa	0.72	Americas	4
Buchenavia viridiflora	0.88	Americas	1
Bucida buceras	0.93	Americas	5
Bursera serrata	0.59	Asia	5
Bursera simaruba	0.29-0.34	Americas	5
Butea monosperma	0.48	Asia	5
Byrsonima coriacea	0.64	Americas	5
Byrsonima spicata	0.61	Americas	4

TABLE 4.13 BASIC WOOD DENSITY (D) OF TROPICAL TREE SPECIES (OVEN-DRY TONNES (MOIST M^{-3}))
1 = Baker *et al.*, 2004b; 2 = Barbosa and Fearnside, 2004;
3 = CTFT, 1989; 4 = Fearnside, 1997; 5 = Reyes *et al.*, 1992

Species	Density	Continent	Reference
Byrsonima verbascifolia	0.33	Americas	2
Cabralea canjerana	0.55	Americas	4
Caesalpinia sp.	1.05	Americas	5
Calophyllum brasiliense	0.53	Americas	4
Calophyllum sp.	0.46	Americas	1
Calophyllum sp.	0.53	Asia	5
Calpocalyx klainei	0.63	Africa	5
Calycarpa arborea	0.53	Asia	5
Calycophyllum spruceanum	0.74	Americas	1
Campnosperma panamensis	0.37	Americas	1
Cananga odorata	0.29	Asia	5
Canarium sp.	0.44	Asia	5
Canthium monstrosum	0.42	Asia	5
Canthium rubrocostratum	0.63	Africa	5
Carallia calycina	0.66	Asia	5
Carapa guianensis	0.55	Americas	4
Carapa procera	0.59	Africa	5
Cariniana integrifolia	0.49	Americas	4
Cariniana micrantha	0.64	Americas	4
Caryocar glabrum	0.65	Americas	1
Caryocar villosum	0.72	Americas	4
Casearia battiscombei	0.50	Africa	5
Casearia sp.	0.62	Americas	5
Cassia javanica	0.69	Asia	5
Cassia moschata	0.71	Americas	5
Cassia scleroxylon	1.01	Americas	4
Cassipourea euryoides	0.70	Africa	5
Cassipourea malosana	0.59	Africa	5
Castanopsis philippensis	0.51	Asia	5
Casuarina equisetifolia	0.81	Americas	5
Casuarina equisetifolia	0.83	Asia	5
Casuarina nodiflora	0.85	Asia	5
Catostemma commune	0.50	Americas	1
Cecropia sp.	0.36	Americas	5
Cedrela odorata	0.42	Americas	1
Cedrela odorata	0.38	Asia	5
Cedrela sp.	0.40-0.46	Americas	5
Cedrela toona	0.43	Asia	5
Cedrelinga catenaeformis	0.45	Americas	1
Ceiba pentandra	0.18-0.39	Africa	3
Ceiba pentandra	0.28	Americas	4
Ceiba pentandra	0.23	Asia	5
Ceiba samauma	0.57	Americas	1
Celtis luzonica	0.49	Asia	5
Celtis schippii	0.59	Americas	1
Celtis sp.	0.59	Africa	5
Centrolobium sp.	0.65	Americas	5
Cespedesia macrophylla	0.63	Americas	5
Cespedesia spathulata	0.54	Americas	1
Chaetocarpus schomburgkianus	0.80	Americas	5
Chisocheton pentandrus	0.52	Asia	5
Chlorophora excelsa	0.48-0.66	Africa	3
Chlorophora tinctoria	0.73	Americas	4
Chloroxylon swietenia	0.76-0.80	Asia	5
Chorisia integrifolia	0.28	Americas	1
Chrysophyllum albidum	0.56	Africa	5
Chukrassia tabularis	0.57	Asia	5
Citrus grandis	0.59	Asia	5
Clarisia racemosa	0.59	Americas	4
Cleidion speciflorum	0.50	Asia	5
Cleistanthus eollinus	0.88	Asia	5
Cleistanthus mildbraedii	0.87	Africa	5
Cleistocalyx sp.	0.76	Asia	5
Cleistopholis patens	0.36	Africa	5
Clusia rosea	0.67	Americas	5
Cochlospermum gossypium	0.27	Asia	5
Cochlospermum orinocensis	0.26	Americas	5
Cocos nucifera	0.50	Asia	5
Coda edulis	0.78	Africa	5
Coelocaryon preussii	0.56	Africa	5
Cola sp.	0.70	Africa	5
Colona serratifolia	0.33	Asia	5
Combretodendron quadrialatum	0.57	Asia	5
Conopharyngia holstii	0.50	Africa	5
Copaifera officinalis	0.61	Americas	1
Copaifera pubifora	0.56	Americas	1
Copaifera religiosa	0.50	Africa	5
Copaifera reticulata	0.63	Americas	4
Cordia alliodora	0.48	Americas	5
Cordia bicolor	0.49	Americas	4
Cordia gerascanthus	0.74	Americas	5
Cordia goeldiana	0.48	Americas	4
Cordia millenii	0.34	Africa	5
Cordia platythyrsa	0.36	Africa	5
Cordia sagotii	0.50	Americas	4
Cordia sp.	0.53	Asia	5
Corynanthe pachyceras	0.63	Africa	5
Corythophora rimosa	0.84	Americas	4
Cotylelobium sp.	0.69	Asia	5
Couepia sp.	0.70	Americas	5
Couma macrocarpa	0.50	Americas	4
Couratari guianensis	0.54	Americas	4
Couratari multiflora	0.47	Americas	4
Couratari oblongifolia	0.49	Americas	4
Couratari stellata	0.63	Americas	4
Crataeva religiosa	0.53	Asia	5
Cratoxylon arborescens	0.40	Asia	5
Croton megalocarpus	0.57	Africa	5
Croton xanthochloros	0.48	Americas	5
Cryptocarya sp.	0.59	Asia	5
Cryptosepalum staudtii	0.70	Africa	5
Ctenolophon englerianus	0.78	Africa	5
Cubilia cubili	0.49	Asia	5
Cullenia excelsa	0.53	Asia	5
Cupressus lusitanica	0.43-0.44	Americas	5
Curatella americana	0.41	Americas	2
Cylicodiscus gabonensis	0.80	Africa	5
Cynometra alexandri	0.74	Africa	5
Cynometra sp.	0.80	Asia	5
Cyrilla racemiflora	0.53	Americas	5
Dacrycarpus imbricatus	0.45-0.47	Asia	5
Dacrydium sp.	0.46	Asia	5
Dacryodes buttneri	0.44-0.57	Africa	3
Dacryodes excelsa	0.52-0.53	Americas	5
Dacryodes sp.	0.61	Asia	5
Dactyodes colombiana	0.51	Americas	5
Dalbergia paniculata	0.64	Asia	5
Dalbergia retusa.	0.89	Americas	5
Dalbergia stevensonii	0.82	Americas	5
Daniellia oliveri	0.53	Africa	3
Declinanona calycina	0.47	Americas	5
Decussocarpus vitiensis	0.37	Asia	5

TABLE 4.13 BASIC WOOD DENSITY (D) OF TROPICAL TREE SPECIES (OVEN-DRY TONNES (MOIST M^{-3}))

1 = Baker *et al.*, 2004b; 2 = Barbosa and Fearnside, 2004; 3 = CTFT, 1989; 4 = Fearnside, 1997; 5 = Reyes *et al.*, 1992

Species	Density	Continent	Reference
Degeneria vitiensis	0.35	Asia	5
Dehaasia triandra	0.64	Asia	5
Dendropanax arboreum	0.40	Americas	4
Desbordesia pierreana	0.87	Africa	5
Detarium senegalensis	0.63	Africa	5
Dialium excelsum	0.78	Africa	5
Dialium guianense	0.88	Americas	4
Dialium sp.	0.80	Asia	5
Dialyanthera sp.	0.36-0.48	Americas	5
Diclinanona calycina	0.47	Americas	4
Dicorynia ghuianensis	0.65	Americas	4
Dicorynia paraensis	0.60	Americas	5
Didelotia africana	0.78	Africa	5
Didelotia letouzeyi	0.50	Africa	5
Didymopanax sp.	0.74	Americas	5
Dillenia sp.	0.59	Asia	5
Dimorphandra mora	0.99	Americas	5
Dinizia excelsa	0.86	Americas	4
Diospyros sp.	0.82	Africa	5
Diospyros sp.	0.47	Americas	1
Diospyros sp.	0.70	Asia	5
Diplodiscus paniculatus	0.63	Asia	5
Diploon cuspidatum	0.85	Americas	4
Diplotropis martiusii	0.74	Americas	1
Diplotropis purpurea	0.78	Americas	4
Dipterocarpus caudatus	0.61	Asia	5
Dipterocarpus eurynchus	0.56	Asia	5
Dipterocarpus gracilis	0.61	Asia	5
Dipterocarpus grandiflorus	0.62	Asia	5
Dipterocarpus kerrii	0.56	Asia	5
Dipterocarpus kunstlerii	0.57	Asia	5
Dipterocarpus sp.	0.61	Asia	5
Dipterocarpus warburgii	0.52	Asia	5
Dipteryx odorata	0.93	Americas	4
Dipteryx polyphylla	0.87	Americas	4
Discoglypremna caloneura	0.32	Africa	5
Distemonanthus benthamianus	0.58	Africa	5
Dracontomelon sp.	0.50	Asia	5
Dryobalanops sp.	0.61	Asia	5
Drypetes sp.	0.63	Africa	5
Drypetes variabilis	0.71	Americas	4
Dtypetes bordenii	0.75	Asia	5
Durio sp.	0.53	Asia	5
Dussia lehmannii	0.59	Americas	5
Dyera costulata	0.36	Asia	5
Dysoxylum quercifolium	0.49	Asia	5
Ecclinusa bacuri	0.59	Americas	4
Ecclinusa guianensis	0.63	Americas	5
Ehretia acuminata	0.51	Africa	5
Elaeocarpus serratus	0.40	Asia	5
Emblica officinalis	0.80	Asia	5
Enantia chlorantha	0.42	Africa	5
Endiandra laxiflora	0.54	Asia	5
Endlicheria sp.	0.50	Americas	1
Endodesmia calophylloides	0.66	Africa	5
Endopleura uchi	0.78	Americas	4
Endospermum sp.	0.38	Asia	5
Entandrophragma utile	0.53-0.62	Africa	3
Enterolobium cyclocarpum	0.34	Americas	4
Enterolobium cyclocarpum	0.35	Asia	5
Enterolobium maximum	0.40	Americas	4
Enterolobium schomburgkii	0.78	Americas	4
Eperua falcata	0.78	Americas	4
Epicharis cumingiana	0.73	Asia	5
Eribroma oblongum	0.60	Africa	5
Eriocoelum microspermum	0.50	Africa	5
Eriotheca longipedicellata	0.45	Americas	4
Erisma uncinatum	0.47	Americas	1
Erismadelphus ensul	0.56	Africa	5
Erythrina sp.	0.23	Americas	5
Erythrina subumbrans	0.24	Asia	5
Erythrina vogelii	0.25	Africa	5
Erythrophleum ivorense	0.70-0.88	Africa	3
Erythrophloeum densiflorum	0.65	Asia	5
Eschweilera amazonica	0.90	Americas	4
Eschweilera coriacea	0.78	Americas	4
Eschweilera ovata	0.81	Americas	4
Eschweilera sagotiana	0.79	Americas	4
Eucalyptus citriodora	0.64	Asia	5
Eucalyptus deglupta	0.34	Asia	5
Eucalyptus robusta	0.51	Americas	5
Eugenia sp.	0.65	Asia	5
Eugenia stahlii	0.73	Americas	5
Euxylophora paraensis	0.70	Americas	4
Fagara macrophylla	0.69	Africa	5
Fagara sp.	0.69	Americas	5
Fagraea sp.	0.73	Asia	5
Ficus benjamina	0.65	Asia	5
Ficus insipida	0.50	Americas	1
Ficus iteophylla	0.40	Africa	5
Fumtumia latifolia	0.45	Africa	5
Gallesia integrifolia	0.51	Americas	1
Gambeya sp.	0.56	Africa	5
Ganua obovatifolia	0.59	Asia	5
Garcinia myrtifolia	0.65	Asia	5
Garcinia punctata	0.78	Africa	5
Garcinia sp.	0.75	Asia	5
Gardenia turgida	0.64	Asia	5
Garuga pinnata	0.51	Asia	5
Genipa americana	0.51	Americas	4
Gilletiodendron mildbraedii	0.87	Africa	5
Gluta sp.	0.63	Asia	5
Glycydendron amazonicum	0.66	Americas	4
Gmelina arborea	0.41-0.45	Asia	5
Gmelina vitiensis	0.54	Asia	5
Gonocaryum calleryanum	0.64	Asia	5
Gonystylus punctatus	0.57	Asia	5
Gossweilerodendron balsamiferum	0.40	Africa	5
Goupia glabra	0.68	Americas	1
Grewia tiliaefolia	0.68	Asia	5
Guarea cedrata	0.48-0.57	Africa	3
Guarea chalde	0.52	Americas	5
Guarea guidonia	0.68	Americas	4
Guarea kunthiana	0.60	Americas	1
Guatteria decurrens	0.52	Americas	1
Guatteria olivacea	0.51	Americas	4
Guatteria procera	0.65	Americas	4

TABLE 4.13 BASIC WOOD DENSITY (D) OF TROPICAL TREE SPECIES (OVEN-DRY TONNES (MOIST M^{-3}))

1 = Baker *et al.*, 2004b; 2 = Barbosa and Fearnside, 2004; 3 = CTFT, 1989; 4 = Fearnside, 1997; 5 = Reyes *et al.*, 1992

Species	Density	Continent	Reference
Guazuma ulmifolia	0.50-0.52	Americas	5
Guibourtia demeusii	0.70-0.84	Africa	3
Guillielma gasipae	0.95-1.25	Americas	5
Gustavia speciosa	0.34	Americas	1
Hannoa klaineana	0.28	Africa	5
Hardwickia binata	0.73	Asia	5
Harpullia arborea	0.62	Asia	5
Harungana madagascariensis	0.45	Africa	5
Helicostylis tomentosa	0.72	Americas	4
Heritiera sp.	0.56	Asia	5
Hernandia Sonora	0.29	Americas	5
Hevea brasiliensis	0.49	Americas	4
Hevea brasiliensis	0.53	Asia	5
Hexalobus crispiflorus	0.48	Africa	5
Hibiscus tiliaceus	0.57	Asia	5
Hieronyma chocoensis	0.59-0.62	Americas	1
Hieronyma laxiflora	0.55	Americas	1
Himatanthus articulatus	0.38	Americas	2
Hirtella davisii	0.74	Americas	5
Holoptelea grandis	0.59	Africa	5
Homalanthus populneus	0.38	Asia	5
Homalium sp.	0.70	Africa	5
Homalium sp.	0.76	Asia	5
Hopea acuminata	0.62	Asia	5
Hopea sp.	0.64	Asia	5
Huberodendron patinoi	0.50	Americas	1
Humiria balsamifera	0.66	Americas	4
Humiriastrum excelsum	0.75	Americas	4
Humiriastrum procera	0.70	Americas	5
Hura crepitans	0.36	Americas	4
Hyeronima alchorneoides	0.64	Americas	4
Hyeronima laxiflora	0.59	Americas	5
Hylodendron gabonense	0.78	Africa	5
Hymenaea courbaril	0.77	Americas	1
Hymenaea davisii	0.67	Americas	5
Hymenaea oblongifolia	0.62	Americas	1
Hymenaea parvifolia	0.95	Americas	4
Hymenolobium excelsum	0.64	Americas	4
Hymenolobium modestum	0.65	Americas	4
Hymenolobium pulcherrimum	0.67	Americas	4
Hymenostegia pellegrini	0.78	Africa	5
Inga alba	0.62	Americas	4
Inga edulis	0.51	Americas	1
Inga paraensis	0.82	Americas	4
Intsia palembanica	0.68	Asia	5
Irvingia grandifolia	0.78	Africa	5
Iryanthera grandis	0.55	Americas	4
Iryanthera sagotiana	0.57	Americas	4
Iryanthera trocornis	0.72	Americas	4
Jacaranda copaia	0.33	Americas	4
Joannesia heveoides	0.39	Americas	4
Julbernardia globiflora	0.78	Africa	5
Kayea garciae	0.53	Asia	5
Khaya ivorensis	0.40-0.48	Africa	3
Kingiodendron alternifolium	0.48	Asia	5
Klainedoxa gabonensis	0.87	Africa	5
Kleinhovia hospita	0.36	Asia	5
Knema sp.	0.53	Asia	5
Koompassia excelsa	0.63	Asia	5
Koordersiodendron pinnatum	0.65-0.69	Asia	5
Kydia calycina	0.72	Asia	5
Lachmellea speciosa	0.73	Americas	5
Laetia procera	0.63	Americas	1
Lagerstroemia sp.	0.55	Asia	5
Lannea grandis	0.50	Asia	5
Lecomtedoxa klainenna	0.78	Africa	5
Lecythis idatimon	0.77	Americas	4
Lecythis lurida	0.83	Americas	4
Lecythis pisonis	0.84	Americas	4
Lecythis poltequi	0.81	Americas	4
Lecythis zabucaja	0.86	Americas	4
Letestua durissima	0.87	Africa	5
Leucaena leucocephala	0.64	Asia	5
Licania macrophylla	0.76	Americas	4
Licania oblongifolia	0.88	Americas	4
Licania octandra	0.77	Americas	4
Licania unguiculata	0.88	Americas	1
Licaria aritu	0.80	Americas	4
Licaria cannella	1.04	Americas	4
Licaria rigida	0.73	Americas	4
Lindackeria sp.	0.41	Americas	5
Linociera domingensis	0.81	Americas	5
Lithocarpus soleriana	0.63	Asia	5
Litsea sp.	0.40	Asia	5
Lonchocarpus sp.	0.69	Americas	5
Lophira alata	0.84-0.97	Africa	3
Lophopetalum sp.	0.46	Asia	5
Lovoa trichilioides	0.45	Africa	5
Loxopterygium sagotii	0.56	Americas	5
Lucuma sp.	0.79	Americas	5
Luehea sp.	0.50	Americas	5
Lueheopsis duckeana	0.62	Americas	4
Mabea piriri	0.59	Americas	5
Macaranga denticulata	0.53	Asia	5
Machaerium sp.	0.70	Americas	5
Maclura tinctoria	0.71	Americas	1
Macoubea guianensis	0.40	Americas	5
Madhuca oblongifolia	0.53	Asia	5
Maesopsis eminii	0.41	Africa	5
Magnolia sp.	0.52	Americas	5
Maguira sclerophylla	0.57	Americas	5
Malacantha sp.	0.45	Africa	5
Mallotus philippinensis	0.64	Asia	5
Malouetia duckei	0.57	Americas	4
Mammea africana	0.62	Africa	5
Mammea americana	0.62	Americas	5
Mangifera indica	0.55	Americas	5
Mangifera sp.	0.52	Asia	5
Manilkara amazonica	0.85	Americas	4
Manilkara bidentata	0.87	Americas	1
Manilkara huberi	0.93	Americas	4
Manilkara lacera	0.78	Africa	5
Maniltoa minor	0.76	Asia	5
Maquira sclerophylla	0.57	Americas	4
Marila sp.	0.63	Americas	5
Markhamia platycalyx	0.45	Africa	5
Marmaroxylon racemosum	0.81	Americas	4
Mastixia philippinensis	0.47	Asia	5
Matayba domingensis	0.70	Americas	5
Matisia hirta	0.61	Americas	5
Mauria sp.	0.31	Americas	1
Maytenus sp.	0.71	Americas	5
Melanorrhea sp.	0.63	Asia	5
Melia dubia	0.40	Asia	5
Melicope triphylla	0.37	Asia	5
Meliosma macrophylla	0.27	Asia	5

TABLE 4.13 BASIC WOOD DENSITY (D) OF TROPICAL TREE SPECIES (OVEN-DRY TONNES (MOIST M^{-3}))

1 = Baker *et al.*, 2004b; 2 = Barbosa and Fearnside, 2004; 3 = CTFT, 1989; 4 = Fearnside, 1997; 5 = Reyes *et al.*, 1992

TABLE 4.13 BASIC WOOD DENSITY (D) OF TROPICAL TREE SPECIES (OVEN-DRY TONNES (MOIST M^{-3}))

1 = Baker *et al.*, 2004b; 2 = Barbosa and Fearnside, 2004; 3 = CTFT, 1989; 4 = Fearnside, 1997; 5 = Reyes *et al.*, 1992

Species	Density	Continent	Reference
Melochia umbellata	0.25	Asia	5
Memecylon capitellatum	0.77	Africa	5
Metrosideros collina	0.70-0.76	Asia	5
Mezilaurus itauba	0.70	Americas	4
Mezilaurus lindaviana	0.68	Americas	4
Michelia sp.	0.43	Asia	5
Michropholis sp.	0.61	Americas	5
Microberlinia brazzavillensis	0.70	Africa	5
Microcos coriaceus	0.42	Africa	5
Microcos stylocarpa	0.40	Asia	5
Micromelum compressum	0.64	Asia	5
Micropholi guyanensis	0.65	Americas	4
Micropholi venulosa	0.67	Americas	4
Milletia sp.	0.72	Africa	5
Milliusa velutina	0.63	Asia	5
Mimusops elengi	0.72	Asia	5
Minquartia guianensis	0.76	Americas	1
Mitragyna parviflora	0.56	Asia	5
Mitragyna stipulosa	0.47	Africa	5
Monopetalanthus heitzii	0.44-0.53	Africa	3
Mora excelsa	0.80	Americas	4
Mora gonggrijpii	0.78	Americas	1
Mora megistosperma	0.63	Americas	1
Mouriri barinensis	0.78	Americas	1
Mouriria sideroxylon	0.88	Americas	5
Musanga cecropioides	0.23	Africa	5
Myrciaria floribunda	0.73	Americas	5
Myristica platysperma	0.55	Americas	4
Myristica sp.	0.53	Asia	5
Myroxylon balsamum	0.78	Americas	1
Myroxylon peruiferum	0.78	Americas	1
Nauclea diderrichii	0.63	Africa	5
Nealchornea yapurensis	0.61	Americas	1
Nectandra rubra	0.57	Americas	5
Neesia sp.	0.53	Asia	5
Neonauclea bernardoi	0.62	Asia	5
Neopoutonia macrocalyx	0.32	Africa	5
Neotrewia cumingii	0.55	Asia	5
Nesogordonia papaverifera	0.65	Africa	5
Ochna foxworthyi	0.86	Asia	5
Ochroma pyramidale	0.30	Asia	5
Ochtocosmus africanus	0.78	Africa	5
Ocotea guianensis	0.63	Americas	4
Ocotea neesiana	0.63	Americas	4
Octomeles sumatrana	0.27-0.32	Asia	5
Odyendea sp.	0.32	Africa	5
Oldfieldia africana	0.78	Africa	5
Ongokea gore	0.72	Africa	5
Onychopetalum amazonicum	0.61	Americas	4
Ormosia coccinea	0.61	Americas	1
Ormosia paraensis	0.67	Americas	4
Ormosia schunkei	0.57	Americas	1
Oroxylon indicum	0.32	Asia	5
Otoba gracilipes	0.32	Americas	1
Ougenia dalbergiodes	0.70	Asia	5
Ouratea sp.	0.66	Americas	5
Oxystigma oxyphyllum	0.53	Africa	5
Pachira acuatica	0.43	Americas	5
Pachyelasma tessmannii	0.70	Africa	5
Pachypodanthium staudtii	0.58	Africa	5
Palaquium sp.	0.55	Asia	5
Pangium edule	0.50	Asia	5
Paraberlinia bifoliolata	0.56	Africa	5
Parashorea stellata	0.59	Asia	5
Paratecoma peroba	0.60	Americas	5
Paratrophis glabra	0.77	Asia	5
Parinari excelsa	0.68	Americas	4
Parinari glabra	0.87	Africa	5
Parinari montana	0.71	Americas	4
Parinari rodolphii	0.71	Americas	4
Parinari sp.	0.68	Asia	5
Parkia multijuga	0.38	Americas	4
Parkia nitada	0.40	Americas	4
Parkia paraensis	0.44	Americas	4
Parkia pendula	0.55	Americas	4
Parkia roxburghii	0.34	Asia	5
Parkia ulei	0.40	Americas	4
Pausandra trianae	0.59	Americas	1
Pausinystalia brachythyrsa	0.56	Africa	5
Pausinystalia sp.	0.56	Africa	5
Payena sp.	0.55	Asia	5
Peltogyne paniculata	0.89	Americas	4
Peltogyne paradoxa	0.91	Americas	4
Peltogyne porphyrocardia	0.89	Americas	1
Peltophorum pterocarpum	0.62	Asia	5
Pentace sp.	0.56	Asia	5
Pentaclethra macroloba	0.43	Americas	1
Pentaclethra macrophylla	0.78	Africa	5
Pentadesma butyracea	0.78	Africa	5
Persea sp.	0.40-0.52	Americas	5
Peru glabrata	0.65	Americas	5
Peru schomburgkiana	0.59	Americas	5
Petitia domingensis	0.66	Americas	5
Phaeanthus ebracteolatus	0.56	Asia	5
Phyllanthus discoideus	0.76	Africa	5
Phyllocladus hypophyllus	0.53	Asia	5
Phyllostylon brasiliensis	0.77	Americas	4
Pierreodendron africanum	0.70	Africa	5
Pinus caribaea	0.51	Americas	5
Pinus caribaea	0.48	Asia	5
Pinus insularis	0.47-0.48	Asia	5
Pinus merkusii	0.54	Asia	5
Pinus oocarpa	0.55	Americas	5
Pinus patula	0.45	Americas	5
Piptadenia communis	0.68	Americas	4
Piptadenia grata	0.86	Americas	1
Piptadenia suaveolens	0.75	Americas	4
Piptadeniastrum africanum	0.56	Africa	5
Piratinera guianensis	0.96	Americas	5
Pisonia umbellifera	0.21	Asia	5
Pithecellobium guachapele	0.56	Americas	5
Pithecellobium latifolium	0.36	Americas	1
Pithecellobium saman	0.49	Americas	1
Pittosporum pentandrum	0.51	Asia	5
Plagiostyles africana	0.70	Africa	5
Planchonia sp.	0.59	Asia	5
Platonia insignis	0.70	Americas	5

TABLE 4.13 BASIC WOOD DENSITY (D) OF TROPICAL TREE SPECIES (OVEN-DRY TONNES (MOIST M^{-3}))
1 = Baker *et al.*, 2004b; 2 = Barbosa and Fearnside, 2004;
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TABLE 4.13 BASIC WOOD DENSITY (D) OF TROPICAL TREE SPECIES (OVEN-DRY TONNES (MOIST M^{-3}))
1 = Baker *et al.*, 2004b; 2 = Barbosa and Fearnside, 2004;
3 = CTFT, 1989; 4 = Fearnside, 1997; 5 = Reyes *et al.*, 1992

Species	Density	Continent	Reference
Platymiscium sp.	0.71-0.84	Americas	5
Podocarpus oleifolius	0.44	Americas	1
Podocarpus rospigliosii	0.57	Americas	1
Podocarpus sp.	0.43	Asia	5
Poga oleosa	0.36	Africa	5
Polyalthia flava	0.51	Asia	5
Polyalthia suaveolens	0.66	Africa	5
Polyscias nodosa	0.38	Asia	5
Pometia sp.	0.54	Asia	5
Poulsenia armata	0.37-0.44	Americas	1
Pourouma sp.	0.32	Americas	5
Pouteria anibifolia	0.66	Americas	1
Pouteria anomala	0.81	Americas	4
Pouteria caimito	0.87	Americas	4
Pouteria guianensis	0.90	Americas	4
Pouteria manaosensis	0.64	Americas	4
Pouteria oppositifolia	0.65	Americas	4
Pouteria villamilii	0.47	Asia	5
Premna angolensis	0.63	Africa	5
Premna tomentosa	0.96	Asia	5
Prioria copaifera	0.40-0.41	Americas	5
Protium heptaphyllum	0.54	Americas	4
Protium tenuifolium	0.65	Americas	4
Pseudolmedia laevigata	0.62-0.63	Americas	1
Pseudolmedia laevis	0.71	Americas	1
Pteleopsis hylodendron	0.63	Africa	5
Pterocarpus marsupium	0.67	Asia	5
Pterocarpus soyauxii	0.62-0.79	Africa	3
Pterocarpus vernalis	0.57	Americas	1
Pterogyne nitens	0.66	Americas	4
Pterygota sp.	0.52	Africa	5
Pterygota sp.	0.62	Americas	1
Pycnanthus angolensis	0.40-0.53	Africa	3
Qualea albiflora	0.50	Americas	5
Qualea brevipedicellata	0.69	Americas	4
Qualea dinizii	0.58	Americas	5
Qualea lancifolia	0.58	Americas	4
Qualea paraensis	0.67	Americas	4
Quararibea asterolepis	0.45	Americas	1
Quararibea bicolor	0.52-0.53	Americas	1
Quararibea cordata	0.43	Americas	1
Quassia simarouba	0.37	Americas	4
Quercus alata	0.71	Americas	5
Quercus costaricensis	0.61	Americas	5
Quercus eugeniaefolia	0.67	Americas	5
Quercus sp.	0.70	Asia	5
Radermachera pinnata	0.51	Asia	5
Randia cladantha	0.78	Africa	5
Raputia sp.	0.55	Americas	5
Rauwolfia macrophylla	0.47	Africa	5
Rheedia sp.	0.60	Americas	1
Rhizophora mangle	0.89	Americas	4
Ricinodendron heudelotii	0.20	Africa	5
Rollinia exsucca	0.52	Americas	4
Roupala moniana	0.77	Americas	4
Ruizierania albiflora	0.57	Americas	4
Saccoglottis gabonensis	0.74	Africa	5
Saccoglottis guianensis	0.77	Americas	4
Salmalia malabarica	0.32-0.33	Asia	5
Samanea saman	0.45-0.46	Asia	5
Sandoricum vidalii	0.43	Asia	5
Santiria trimera	0.53	Africa	5
Sapindus saponaria	0.58	Asia	5
Sapium ellipticum	0.50	Africa	5
Sapium luzontcum	0.40	Asia	5
Sapium marmieri	0.40	Americas	1
Schefflera morototoni	0.36	Americas	1
Schizolobium parahyba	0.40	Americas	1
Schleichera oleosa	0.96	Asia	5
Schrebera arborea	0.63	Africa	5
Schrebera swietenoides	0.82	Asia	5
Sclerolobium chrysopyllum	0.62	Americas	4
Sclerolobium paraense	0.64	Americas	4
Sclerolobium peoppigianum	0.65	Americas	4
Scleronema micranthum	0.61	Americas	4
Sclorodophloeus zenkeri	0.68	Africa	5
Scottellia coriacea	0.56	Africa	5
Scyphocephalium ochocoa	0.48	Africa	5
Scytopetalum tieghemii	0.56	Africa	5
Semicarpus anacardium	0.64	Asia	5
Serialbizia acle	0.57	Asia	5
Serianthes melanesica	0.48	Asia	5
Sesbania grandiflora	0.40	Asia	5
Shorea assamica forma philippinensis	0.41	Asia	5
Shorea astylosa	0.73	Asia	5
Shorea ciliata	0.75	Asia	5
Shorea contorta	0.44	Asia	5
Shorea palosapis	0.39	Asia	5
Shorea plagata	0.70	Asia	5
Shorea polita	0.47	Asia	5
Shorea robusta	0.72	Asia	5
Shorea sp. (balau)	0.70	Asia	5
Shorea sp. (dark red meranti)	0.55	Asia	5
Shorea sp. (light red meranti)	0.40	Asia	5
Sickingia sp.	0.52	Americas	5
Simaba multiflora	0.51	Americas	5
Simarouba amara	0.36	Americas	1
Simira sp.	0.65	Americas	1
Sindoropsis letestui	0.56	Africa	5
Sloanea guianensis	0.79	Americas	5
Sloanea javanica	0.53	Asia	5
Sloanea nitida	1.01	Americas	4
Soymida febrifuga	0.97	Asia	5
Spathodea campanulata	0.25	Asia	5
Spondias lutea	0.38	Americas	4
Spondias mombin	0.31-0.35	Americas	1
Spondias purpurea	0.40	Americas	4
Staudtia stipitata	0.75	Africa	5
Stemonurus luzoniensis	0.37	Asia	5
Sterculia apetala	0.33	Americas	4
Sterculia pruriens	0.46	Americas	4
Sterculia rhinopetala	0.64	Africa	5
Sterculia speciosa	0.51	Americas	4
Sterculia vitiensis	0.31	Asia	5
Stereospermum suaveolens	0.62	Asia	5
Strephonema pseudocola	0.56	Africa	5
Strombosia philippinensis	0.71	Asia	5
Strombosiopsis tetrandra	0.63	Africa	5
Strychnos potatorum	0.88	Asia	5
Stylogyne sp.	0.69	Americas	5
Swartzia fistuloides	0.82	Africa	5
Swartzia laevicarpa	0.61	Americas	1
Swartzia panacoco	0.97	Americas	4
Swietenia macrophylla	0.43	Americas	1
Swietenia macrophylla	0.49-0.53	Asia	5

TABLE 4.13 BASIC WOOD DENSITY (D) OF TROPICAL TREE SPECIES (OVEN-DRY TONNES (MOIST M^{-3}))

1 = Baker *et al.*, 2004b; 2 = Barbosa and Fearnside, 2004; 3 = CTFT, 1989; 4 = Fearnside, 1997; 5 = Reyes *et al.*, 1992

Species	Density	Continent	Reference
Swintonia foxworthyi	0.62	Asia	5
Swintonia sp.	0.61	Asia	5
Sycopsis dunni	0.63	Asia	5
Symphonia globulifera	0.58	Africa	5
Symphonia globulifera	0.58	Americas	1
Syzygium cordatum	0.59	Africa	5
Syzygium sp.	0.69-0.76	Asia	5
Tabebuia rosea	0.54	Americas	1
Tabebuia serratifolia	0.92	Americas	1
Tabebuia stenocalyx	0.55-0.57	Americas	5
Tachigalia myrmecophylla	0.53	Americas	4
Talisia sp.	0.84	Americas	5
Tamarindus indica	0.75	Asia	5
Tapirira guianensis	0.50	Americas	4
Taralea oppositifolia	0.80	Americas	1
Tectona grandis	0.50-0.55	Asia	5
Terminalia amazonica	0.65	Americas	1
Terminalia citrina	0.71	Asia	5
Terminalia copelandii	0.46	Asia	5
Terminalia ivorensis	0.40-0.59	Africa	3
Terminalia microcarpa	0.53	Asia	5
Terminalia nitens	0.58	Asia	5
Terminalia oblonga	0.73	Americas	1
Terminalia pterocarpa	0.48	Asia	5
Terminalia superba	0.40-0.66	Africa	3
Terminalia tomentosa	0.73-0.77	Asia	5
Ternstroemia megacarpa	0.53	Asia	5
Tessmania africana	0.85	Africa	5
Testulea gabonensis	0.60	Africa	5
Tetragastris altissima	0.74	Americas	4
Tetragastris panamensis	0.76	Americas	4
Tetrameles nudiflora	0.30	Asia	5
Tetramerista glabra	0.61	Asia	5
Tetrapleura tetraptera	0.50	Africa	5
Thespesia populnea	0.52	Asia	5
Thyrsodium guianensis	0.63	Americas	4
Tieghemella africana	0.53-0.66	Africa	3
Toluifera balsamum	0.74	Americas	5
Torrubia sp.	0.52	Americas	5
Toulicia pulvinata	0.63	Americas	5
Tovomita guianensis	0.60	Americas	5
Trattinickia sp.	0.38	Americas	5
Trema orientalis	0.31	Asia	5
Trema sp.	0.40	Africa	5
Trichilia lecointei	0.90	Americas	4
Trichilia prieureana	0.63	Africa	5
Trichilia propingua	0.58	Americas	5
Trichoscypha arborea	0.59	Africa	5
Trichosperma mexicanum	0.41	Americas	5
Trichospermum richii	0.32	Asia	5
Triplaris cumingiana	0.53	Americas	5
Triplochiton scleroxylon.	0.28-0.44	Africa	3
Tristania sp.	0.80	Asia	5
Trophis sp.	0.44	Americas	1
Turpinia ovalifolia	0.36	Asia	5
Vantanea parviflora	0.86	Americas	4
Vatairea guianensis	0.70	Americas	4
Vatairea paraensis	0.78	Americas	4
Vatairea sericea	0.64	Americas	4
Vateria indica	0.47	Asia	5
Vatica sp.	0.69	Asia	5
Vepris undulata	0.70	Africa	5
Virola michelii	0.50	Americas	4
Virola reidii	0.35	Americas	1
Virola sebifera	0.37	Americas	1
Vismia sp.	0.41	Americas	5
Vitex doniana	0.40	Africa	5
Vitex sp.	0.52-0.57	Americas	5
Vitex sp.	0.65	Asia	5
Vitex stahelii	0.60	Americas	5
Vochysia densiflora	0.29	Americas	1
Vochysia ferruginea	0.37	Americas	1
Vochysia guianensis	0.53	Americas	4
Vochysia lanceolata	0.49	Americas	1
Vochysia macrophylla	0.36	Americas	1
Vochysia maxima	0.47	Americas	4
Vochysia melinonii	0.51	Americas	4
Vochysia obidensis	0.50	Americas	4
Vochysia surinamensis	0.66	Americas	4
Vouacapoua americana	0.79	Americas	4
Warszewicsia coccinea	0.56	Americas	5
Wrightia tinctorea	0.75	Asia	5
Xanthophyllum excelsum	0.63	Asia	5
Xanthoxylum martinicensis	0.46	Americas	5
Xanthoxylum sp.	0.44	Americas	5
Xylia xylocarpa	0.73-0.81	Asia	5
Xylopia frutescens	0.64	Americas	5
Xylopia nitida	0.57	Americas	4
Xylopia staudtii	0.36	Africa	5
Zanthoxylum rhetsa	0.33	Asia	5
Zizyphus sp.	0.76	Asia	5

TABLE 4.14
BASIC WOOD DENSITY (D) OF SELECTED TEMPERATE AND BOREAL TREE TAXA

Taxon	**D [oven-dry tonnes (moist m^{-3})]**	**Source**
Abies spp.	0.40	2
Acer spp.	0.52	2
Alnus spp.	0.45	2
Betula spp.	0.51	2
Fagus sylvatica	0.58	2
Fraxinus spp.	0.57	2
Larix decidua	0.46	2
Picea abies	0.40	2
Picea sitchensis	0.40	3
Pinus pinaster	0.44	4
Pinus radiata	0.38 (0.33 - 0.45)	1
Pinus strobus	0.32	2
Pinus sylvestris	0.42	2
Populus spp.	0.35	2
Prunus spp.	0.49	2
Pseudotsuga menziesii	0.45	2
Quercus spp.	0.58	2
Salix spp.	0.45	2
Tilia spp.	0.43	2

1 = Beets et al., 2001

2 = Dietz, 1975

3 = Knigge and Shulz, 1966

4 = Rijsdijk and Laming, 1994

Annex 4A.1 Glossary for Forest Land

Terminology for stocks and changes in forests as defined in this volume			
Component	**State**	**Increase**	**Decrease from harvest**
Merchantable volume	growing stock	net annual increment	removals
Biomass in the merchantable volume	growing stock biomass	increment biomass	removals biomass
Total above-ground biomass	above-ground biomass	above-ground biomass growth	above-ground biomass removals
Total below-ground biomass	below-ground biomass	below-ground biomass growth	below-ground biomass[1] removals
Total above-ground and below-ground biomass	total biomass	total biomass growth	biomass removals
Carbon	carbon in … (in any of the compartments above, e.g., carbon in growing stock or biomass removals), or in litter, dead wood and soil organic matter		

ABOVE-GROUND BIOMASS

All biomass of living vegetation, both woody and herbaceous, above the soil including stems, stumps, branches, bark, seeds, and foliage.

Note: In cases where forest understory is a relatively small component of the above-ground biomass carbon pool, it is acceptable for the methodologies and associated data used in some tiers to exclude it, provided the tiers are used in a consistent manner throughout the inventory time series.

ABOVE-GROUND BIOMASS GROWTH

Oven-dry weight of net annual increment (s.b.) of a tree, stand or forest plus oven-dry weight of annual growth of branches, twigs, foliage, top and stump. The term "growth" is used here instead of "increment", since the latter term tends to be understood in terms of merchantable volume.

AFFORESTATION[2]

The direct human-induced conversion of land that has not been forested for a period of at least 50 years to forested land through planting, seeding and/or the human-induced promotion of natural seed sources.

AGROFORESTRY

A land-use system that involves deliberate retention, introduction, or mixture of trees or other woody perennials in crop and animal production systems to take advantage of economic or ecological interactions among the components (Dictionary of Forestry, helms, 1998, Society of American Foresters).

BASIC WOOD DENSITY

Ratio between oven dry mass and fresh stem-wood volume without bark.

BELOW-GROUND BIOMASS

All biomass of live roots. Fine roots of less than (suggested) 2mm diameter are often excluded because these often cannot be distinguished empirically from soil organic matter or litter.

BIOMASS CONVERSION AND EXPANSION FACTOR (BCEF)

A multiplication factor that coverts merchantable volume of growing stock, merchantable volume of net annual increment, or merchantable volume of wood-removal and fuelwood-removals to above-ground biomass, above-ground biomass growth, or biomass removals, repectively. Biomass conversion and expansion factors for

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[1] Occurs in some cases, e.g., where root stocks (walnut) or entire root systems are removed (biomass harvesting).

[2] In the context of the Kyoto Protocol, as stipulated by the Marrakesh Accords, cf. paragraph 1 of the Annex to draft decision -/CMP.1 (Land Use, Land-use Change and Forestry) contained in document FCCC/CP/2001/13/Add.1, p.58.

growing stock ($BCEF_S$), for net annual increment ($BCEF_I$), and for wood-removal and fuelwood-removals ($BCEF_R$) usually differ. As used in these guidelines, they account for above-ground components only. For more detail see Box 4.2.

BIOMASS EXPANSION FACTOR (BEF)

A multiplication factor that expands the dry-weight of *growing stock biomass*, *increment biomass*, and biomass of *wood-removal or fuelwood-removals* to account for non-merchantable or non-commercial biomass components, such as stump, branches, twigs, foliage, and, sometimes, non-commercial trees. Biomass expansion factors usually differ for growing stock (BEF_S), net annual increment (BEF_I), and wood-removal and fuelwood-removals (BEF_R). As used in these guidelines, biomass expansion factors account for above-ground components only. For more detail see Box 4.2.

BIOMASS REMOVALS

Biomass of wood-removal and firewood-removals (s.b.) plus oven-dry weight of branches, twigs, foliage of the trees or stands removed.

CANOPY COVER

See crown cover

CARBON CONTENT

Absolute amount of carbon in a pool or parts of it.

CARBON FRACTION

Tonnes of carbon per tonne of biomass dry matter.

CARBON IN...

See table above; absolute amount in tonnes, obtained by multiplying amount of biomass in respective component by the applicable carbon fraction, usually 50%.

CARBON STOCK

The quantity of carbon in a pool.

CARBON STOCK CHANGE

The carbon stock in a pool changes due to gains and losses. When losses exceed gains, the stock decreases, and the pool acts as a source; when gains exceed losses, the pools accumulate carbon, and the pools act as a sink.

CLOSED FOREST

Formations where trees, in the various stories and the undergrowth, cover a high proportion of the ground (>40%).

CONVERSION

Change of one land use to another.

CONVERSION FACTOR

Multiplier that transforms the measurement units of an item without affecting its size or amount. For example, basic wood density is a conversion factor that transforms green volume of wood into dry weight.

CROWN COVER

The percentage of the ground covered by a vertical projection of the outermost perimeter of the natural spread of the foliage (cannot exceed 100%).

DEAD WOOD

Includes all non-living woody biomass not contained in the litter, either standing, lying on the ground, or in the soil. Dead wood includes wood lying on the surface, dead roots, and stumps, larger than or equal to 10cm in diameter (or the diameter specified by the country).

DEAD WOOD BIOMASS

All non-living woody biomass not contained in the litter, either standing, lying on the ground, or in the soil. Dead wood includes wood lying on the surface, dead roots down to a diameter of 2mm, and stumps larger than or equal to 10cm in diameter or any other diameter used by the country.

DEFORESTATION[3]

The direct human-induced conversion of forested land to non-forested land.

DISTURBANCE

A disturbance is defined as an environmental fluctuation and destructive event that disturb forest health, structure, and/or change resources or physical environment at any given spatial or temporal scale. Disturbances that affect health and vitality which include biotic agents such as insects and diseases, and abiotic agents such as fire, pollution, and extreme weather conditions (see also below, mortality and other disturbance).

DISTURBANCE BY DISEASES

Disturbances caused by diseases attributable to pathogens such as bacteria, fungi, phytoplasma, or virus.

DISTURBANCE BY FIRE

Disturbance caused by wildfire regardless of whether it broke out inside or outside the Forest. A wildfire is any unplanned and uncontrolled wildland fire which, regardless of ignition source, may require suppression response.

DISTURBANCE BY INSECTS

Disturbance caused by insect pests that are detrimental to tree health.

DRY (FOREST)

Moisture regimes for boreal and temperate zones are defined by the ratio of mean annual precipitation (MAP) and potential evapotranspiration (PET): Dry (MAP/PET < 1) and Wet (MAP/PET > 1); and for tropical zones by precipitation alone: Dry (MAP < 1,000mm), Moist (MAP: 1,000-2,000mm) and Wet (MAP > 2,000mm).

DRY MATTER (D.M.)

Dry matter refers to biomass that has been dried to an oven-dry state, often at 70ºC.

FELLINGS

Volume (over bark) of all trees, living or dead, above a 10cm diameter at breast height, felled annually in forests or other wooded land. It includes volume of all felled trees whether or not they are removed. It includes silvicultural and pre-commercial thinning and cleanings of trees of more than 10cm diameter, left in the forest, and natural losses that are recovered.

Note: In these guidelines, only the terms “wood-removal” and “fuelwood-removals” are used, consistent with GFRA 2005. Removals are generally a subset of fellings.

FOREST[4]

Forest is a minimum area of land of 0.05 – 1.0 hectares with tree crown cover (or equivalent stocking level) of more than 10 – 30 per cent with trees with the potential to reach a minimum height of 2 – 5 metres at maturity *in situ*. A forest may consist either of closed forest formations where trees of various storeys and undergrowth cover a high portion of the ground or open forest. Young natural stands and all plantations which have yet to reach a crown density of 10 – 30 per cent or tree height of 2 – 5 metres are included under forest, as are areas normally forming part of the forest area which are temporarily unstocked as a result of human intervention such as harvesting or natural causes but which are expected to revert to forest.

FOREST INVENTORY

System for measuring the extent, quantity, and condition of a forest, usually by sampling:

1. A set of objective sampling methods designed to quantify the spatial distribution, composition, and rates of change of forest parameters within specified levels of precision for the purpose of management;
2. The listing of data from such a survey. May be made of all forest resources including trees and other vegetation, fish, insects, and wildlife, as well as street trees and urban forest trees.

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[3] In the context of the Kyoto Protocol, as stipulated by the Marrakesh Accords, cf. paragraph 1 of the Annex to draft decision -/CMP.1 (Land Use, Land-use Change and Forestry) contained in document FCCC/CP/2001/13/Add.1, p.58.

[4] In the context of the Kyoto Protocol, as stipulated by the Marrakesh Accords, cf. paragraph 1 of the Annex to draft decision -/CMP.1 (Land Use, Land-use Change and Forestry) contained in document FCCC/CP/2001/13/Add.1, p.58.

FOREST LAND

This category includes all land with woody vegetation consistent with thresholds used to define Forest Land in the national greenhouse gas inventory. It also includes systems with a vegetation structure that currently fall below, but *in situ* could potentially reach the threshold values used by a country to define the Forest Land category.

FOREST MANAGEMENT[5]

A system of practices for stewardship and use of forest land aimed at fulfilling relevant ecological (including biological diversity), economic and social functions of the forest in a sustainable manner.

FOREST PLANTATION

Forest stands established by planting or/and seeding in the process of afforestation or reforestation. They are either of introduced species (all planted stands), or intensively managed stands of indigenous species, which meet all the following criteria: one or two species at planting, even age class, and regular spacing.

FUELWOOD-REMOVAL

The wood removed for energy production purposes, regardless of whether for industrial, commercial, or domestic use. Fuel wood includes wood collected or removed directly from forest or other wooded land for energy purposes only. It excludes fuelwood which is produced as a by-product or residual matter from the industrial processing of round wood. It includes removal from fellings in an earlier period and from trees killed or damaged by natural causes. It also includes removal by local people or owners for their own use.

GROWING STOCK

Volume over bark of all living trees more than X cm in diameter at breast height. It includes the stem from ground level or stump height up to a top diameter of Y cm, and may also include branches to a minimum diameter of W cm. Countries indicate the three thresholds (X, Y, W in cm) and the parts of the tree that are not included in the volume. Countries also indicate whether the reported figures refer to volume above ground or above stump. The diameter is measured at 30cm above the end of the buttresses if these are higher than 1 meter. It includes windfallen living trees and excludes smaller branches, twigs, foliage, flowers, seeds, and roots.

GROWING STOCK BIOMASS

Oven-dry weight of the growing stock (s.a.).

HARVEST LOSS

Difference between the assessed merchantable volume of growing stock and the actual volume of the harvested timber. Due to different measurement rules for standing and felled timber, losses are from bucking, breakage, defect.

INCREMENT BIOMASS

Oven-dry weight of (merchantable) net annual increment of a tree, stand, or forest.

INTENSIVE FOREST MANAGEMENT

A regime of forest management, where silvicultural practices define the structure and composition of forest stands. A formal or informal forest management plan exists.

A forest is not under intensive management, if mainly natural ecological processes define the structure and composition of stands.

INTRODUCED SPECIES

A species introduced outside of its normal past and current distribution.

LITTER

Includes all non-living biomass with a size greater than the limit for soil organic matter (suggested 2mm) and less than the minimum diameter chosen for dead wood (e.g., 10cm), lying dead, in various states of decomposition above or within the mineral or organic soil. This includes the litter layer as usually defined in soil

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[5] Forest management has particular meaning under the Marrakesh Accords, which may require subdivision of the managed forest as described in Chapter 4.

typologies. Live fine roots above the mineral or organic soil (of less than the minimum diameter limit chosen for below-ground biomass) are included in litter where they cannot be distinguished from it empirically.

LOW ACTIVITY CLAY (LAC) SOILS

Soils with low activity clay (LAC) minerals are highly weathered soils dominated by 1:1 clay mineral and amorphous iron and aluminium oxides (in FAO classification included: Acrisols, Nitosols, Ferrasols).

MANAGED FOREST

A managed forest is forest land subjected to conditions defined for managed land.

MANAGED LAND

Managed land is land where human interventions and practices have been applied to perform production, ecological or social functions.

MERCHANTABLE VOLUME

Mechantable volume is the volume overbark of all trees defined using the conditions described for growing stocks. Further, this can be applied to growing stocks as well as net annual increment and wood removals.

MOIST (FOREST)

Moisture regimes for boreal and temperate zones are defined by the ratio of mean annual precipitation (MAP) and potential evapotranspiration (PET): Dry (MAP/PET < 1) and Wet (MAP/PET > 1); and for tropical zones by precipitation alone: Dry (MAP < 1,000mm), Moist (MAP: 1,000-2,000mm) and Wet (MAP > 2,000mm).

MORTALITY

Trees dying naturally from competition in the stem-exclusion stage of a stand or forest. As used here, mortality does not include losses due to disturbances (s.a.).

NATURAL FOREST

A forest composed of indigenous trees and not classified as a forest plantation.

NATURAL REGENERATION

Re-establishment of a forest stand by natural means i.e., by natural seeding or vegetative regeneration. It may be assisted by human intervention e.g., by scarification of the soil or fencing to protect against wildlife or domestic animal grazing.

NET ANNUAL INCREMENT

Average annual volume of gross increment over the given reference period minus mortality (s.a.), of all trees to a specified minimum diameter at breast height. As used here, it is not net of losses due to disturbances (s.a.).

ORGANIC SOILS

Soils are organic if they satisfy the requirements 1 and 2, or 1 and 3 below (FAO, 1998):

1) Thickness of organic horizon greater than or equal to 10cm. A horizon of less than 20cm must have 12 percent or more organic carbon when mixed to a depth of 20cm.
2) Soils that are never saturated with water for more than a few days must contain more than 20 percent organic carbon by weight (i.e., about 35 percent organic matter).
3) Soils are subject to water saturation episodes and has either:
    a. At least 12 percent organic carbon by weight (i.e., about 20 percent organic matter) if the soil has no clay; or
    b. At least 18 percent organic carbon by weight (i.e., about 30 percent organic matter) if the soil has 60% or more clay; or
    c. An intermediate, proportional amount of organic carbon for intermediate amounts of clay.

OTHER DISTURBANCE

Disturbance caused by factors other than fire, insects, or diseases. May include areas affected by drought, flooding, windfalls, acid rain, etc.

PEAT SOIL (ALSO HISTOSOL)

A typical wetland soil with a high water table and an organic layer of at least 40cm thickness (poorly drained organic soil).

POOL/CARBON POOL

A reservoir. A system which has the capacity to accumulate or release carbon. Examples of carbon pools are forest biomass, wood products, soils, and the atmosphere. The units are in mass.

REFORESTATION[6]

Direct human-induced conversion of non-forested land to forested land through planting, seeding and/or the human-induced promotion of natural seed sources, on land that was forested but that has been converted to non-forested land. For the first commitment period, reforestation activities will be limited to reforestation occurring on those lands that did not contain forest on 31 December 1989.

REMOVAL BIOMASS

Oven dry weight of wood removals.

REVEGETATION[7]

A direct human-induced activity to increase carbon stocks on sites through the establishment of vegetation that covers a minimum area of 0.05 hectares and does not meet the definitions of afforestation and reforestation contained here.

ROOT-SHOOT RATIO

Ratio of below-ground biomass to above-ground biomass; applies to above-ground biomass, above-ground biomass growth, biomass removals and may differ for these components.

ROUNDWOOD

All round wood felled or otherwise harvested and removed; it comprises all wood obtained from removals e.g., quatities removed from forests and from trees outside forests, including wood recovered from natural felling and logging losses during a period. In the production statistics, it represents the sum of fuelwood, including wood for charcoal, saw-and veneer logs, pulpwood and other industrial roundwood. In the trade statistics, it represents the sum of industrial roundwood, and fuelwood, including wood for charcoal. It is reported in cubic meters *excluding bark.*

SANDY SOILS

Includes all soils (regardless of taxonomic classification) having > 70% sand and < 8% clay (based on standard textural measurements (in FAO classification include: Arenosols, sandy Regosols)).

SAVANNA

Savannas are tropical and subtropical formations with continuous grass cover, occasionally interrupted by trees and shrubs. Savannas are found in Africa, Latin America, Asia and Australia.

SEASONAL (FOREST)

Semi-deciduous forests with a distinct wet and dry season and rainfall between 1,200 and 2,000 mm per year.

STAND–REPLACING DISTURBANCES

Major disturbances which kill or remove all the existing trees above the forest floor vegetation. Minor disturbances leave some of the pre-disturbance trees alive.

SHRUB

Woody perennial plants, generally more than 0.5 meters and less than 5 meters in height at maturity and without definite crown. Height limits for trees and shrubs should be interpreted with flexibility, particularly the minimum tree and maximum shrub height, which may vary between 5 and 7 meters.

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[6] In the context of the Kyoto Protocol, as stipulated by the Marrakesh Accords, cf. paragraph 1 of the Annex to draft decision -/CMP.1 (Land Use, Land-use Change and Forestry) contained in document FCCC/CP/2001/13/Add.1, p.58.

[7] In the context of the Kyoto Protocol, as stipulated by the Marrakesh Accords, cf. paragraph 1 of the Annex to draft decision -/CMP.1 (Land Use, Land-use Change and Forestry) contained in document FCCC/CP/2001/13/Add.1, p.58.

SOIL CARBON

Organic carbon in mineral and organic soils (including peat) to a specified depth chosen by the country and applied consistently through the time series. Live fine roots of less than 2mm (or other value chosen by the country as diameter limit for below-ground biomass) are included with soil organic matter where they cannot be distinguished from it empirically.

SOIL ORGANIC MATTER

Includes organic carbon in mineral soils to a specified depth chosen by the country and applied consistently through the time series. Live and dead fine roots and DOM within the soil, that are less than the minimum diameter limit (suggested 2mm) for roots and DOM, are included with soil organic matter where they cannot be distinguished from it empirically. The default for soil depth is 30cm and guidance on determining country-specific depths is given in Chapter 2.3.3.1.

SPODIC SOILS

Soils exhibiting strong podzolization (in FAO classification includes many Podzolic groups).

TOTAL BIOMASS

Growing stock biomass of trees, stands or forests plus biomass of branches, twigs, foliage, seeds, stumps, and sometimes, non-commercial trees. Differentiated into above-ground biomass and below-ground biomass (s.a.). If there is no misunderstanding, possible also just to use “biomass” with the same meaning.

TOTAL BIOMASS GROWTH

Biomass of the net annual increment (s.a.) of trees, stands, or forests, plus the biomass of the growth of branches, twigs, foliage, seeds, stumps, and sometimes, non-commercial trees. Differentiated into above-ground biomass growth and below-ground biomass growth (s.a.). If there is no misunderstanding, possible also just to use “biomass growth” with the same meaning. The term “growth” is used here instead of “increment”, since the latter term tends to be understood in terms of merchantable volume.

TREE

A woody perennial with a single main stem, or in the case of coppice with several stems, having a more or less definitive crown. Includes bamboos, palms, and other woody plants meeting the above criteria.

VOLUME OVERBARK

Growing stock or merchantable wood measured outside, that is including the bark. Bark adds 5-25% of total volume, depending on tree diameter and bark thickness of species. The weighted average bark percentage calculated from the data of TBFRA 2000 is 11% of the volume outside bark.

VOLUME UNDERBARK

Growing stock or merchantable wood without the bark. See above.

WET (FOREST)

Moisture regimes for boreal and temperate zones are defined by the ratio of mean annual precipitation (MAP) and potential evapotranspiration (PET): Dry (MAP/PET < 1) and Wet (MAP/PET > 1); and for tropical zones by precipitation alone: Dry (MAP < 1,000mm), Moist (MAP: 1,000-2,000mm) and Wet (MAP > 2,000mm).

WOODY BIOMASS

Biomass from trees, bushes and shrubs, for palms, bamboos not strictly correct in the botanical sense.

WOOD FUEL

Also wood-based fuels, wood-derived biofuels. All types of biofuels originating directly or indirectly from woody biomass.

WOOD-REMOVAL

The wood removed (volume of round wood over bark) for production of goods and services other than energy production (fuelwood). The term removal differs from fellings as it excludes felled trees left in the forest. It includes removal from fellings of an earlier period and from trees killed or damaged by natural causes. It also includes removal by local people or owners for their own use. As the term “removal” is used in the context of climate change to indicate sequestration of greenhouse gases from the atmosphere, removal in the context of forest harvesting should always be used as “wood-removal or fuelwood-removal” to avoid misunderstandings.

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CHAPTER 6

GRASSLAND

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Contents

6 Grassland

Figure

Tables

6 GRASSLAND

6.1 INTRODUCTION

Grasslands cover about one-quarter of the earth's land surface (Ojima *et al.*, 1993) and span a range of climate conditions from arid to humid. Grasslands vary greatly in their degree and intensity of management, from extensively managed rangelands and savannahs – where animal stocking rates and fire regimes are the main management variables – to intensively managed (e.g., with fertilization, irrigation, species changes) continuous pasture and hay land. Grasslands generally have vegetation dominated by perennial grasses, and grazing is the predominant land use.

Grasslands are generally distinguished from "forest" as ecosystems having a tree canopy cover of less than a certain threshold, which varies from region to region. Below-ground carbon dominates in grassland, and is mainly contained in roots and soil organic matter. The transition along rainfall or soil gradients from grassland to forest is often gradual. Many shrublands with high proportions of perennial woody biomass may be considered to be a type of grassland and countries may elect to account for some or all of these shrublands in the Grassland category.

Many grassland species have developed adaptations to cope with grazing and the common perturbation of fire and consequently both the vegetation and soil carbon are relatively resistant to moderate disturbances from grazing and fire regimes (Milchunas and Lauenroth, 1993). In many types of grassland, the presence of fire is a key factor in preventing the invasion of woody species which can significantly affect ecosystem carbon stores (Jackson *et al.*, 2002).

The *1996 IPCC Guidelines* dealt only with emissions from tropical savannah burning and changes in biomass associated with conversion of Grassland to other land use. Three sets of calculations were used to produce estimates of CO_2 emissions due to Grassland conversion: (i) carbon dioxide emitted by burning above-ground biomass, (ii) carbon dioxide released by decay of above-ground biomass, and (iii) carbon dioxide released from soil. No explicit provisions were made for reporting changes in the carbon stocks of grasslands associated with changes in woody perennial biomass cover or from changes in management of these systems.

These *Guidelines* update the *1996 IPCC Guidelines*, and allow for the estimation of carbon emissions and removals in grasslands due to changes in stocks in above-ground and below-ground biomass, emissions of non-CO_2 greenhouse gases due to biomass burning, and carbon emissions and removals in grasslands due to changes in soil C stocks. They incorporate several new methodologies that were developed in the *GPG-LULUCF* (IPCC, 2003). New elements relative to the *1996 IPCC Guidelines* include:

- Methodologies to address C stock changes in the two main pools in grassland: biomass and soils;
- Explicit inclusion of impacts of natural disturbances and fires on managed grassland;
- Estimation of emissions and removals on *Land Converted to Grassland*;
- Extension of methods for estimation of non-CO_2 greenhouse gas emissions due to biomass burning from savannas to all grasslands;
- Estimation of non-CO_2 greenhouse gas emissions due to biomass burning during conversion to grasslands; and
- New stock change rate factors and reference C stocks for soil organic C.

This chapter provides guidelines for default and advanced approaches to estimating and reporting on emissions and removals from grasslands. Methods and guidance are given for *Grassland Remaining Grassland* (Section 6.2) and *Land Converted to Grassland* (Section 6.3). For *Grassland Remaining Grassland*, carbon emissions and removals are based on estimating the effects of changes in management practices on carbon stocks. For lands converted to Grassland, carbon emissions and removals are based on estimating the effects of replacement of one vegetation type by grassland vegetation. If data are not available to segregate grassland area into *Grassland Remaining Grassland* and *Land Converted to Grassland*, the default approach is to consider all grasslands under the category *Grassland Remaining Grassland.*

Inter-annual climatic variability is an important factor for consideration when compiling a carbon inventory for grasslands. Large changes in standing biomass can occur from year to year that is associated with differences in annual rainfall. Inter-annual rainfall variability may also affect management decisions such as irrigation or fertilizer application. The inventory compiler needs to be aware of this and factor these effects into the inventory as appropriate.

6.2 GRASSLAND REMAINING GRASSLAND

Grassland Remaining Grassland includes managed pastures which have always been under grassland vegetation and pasture use or other land categories converted to grassland more than 20 years ago. Constructing a greenhouse gas inventory for the land-use category *Grassland Remaining Grassland* (GG) involves estimation of changes in carbon stock from five carbon pools (i.e., above-ground biomass, below-ground biomass, dead wood, litter, and soil organic matter), as well as emissions of non-CO_2 gases. The principal sources of emissions and removals of greenhouse gases in this category are associated with grassland management and changes in management. The change in C stocks in *Grassland Remaining Grassland* is estimated using Equation 2.3 in Chapter 2. The decision tree in, Figure 1.2 (Chapter 1) provides guidance for selecting the appropriate tier (level of methodological complexity) for the implementation of estimation procedures for GG.

6.2.1 Biomass

Carbon stocks in permanent grassland are influenced by human activities and natural disturbances, including: harvesting of woody biomass, rangeland degradation, grazing, fires, pasture rehabilitation, pasture management, etc. Annual production of biomass in grassland can be large, but due to rapid turnover and losses through grazing and fire, and annual senescence of herbaceous vegetation, standing stock of above-ground biomass in many grasslands rarely exceeds a few tonnes per hectare. Larger amounts can accumulate in the woody component of vegetation, in root biomass and in soils. The extent to which carbon stocks increase or decrease in each of these pools is affected by management practices such as those described above.

This section provides guidance for estimating carbon stock changes in biomass for *Grassland Remaining Grassland*, including increased cover of woody vegetation, effects of organic matter additions and effects of management and liming. The concepts underlying carbon stock changes in biomass of *Grassland Remaining Grassland* are tied to management practices. The decision tree in Figure 2.2 (Chapter 2) provides guidance on the choice of tiers for reporting changes in biomass C stocks.

Because data on below-ground biomass are often lacking for specific ecosystems, a simplified approach based upon below-ground to above-ground biomass ratios is used. With this approach, estimates of below-ground biomass are closely tied to estimates of above-ground biomass. Hence, for simplicity, above-ground and below-ground biomasses are combined for estimation and reporting.

Although the methods for estimating biomass changes are conceptually similar among Grassland, Cropland, and Forest Land, grasslands are unique in a number of ways. Large areas of grasslands are subject to frequent fires that can influence the abundance of woody vegetation, mortality and regrowth of woody and herbaceous vegetation, and the partitioning of carbon above and below ground. Climate variability and other management activities, such as tree and brush removal, pasture improvement, tree planting, as well as overgrazing and degradation can influence biomass stocks. For woody species in savannahs (grassland with trees), the allometric relationships differ from those used in Forest Land because of large numbers of multi-stem trees, large number of shrubs, hollow trees, high proportion of standing dead trees, high root-to-shoot ratios and coppicing regeneration.

6.2.1.1 CHOICE OF METHOD

The decision tree in Chapter 1, Figure 1.2 provides guidance in the selection of the appropriate tier for the implementation of estimation procedures. Estimation of changes in carbon stocks in biomass requires an estimate of changes in stocks of above-ground biomass and changes in carbon stocks in below-ground biomass.

Depending on the tier used and data availability, grassland can be disaggregated by type, region or climatic zone, and management system. It is *good practice* for countries to strive to improve inventory and reporting approaches by advancing to the highest tier possible given national circumstances. It is *good practice* to use a Tier 2 or Tier 3 approach if carbon emissions and removals in *Grassland Remaining Grassland* is a key category and if the sub-category of biomass is considered significant based on principles outlined in Volume 1, Chapter 4.

Tier 1

A Tier 1 approach assumes no change in biomass in *Grassland Remaining Grassland*. In grassland where there is no change in either type or intensity of management, biomass will be in an approximate steady-state (i.e., carbon accumulation through plant growth is roughly balanced by losses through grazing, decomposition and fire). In grassland where management changes are occurring over time (e.g., through introduction of silvopastoral systems, tree/brush removal for grazing management, improved pasture management or other practices), the carbon stock changes can be significant. If it is reasonable to assume that grassland is not a key source, a country may apply the Tier 1 assumption of no change in biomass. However, if information is available to develop reliable estimates of rates of change in biomass in *Grassland Remaining Grassland*, a country may use a higher Tier, even if *Grassland Remaining Grassland* is not a key source, particularly if management changes are likely.

Tier 2

Tier 2 allows for estimation of changes in biomass due to management practices. Two methods are suggested for estimating the carbon stock change in biomass.

Gain-Loss Method *(see Equation 2.7 in Chapter 2):* This method involves estimating the area of grassland according to management categories and the average annual growth and loss of biomass stocks. This requires an estimate of area under *Grassland Remaining Grassland* according to different climate or ecological zones or grassland types, disturbance regime, management regime, or other factors that significantly affect biomass carbon pools and the growth and loss of biomass according to different grassland types.

Stock-Difference Method *(see Equation 2.8 in Chapter 2):* The Stock-Difference Method involves estimating the area of grassland and the biomass stocks at two periods of time, t_1 and t_2. The average annual biomass stock differences for the inventory year are obtained by dividing the stock difference by the period (years) between inventories. This method is feasible for countries which have periodic inventories, and may be more suitable for countries adopting Tier 3 methods. This method may not be well suited to regions with very variable climates and may produce spurious results unless annual inventories can be made.

Tier 3

Tier 3 methods are used where countries have country-specific emission factors, and substantial national data. Country-defined methodology may be based on detailed inventories of permanent sample plots for their grasslands, and/or models.

For Tier 3, countries should develop their own methodologies and parameters for estimating changes in biomass. These methodologies may be derived from Equation 2.7 or Equation 2.8 specified above, or may be based on other approaches. The method used needs to be clearly documented.

Estimates of carbon stocks in biomass at the national level should be determined as part of a national grasslands inventory, national level models, or from a dedicated greenhouse gas (GHG) inventory programme, with periodic sampling according to the principles set out in Volume 1. Inventory data can be coupled with modelling studies to capture the dynamics of all grassland carbon pools.

Tier 3 methods provide estimates of greater certainty than lower tiers and feature a greater link between individual carbon pools. Some countries have developed disturbance matrices that provide a carbon reallocation pattern among different pools for each type of disturbance.

6.2.1.2 CHOICE OF EMISSION/REMOVAL FACTORS

Emission and removal factors that are required to estimate the changes in biomass resulting from management include biomass growth rate, loss of biomass, and expansion factor for below-ground biomass. Emission and removal factors are used to estimate biomass growth and loss resulting from encroachment of woody perennial vegetation into grassland, degradation due to overgrazing, and other management effects.

Tier 1

Tier 1 is to be chosen when there are no significant emissions or removals in *Grassland Remaining Grassland*. The assumption in Tier 1 is that the biomass in all *Grassland Remaining Grassland* is stable. Countries experiencing significant changes in grassland management or disturbance are encouraged to develop domestic data to estimate this impact, and report it under a Tier 2 or 3 methodology.

Tier 2

It is *good practice* to use country level data on biomass C stocks for different grassland categories, in combination with default values, if country or regional values are not available for some grassland categories. Country-specific values for net biomass increment as well as losses from harvested live trees and grasses to harvest residues and decomposition rates, in the case of the Gain-Loss Method, or the net change in biomass stocks, in the case of the Stock-Difference Method can be derived from country-specific data, taking into account the grassland type, the rate of biomass utilization, harvesting practices and the amount of damaged vegetation during harvesting operations. Country-specific values for disturbance regimes should be derived from scientific studies.

Estimating below-ground biomass can be an important component of biomass surveys of grassland but field measurements are laborious and difficult. Hence, expansion factors to estimate below-ground biomass from above-ground biomass are often used. Adaptations to fire and grazing have led to higher root-to-shoot ratios compared to many other ecosystems; thus biomass expansion factors from undisturbed ecosystems cannot be applied without modification. Root-to-shoot ratios vary significantly at both individual species (e.g., Anderson *et al.*, 1972) and community scales (e.g., Jackson *et al.*, 1996; Cairns *et al.*, 1997). Thus it is recommended to use, as far as possible, empirically-derived root-to-shoot ratios specific to a region or vegetation type. Table 6.1 provides default root-to-shoot ratios (all vegetation) for grassland ecosystems in the major climate zones of the world (IPCC climate zones taken from Annex 3A.5). These values can be used as defaults when countries do not have more specific information to develop country-specific ratios. Ratios for woodland/savannah and shrublands are also included for use by countries that include these lands in the grassland section of their inventory.

TABLE 6.1
DEFAULT EXPANSION FACTORS OF THE RATIO OF BELOW-GROUND BIOMASS TO ABOVE-GROUND BIOMASS (R) FOR THE MAJOR GRASSLAND ECOSYSTEMS OF THE WORLD

Land-use category	Vegetation type	Approximate IPCC climate zone[1]	R [tonne d.m. below-ground biomass (tonne d.m. above-ground biomass) $^{-1}$]	n	Error[2]
Grassland	Steppe/tundra/prairie grassland	Boreal – Dry & Wet Cold Temperate – Wet Warm Temperate – Wet	4.0	7	± 150%
	Semi-arid grassland	Cold Temperate – Dry Warm Temperate – Dry Tropical – Dry	2.8	9	± 95%
	Sub-tropical/ tropical grassland	Tropical – Moist & Wet	1.6	7	± 130%
Other	Woodland/savannah		0.5	19	± 80%
	Shrubland		2.8	9	± 144%

[1] Classification of the source data was by grassland biome types and thus correspondence to the IPCC climate zones are approximations.

[2] Error estimates are given as two times standard deviation, as a percentage of the mean.

Tier 3

Tier 3 approaches consist of using a combination of dynamic models and inventory measurements of biomass stock changes. This approach does not employ simple stock changes or emission factors *per se*. Estimates of emissions/removals using model-based approaches are derived from the interaction of multiple equations that estimate the net change of biomass stocks within the models. Models, jointly with periodic sampling-based stock estimates similar to those used in detailed forest inventories, could be applied to estimate stock changes or inputs and outputs as in Tier 2 to make spatial extrapolations for grassland areas. For example, validated species-specific growth models that incorporate management effects such as grazing intensity, fire, and fertilization, with corresponding data on management activities, can be used to estimate net changes in grassland biomass over time.

6.2.1.3 CHOICE OF ACTIVITY DATA

Activity data consist of areas of *Grassland Remaining Grassland* summarised by major grassland types, management practices, and disturbance regimes. Total grassland areas should be determined according to Approaches laid out in Chapter 3 and should be consistent with those reported under other sections of this chapter, notably under the DOM and soil C sections of *Grassland Remaining Grassland*. The assessment of changes in biomass will be greatly facilitated if this information can be used in conjunction with national soils and climate data, vegetation inventories, and other biophysical data.

6.2.1.4 CALCULATION STEPS FOR TIERS 1 AND 2

The following summarizes steps for estimating change in carbon stocks in biomass (ΔC_B)

Tier 1

Once countries choose to apply a Tier 1 approach, no further work is necessary, as the ecosystem is assumed to be in steady state, where no changes in carbon stocks are expected to occur. Thus, there is no worksheet for biomass.

Tier 2 (Gain-Loss Method – Equation 2.7 in Chapter 2)

Step 1: Determine the grassland categories to be used in this assessment and the representative areas. The categories consist of definitions of the grassland type (e.g., stratified by climate zone and species assemblage) and the state or management of that type [e.g., ‘degraded tall grass prairie’ (USA, Canada), or ‘grazed campo limpo’ (Brazil)]. Area data should be obtained using the methods described in Chapter 3.

Step 2: Determine the biomass increment and loss of woody biomass (using Equations 2.9 and 2.11), for each stratum, and use these to estimate the net change in biomass (using Equation 2.7). Where data exist only for above-ground biomass, countries may use expansion factors for below-ground to above-ground biomass ratios to estimate the below-ground portion of the biomass. Multiply the change in biomass by the carbon content of the dry biomass. The default value is 0.50 tonne of C per tonne of biomass (dry weight). A Tier 2 approach may use default expansion factors provided in Table 6.1 to estimate below-ground biomass when country-specific factors are not available.

Step 3: Determine the average biomass increment and loss of herbaceous biomass and use these to estimate the net change in biomass using Equation 2.7. An approach based upon Equations 2.9 and 2.11 may be devised for herbaceous biomass. Where data exist only for above-ground biomass, countries may use expansion factors for below-ground to above-ground biomass ratios to estimate the below-ground portion of the biomass. Multiply the change in biomass by the carbon content of the dry biomass. The default value is 0.47 tonne of C per tonne of biomass (dry weight). This default value differs from the one in the *GPG-LULUCF* (IPCC, 2003), but is more realistic for herbaceous biomass. A Tier 3 approach requires country-specific or ecosystem-specific expansion factors. A Tier 2 approach may use default expansion factors provided in Table 6.1 to estimate below-ground biomass when country specific factors are not available.

Step 4: If increment and loss were calculated on a per area basis, estimate the total change in the biomass carbon stocks for each category by multiplying the representative area of each category by the net change in biomass for that category. Otherwise, proceed to step 5.

Step 5: Estimate the total net change in carbon stocks in biomass by summing up the net changes in herbaceous and woody perennial biomass.

Tier 2 (Stock-Difference Method – Equation 2.8 in Chapter 2)

Step 1: Same as for Gain-Loss Method (see above).

Step 2: Determine the inventory time interval, the average woody biomass at the initial inventory (t_1), and the average woody biomass at the final inventory (t_2). Use these figures to estimate the net annual change in woody biomass (Equation 2.8). Where data exist only for above-ground biomass, countries may use expansion factors for below-ground to above-ground biomass ratios (R) to estimate the below-ground portion of the biomass. Multiply the change in biomass by the carbon content of the dry biomass. The default value is 0.50 tonne of C per tonne of biomass (dry weight). A Tier 3 approach requires country-specific or ecosystem-specific expansion factors. A Tier 2 approach may use default expansion factors provided in Table 6.1 to estimate below-ground biomass or country-specific or ecosystem-specific expansion factors, if available. Note the R values in Table 6.1 are whole ecosystem R values. Thus, to use these values, one must first sum the above-ground herbaceous and woody biomass and then multiply by R to obtain the value for below-ground biomass.

Step 3: Determine the inventory time interval, the average herbaceous biomass at the initial inventory (Ct1), and the herbaceous biomass at the final inventory (Ct_2). Use these figures, and the inventory time interval, to estimate the net annual change in herbaceous biomass (Equation 2.8). Where data exist only for above-ground biomass, countries may use expansion factors for below-ground to above-ground biomass ratios to estimate the below-ground portion of the biomass. Multiply the change in biomass by the carbon content of the dry biomass. The default value is 0.47 tonne of C per tonne of biomass (dry weight). This default value differs from the one in the *GPG-LULUCF* (IPCC, 2003), but is more realistic for herbaceous biomass. A Tier 3 approach requires country-specific or ecosystem-specific expansion factors. A Tier 2 approach may use default expansion factors provided in Table 6.1 to estimate below-ground biomass when country specific factors are not available.

Step 4: Estimate the total change in the biomass carbon stocks for each category using Equation 2.8.

Step 5: Estimate the total net change in carbon stocks in biomass by summing up the net changes in herbaceous and woody perennial biomass.

6.2.1.5 UNCERTAINTY ASSESSMENT

This section considers source-specific uncertainties relevant to estimates made for biomass C in *Grassland Remaining Grassland*. Two sources of uncertainty exist in C inventories: 1) uncertainties in land-use and management activity and environmental data; 2) uncertainties in carbon increase and loss, carbon stocks and expansion factor terms in the stock change/emission factors for Tier 2 approaches, model structure/parameter error for Tier 3 model-based approaches, or measurement error/sampling variability associated with Tier 3 measurement-based inventories. In general, precision of an inventory is increased and confidence ranges are narrower with greater sampling intensity to estimate values for each category, while reducing bias (i.e., improve accuracy) is more likely to occur through the development of a higher Tier inventory that incorporates country-specific information. Error estimates (i.e., standard deviations, standard error, or ranges) must be calculated for each of the country-defined terms used in a basic uncertainty assessment.

Uncertainties in land-use and management data will need to be addressed by the inventory compiler, and then combined with uncertainties for default factors and reference C stocks using an appropriate method, such as simple error propagation equations. For Tier 2 methods, country-specific information is incorporated into the inventory analysis for purposes of reducing bias. It is *good practice* to evaluate dependencies among the factors, reference C stocks or land-use and management activity data. In particular, strong dependencies are common in land-use and management activity data because management practices tend to be correlated in time and space. Combining uncertainties in stock change/emission factors, reference C stocks and activity data can be done using methods such as simple error propagation equations or Monte-Carlo procedures to estimate means and standard deviations for the change in biomass C stocks (Ogle *et al*., 2003, Vanden Bygaart *et al*., 2004).

Tier 3 models are more complex and simple error propagation equations may not be effective at quantifying the associated uncertainty in resulting estimates. Monte Carlo analyses are possible (Smith and Heath, 2001), but can be difficult to implement if the model has many parameters (some models can have several hundred parameters) because joint probability distribution functions must be constructed quantifying the variance as well as covariance among the parameters. Other methods are also available such as empirically-based approaches (Monte *et al*., 1996), which use measurements from a monitoring network to statistically evaluate the relationship between measured and modelled results (Falloon and Smith, 2003). In contrast to modelling, uncertainties in measurement-based Tier 3 inventories can be estimated directly from the sample variance, estimated measurement error and other relevant sources in uncertainty.

Expansion factor uncertainties

Default uncertainty estimates provided in Table 6.1 can be used for the uncertainty expressed for below-ground biomass expansion factors. Uncertainties associated with expansion factors for carbon content of woody and herbaceous biomass, are relatively small, and are on the order of 2 to 6 percent. For Tiers 2 and 3 estimates, country-specific or regionally derived values will be used. These reference C stocks and stock change factors can have inherently high uncertainties, particularly bias, when applied to specific countries. Defaults represent averaged values of land-use and management impacts or reference C stocks that may vary from site-specific values. It is *good practice* for countries to determine the uncertainties of their default factors for above-ground and below-ground biomass.

Activity data uncertainties

Area data and estimates of uncertainty should be obtained using the methods in Chapter 3. Tiers 2 and 3 approaches may also use finer resolution activity data, such as area estimates for different climatic regions or for grassland management systems within national boundaries. The finer-resolution data will reduce uncertainty levels when associated with carbon accumulation factors defined for those finer-scale land databases. If using aggregate land-use area statistics for activity data (e.g., FAO data), the inventory agency may have to apply a default level of uncertainty for the land area estimates (±50%). However, it is *good practice* for the inventory compiler to derive uncertainties from country-specific activity data instead of using a default level. For Tiers 2 and 3, use of higher resolution activity data (such as area estimates for different climatic regions or for grassland management systems within national boundaries) will reduce uncertainty levels when all necessary carbon accumulation/loss parameters are suitably stratified. Uncertainties in land-use activity statistics may be reduced through a better national system, such as developing or extending a ground-based survey with additional sample locations and/or incorporating remote sensing to provide additional coverage. It is *good practice* to design a classification system that captures the majority of land-use and management activities with a sufficient sample size to minimize uncertainty at the national scale.

6.2.2 Dead organic matter

Methods for estimating carbon stock changes associated with dead organic matter (DOM) pools are provided for two types of dead organic matter pools: 1) dead wood and 2) litter. Chapter 1 of this report provides detailed definitions of these pools.

Dead wood is a diverse pool which is difficult to measure in the field, with associated uncertainties about rates of transfer to litter, soil, or emissions to the atmosphere. Amounts of dead wood depend on the time since last disturbance, the amount of input (mortality) at the time of the disturbance, natural mortality rates, decay rates, and management.

Litter accumulation is a function of the annual amount of litterfall, which includes all leaves, twigs and small branches, fruits, flowers, and bark, minus the annual rate of decomposition of these inputs. The litter mass is also influenced by the time since the last disturbance, and the type of disturbance. Management practices also alter litter properties, but there are few studies clearly documenting the effects of management on litter carbon.

6.2.2.1 CHOICE OF METHOD

Estimation of changes in carbon stocks in DOM requires an estimate of changes in stocks of dead wood and changes in litter stocks (refer to Equation 2.17 in Chapter 2). The decision tree in Chapter 1, Figure 1.2 helps in the selection of the appropriate tier level for the implementation of estimation procedures.

The dead wood and litter pools are treated separately, but the method for estimating changes in each pool is the same.

Tier 1
The Tier 1 method assumes that the dead wood and litter stocks are at equilibrium, so there is no need to estimate the carbon stock changes for these pools. Thus, there is no worksheet provided for DOM in *Grassland Remaining Grassland.* Countries experiencing significant changes in grassland types or disturbance or management regimes in their grasslands are encouraged to develop domestic data to quantify this impact and report it under Tier 2 or 3 methodologies.

Tiers 2 and 3
Tiers 2 and 3 allow for calculation of changes in dead wood and litter carbon due to management practices. Two methods are suggested for estimating the carbon stock change in DOM.

Gain-Loss Method (Equation 2.18 in Chapter 2): This method involves estimating the area of grassland management categories and the average annual transfer into and out of dead wood and litter stocks. This requires: (i) an estimate of the area under *Grassland Remaining Grassland* according to different climate or ecological zones or grassland types, disturbance regime, management regime, or other factors significantly affecting dead wood and litter carbon pools; (ii) the quantity of biomass transferred into dead wood and litter stocks; and (iii) the quantity of biomass transferred out of the dead wood and litter stocks on per hectare basis according to different grassland types.

Stock-Difference Method (Equation 2.19 in Chapter 2): This method involves estimating the area of grassland and the dead wood and litter stocks at two periods of time, t_1 and t_2. The dead wood and litter stock changes for the inventory year are obtained by dividing the stock changes by the period (years) between two measurements. The Stock-Difference Method is feasible for countries, which have periodic grassland inventories. This method may not be well suited to regions with very variable climates and may produce spurious results unless annual inventories can be made. This method is more suitable for countries adopting Tier 3 methods. Tier 3 methods are used where countries have country-specific emission factors, and substantial national data. Country-defined methodology may be based on detailed inventories of permanent sample plots for their grasslands and/or models.

6.2.2.2 CHOICE OF EMISSION/REMOVAL FACTORS

Carbon fraction: The carbon fraction of dead wood and litter is variable and depends on the stage of decomposition. Wood is much less variable than litter and a value of 0.50 tonne C (tonne d.m.)$^{-1}$ can be used for the carbon fraction. The carbon fraction values for litter in grasslands range from 0.05 to 0.50 (Naeth *et al.*, 1991; Kauffman *et al.*, 1997). When country-specific or ecosystem-specific data are not available, it is suggested that a carbon fraction value of 0.40 be used.

Tier 1
Estimates of emission/removal factors are not needed, as the assumption in Tier 1 is that the DOM carbon stocks in all *Grassland Remaining Grassland* are stable.

Tier 2

It is *good practice* to use country-level DOM data on for different grassland categories, in combination with default values if country or regional values are not available for some grassland categories. Country-specific values for transfer of carbon from live trees and grasses that are harvested to harvest residues and decomposition rates, in the case of the Gain-Loss Method or the net change in DOM pools, in the case of the Stock Difference Method, can be derived from domestic expansion factors, taking into account the grassland type, the rate of biomass utilization, harvesting practices and the amount of damaged vegetation during harvesting operations. Country-specific values for disturbance regimes should be derived from scientific studies.

Tier 3

For Tier 3, countries should develop their own methodologies and emission factors needed for estimating changes in DOM. These methodologies may be derived from methods specified above, or may be based on other approaches. The method used needs to be clearly documented.

National-level disaggregated DOM carbon estimates should be determined as part of a national grasslands inventory, national level models, or from a dedicated greenhouse gas inventory programme, with periodic sampling according to the principles set out in Chapter 3, Annex 3A.3. Inventory data can be coupled with modelling studies to capture the dynamics of all grassland carbon pools.

Tier 3 methods provide estimates of greater certainty than lower tiers and feature greater links between individual carbon pools. Some countries have developed disturbance matrices (see Table 2.1 in Chapter 2) that provide a carbon reallocation pattern among different pools for each type of disturbance. Other important parameters in a modelled DOM carbon budget are decay rates, which may vary with the type of wood and microclimatic conditions, and site preparation procedures (e.g., controlled broadcast burning, or burning of piles).

6.2.2.3 CHOICE OF ACTIVITY DATA

Activity data consist of areas of *Grassland Remaining Grassland* summarised by major grassland types, management practices, and disturbance regimes. Total grassland areas should be consistent with those reported under other sections of this chapter, notably under the biomass section of *Grassland Remaining Grassland*. The assessment of changes in dead organic matter will be greatly facilitated if this information can be used in conjunction with national soils and climate data, vegetation inventories, and other geophysical data. Area estimates should be obtained using methods described in Chapter 3.

6.2.2.4 CALCULATION STEPS FOR TIERS 1 AND 2

The following summarizes steps for estimating change in DOM carbon stocks:

Tier 1

Once the decision is made that reporting for this category will be done using a Tier 1 approach, no further work is necessary as the ecosystem is assumed to be in steady-state and there are no expected changes in dead wood or litter carbon stocks.

Tier 2 (Gain-Loss Method) – Equation 2.18 in Chapter 2

Each of the DOM pools (dead wood and litter) is to be treated separately, but the method for each pool is the same.

Step 1: Determine the categories of grassland types to be used in this assessment and the representative area.

Step 2: Determine the input and output rates of dead wood and litter to the respective pools. Identify values from inventories or scientific studies for the average inputs and outputs of dead wood or litter for each category. No default factors exist for inputs and outputs from these pools, so countries should use locally available data. Calculate the net change in the DOM pools by subtracting the outputs from the inputs. Negative values indicate a net decrease in the stock.

Step 3: Determine the net change in DOM stocks for each category by subtracting the outputs from the inputs. Convert the net change in DOM biomass stocks to carbon stocks for each category by multiplying the carbon fraction. The default carbon fractions are 0.50 tonne C (tonne d.m.)$^{-1}$ for dead wood and 0.40 tonne C (tonne d.m.)$^{-1}$ for litter. A Tier 2 approach requires country-specific or ecosystem-specific stock change rate factors.

Step 4: Estimate the total change in the DOM carbon pools for each category by multiplying the representative area of each category by the net change in DOM carbon stocks for that category.

Step 5: Estimate the total change in carbon stocks in dead wood by taking the sum of the total changes in DOM across all categories.

Tier 2 (Stock-Difference Method) – Equation 2.19 in Chapter 2

Each of the DOM pools is to be treated separately, but the method for each pool is the same.

Step 1: Determine the categories of grassland types to be used in this assessment and the representative area.

Step 2: Determine the net change in DOM stocks for each category. From the inventory data, identify the inventory time interval, the average stock of DOM at the initial inventory (t_1), and the average stock of DOM at the final inventory (t_2). Use these figures to estimate the net annual change in DOM stocks by subtracting the DOM stock at t_1 from the DOM stock at t_2 and dividing this difference by the time interval (Equation 2.19). A negative value indicates a decrease in the DOM stock.

Step 3: Determine the net change in DOM carbon stocks for each category. Determine the net change in DOM carbon stocks by multiplying the net change in DOM stocks for each category by the carbon fraction of the DOM. A Tier 2 approach requires country-specific or ecosystem-specific expansion factors.

Steps 4 and 5: Same as for Gain-Loss Method.

6.2.2.5 UNCERTAINTY ASSESSMENT

This section considers source-specific uncertainties relevant to estimates made for DOM in *Grassland Remaining Grassland*. Two sources of uncertainty exist in C inventories: 1) uncertainties in land-use and management activity and environmental data; 2) uncertainties in carbon increase and loss, carbon stocks and expansion factor terms in the stock change/emission factors for Tier 2 approaches, model structure/parameter error for Tier 3 model-based approaches, or measurement error/sampling variability associated with Tier 3 measurement-based inventories. In general, precision of an inventory is increased and confidence ranges are narrower with greater sampling intensity to estimate values for each category, while reducing bias (i.e., improve accuracy) is more likely to occur through the development of a higher Tier inventory that incorporates country-specific information. Error estimates (i.e., standard deviations, standard error, or ranges) must be calculated for each of the country-defined terms used in a basic uncertainty assessment.

Uncertainties in land-use and management data will need to be addressed by the inventory compiler, and then combined with uncertainties for default factors and reference C stocks using an appropriate method, such as simple error propagation equations. For Tier 2 methods, country-specific information is incorporated into the inventory analysis for purposes of reducing bias. It is *good practice* to evaluate dependencies among the factors, reference C stocks or land-use and management activity data. In particular, strong dependencies are common in land-use and management activity data because management practices tend to be correlated in time and space. Combining uncertainties in stock change/emission factors, reference C stocks and activity data can be done using methods such as simple error propagation equations or Monte-Carlo procedures to estimate means and standard deviations for the change in DOM C stocks (Ogle *et al*., 2003; Vanden Bygaart *et al*., 2004).

Tier 3 models are more complex and simple error propagation equations may not be effective at quantifying the associated uncertainty in resulting estimates. Monte Carlo analyses are possible (Smith and Heath, 2001), but can be difficult to implement if the model has many parameters (some models can have several hundred parameters) because joint probability distribution functions must be constructed quantifying the variance as well as covariance among the parameters. Other methods are also available such as empirically-based approaches (Monte *et al*., 1996), which use measurements from a monitoring network to statistically evaluate the relationship between measured and modelled results (Falloon and Smith, 2003). In contrast to modelling, uncertainties in measurement-based Tier 3 inventories can be estimated directly from the sample variance, estimated measurement error and other relevant sources in uncertainty.

Emission/removal factor uncertainties

No uncertainty analysis is needed for Tier 1 since the default assumption is unchanging carbon stocks in DOM. For Tiers 2 and 3 estimates, country-specific or regionally derived values will be used. These reference C stocks and stock change factors can have inherently high uncertainties, particularly bias, when applied to specific countries. Defaults represent averaged values of land-use and management impacts or reference C stocks that may vary from site-specific values. It is *good practice* for countries to determine the uncertainties of their default factors for dead wood and litter.

Activity data uncertainties

Area data and estimates of uncertainty should be obtained using the methods in Chapter 3. If using aggregate land-use area statistics for activity data (e.g., FAO data), the inventory agency may have to apply a default level of uncertainty for the land area estimates (±50%). However, it is *good practice* for the inventory compiler to derive uncertainties from country-specific activity data instead of using a default level. For Tiers 2 and 3, use of higher resolution activity data (such as area estimates for different climatic regions or for grassland management systems within national boundaries) will reduce uncertainty levels when all necessary carbon accumulation/loss parameters are suitably stratified. Uncertainties in land-use activity statistics may be reduced through a better national system, such as developing or extending a ground-based survey with additional sample locations and/or incorporating remote sensing to provide additional coverage. It is *good practice* to design a classification system that captures the majority of land-use and management activities with a sufficient sample size to minimize uncertainty at the national scale.

6.2.3 Soil carbon

This section deals with the impacts of grassland management on soil organic C stocks, primarily by influencing C inputs to the soil, and thus soil C storage, by affecting net primary production, root turnover, and allocation of C between roots and shoots. Soil C stocks in grassland are influenced by fire, grazing intensity, fertilizer management, liming, irrigation, re-seeding with more or less productive grass species and mixed swards with N-fixing legumes (Conant *et al*., 2001; Follett *et al*., 2001; Ogle *et al*., 2004). In addition, drainage of organic soils for grassland management causes losses of soil organic C (Armentano and Menges, 1986).

General information and guidance for estimating changes in soil C stocks are provided in Chapter 2, Section 2.3.3 (including equations), and this section needs to be read before proceeding with a consideration of specific guidelines dealing with grassland soil C stocks. The total change in soil C stocks for grassland is estimated using Equation 2.24 (Chapter 2), which combines the change in soil organic C stocks for mineral soils and organic soils; and stock changes associated with soil inorganic C pools (if estimated at Tier 3). This section provides specific guidance for estimating soil organic C stocks. There is a general discussion in Section 2.3.3.1 on soil inorganic C and no additional information on this is provided here.

To account for changes in soil C stocks associated with *Grassland Remaining Grassland*, countries need to have, at a minimum, estimates of grassland areas at the beginning and end of the inventory time period. If land-use and management data are limited, aggregate data, such as FAO statistics on grassland, can be used as a starting point, along with knowledge of country experts about the approximate distribution of land management systems (e.g., degraded, nominal and improved grassland/grazing systems). Grassland management classes must be stratified according to climate regions and major soil types, which could either be based on default or country-specific classifications. This can be accomplished with overlays of land use on suitable climate and soil maps.

6.2.3.1 CHOICE OF METHOD

Inventories can be developed using a Tier 1, 2 or 3 approach, with each successive Tier requiring more details and resources than the previous one. It is also possible that countries will use different tiers to prepare estimates for the separate sub-categories of soil C (i.e., soil organic C stocks changes in mineral and organic soils; and stock changes associated with soil inorganic C pools). Decision trees are provided for mineral (Figure 2.4) and organic soils (Figure 2.5) in Section 2.3.3.1 (Chapter 2) to assist inventory compilers with the selection of the appropriate tier for their soil C inventory.

Mineral soils

Tier 1

For mineral soils, the estimation method is based on changes in soil organic C stocks over a finite period following changes in management that impact soil organic C storage. After a finite transition period, one can assume a steady state for this stock. Equation 2.25 (Chapter 2) is used to estimate change in soil organic C stocks in mineral soils by subtracting the C stock in the last year of an inventory time period (SOC_0) from the C stock at the beginning of the inventory time period ($SOC_{(0-T)}$) and dividing by the time dependence of the stock change factors (D). Note that area of exposed bedrock in grasslands are not included in the soil C stock calculation (assume a stock of 0). In practice, country-specific data on grassland management activity should be obtained and classified into appropriate land management systems, and then stratified by IPCC climate regions and soil types (see Chapter 3). Soil organic C stocks (SOC) are estimated for each time period in the inventory using default reference carbon stocks (SOC_{ref}) and default stock change factors (F_{LU}, F_{MG}, F_I).

Tier 2

The Tier 2 method for mineral soils also uses Equation 2.25 (Chapter 2), but the inventory approach is further developed with country-specific information to better specify stock change factors, reference C stocks, climate regions, soil types, and/or the land management classification system.

Tier 3

Tier 3 approaches do not employ simple stock change factor *per se*, but rather use dynamic models and/or detailed soil C inventory measurements as the basis for estimating annual stock changes.

Estimates of stock changes using model-based approaches are computed from the coupled equations that estimate the net change of soil carbon. A variety of models designed to simulate soil carbon dynamics exist (for example, see reviews by McGill *et al.*, 1996; Smith *et al.*, 1997). Key criteria in selecting an appropriate model include its capability of representing all of the relevant management practices/systems for grasslands; model inputs (i.e., driving variables) are compatible with the availability of country-wide input data; and the model sufficiently represents stock changes based on comparisons with experimental data.

A Tier 3 approach may also be developed using a measurement-based approach in which a monitoring network is sampled periodically to estimate soil organic C stock changes. In contrast to a network associated with model validation, a much higher density of benchmark sites will be needed to adequately represent the combination of land-use and management systems, climate and soil types. Additional guidance is provided in Section 2.3.3.1 (Chapter 2).

Organic soils

Tier 1

Equation 2.26 (Chapter 2) is used to estimate C stock change in managed grassland on organic soils (e.g., peat-derived, Histosols). The methodology is to stratify managed organic soils by climate region and assign a climate-specific annual emission rate. Land areas are multiplied by the emission factor and then summed to derive annual C emissions. Natural grasslands that may be used for seasonal grazing but have not been artificially drained should not be included in this category.

Tier 2

The Tier 2 approach also uses Equation 2.26 (Chapter 2), but country-specific information is incorporated to better specify emission factors, climate regions, and/or the land management classification system.

Tier 3

Tier 3 approaches for organic soils use dynamic models and/or measurement networks (*see Mineral Soils* above for additional discussion).

6.2.3.2 CHOICE OF STOCK CHANGE AND EMISSION FACTOR

Mineral soils

Tier 1

For the Tier 1 approach, default stock change factors are provided in Table 6.2, which includes values for land use factor (F_{LU}), input factor (F_I), and management factor (F_{MG}). The method and studies that were used to derive the default stock change factors are provided in Annex 6A.1. The time dependence (D) is 20 years for default stock change factors in grasslands, and they represent the influence of management to a depth of 30cm. Default reference soil organic C stocks are found in Table 2.3 of Chapter 2. The reference stock estimates are for the top 30cm of the soil profile, to be consistent with the depth increment for default stock change factors.

Tier 2

Estimation of country-specific stock change factors is an important advancement for improving an inventory that can be developed in the Tier 2 approach. Derivations of management factor (F_{MG}) and input factor (F_I) factor are based on experimental comparisons to nominally-managed grasslands with medium input, respectively, because these classes are considered the nominal practices in the IPCC default classification scheme for management systems (see Choice of Activity Data). It is considered *good practice* to derive values for more detailed classification schemes of management, climate and soil types, if there are significant differences in the stock change factors among finer categories based on an empirical analysis. Reference C stocks can also be derived from country-specific data in a Tier 2 approach. Additional guidance is provided in Section 2.3.3.1 (Chapter 2).

Tier 3

Constant stock change rate factors *per se* are less likely to be estimated in favor of variable rates that more accurately capture land-use and management effects. See Section 2.3.3.1 (Chapter 2) for further discussion.

TABLE 6.2
RELATIVE STOCK CHANGE FACTORS FOR GRASSLAND MANAGEMENT

Factor	Level	Climate regime	IPCC default	Error[1,2]	Definition
Land use (F_{LU})	All	All	1.0	NA	All permanent grassland is assigned a land-use factor of 1.
Management (F_{MG})	Nominally managed (non –degraded)	All	1.0	NA	Represents non-degraded and sustainably managed grassland, but without significant management improvements.
Management (F_{MG})	Moderately degraded grassland	Temperate /Boreal	0.95	± 13%	Represents overgrazed or moderately degraded grassland, with somewhat reduced productivity (relative to the native or nominally managed grassland) and receiving no management inputs.
		Tropical	0.97	± 11%	
		Tropical Montane[3]	0.96	± 40%	
Management (F_{MG})	Severely degraded	All	0.7	± 40%	Implies major long-term loss of productivity and vegetation cover, due to severe mechanical damage to the vegetation and/or severe soil erosion.
Management (F_{MG})	Improved grassland	Temperate /Boreal	1.14	± 11%	Represents grassland which is sustainably managed with moderate grazing pressure and that receive at least one improvement (e.g., fertilization, species improvement, irrigation).
		Tropical	1.17	± 9%	
		Tropical Montane[3]	1.16	± 40%	
Input (applied only to improved grassland) (F_I)	Medium	All	1.0	NA	Applies to improved grassland where no additional management inputs have been used.
Input (applied only to improved grassland) (F_I)	High	All	1.11	± 7%	Applies to improved grassland where one or more additional management inputs/improvements have been used (beyond that is required to be classified as improved grassland).

[1] ± two standard deviations, expressed as a percent of the mean; where sufficient studies were not available for a statistical analysis a default, based on expert judgement, of ± 40% is used as a measure of the error. NA denotes 'Not Applicable', for factor values that constitute reference values or nominal practices for the input or management classes.

[2] This error range does not include potential systematic error due to small sample sizes that may not be representative of the true impact for all regions of the world.

[3] There were not enough studies to estimate stock change factors for mineral soils in the tropical montane climate region. As an approximation, the average stock change between the temperate and tropical regions was used to approximate the stock change for the tropical montane climate.

Note: See Annex 6A.1 for estimation of default stock change factors for mineral soil C emissions/removals for Grassland.

Organic soils

Tier 1

For a Tier 1 approach, default emission factors are provided in Table 6.3 to estimate the loss of C associated with drainage of organic soils.

Tier 2

Emission factors are derived from country-specific experimental data in a Tier 2 approach. It is *good practice* for emission factors to be derived for specific land management categories of grassland on organic soils and/or a finer classification of climate regions, assuming the new categories capture significant differences in C loss rates. More discussion is provided in Section 2.3.3.1 (Chapter 2).

Tier 3

Constant emission rate factors *per se* are less likely to be estimated in favor of variable rates that more accurately capture land-use and management effects. See Section 2.3.3.1 (Chapter 2) for further discussion.

TABLE 6.3
ANNUAL EMISSION FACTORS (EF) FOR DRAINED GRASSLAND ORGANIC SOILS

Climatic temperature regime	IPCC default (tonne C ha^{-1} yr^{-1})	Error [1]
Boreal/Cold Temperate	0.25	± 90%
Warm Temperate	2.5	± 90%
Tropical/Sub-Tropical	5.0	± 90%

[1] Represents a nominal estimate of error, equivalent to two times standard deviation, as a percentage of the mean.

These values represent one quarter of the loss on drained croplands (see Table 5.6 in Chapter 5), which is approximately the proportional loss of C on drained grassland relative to croplands according to data presented in Armentano and Menges (1986). These values have a degree of uncertainty as reflected in the error column.

6.2.3.3 CHOICE OF ACTIVITY DATA

Mineral soils

Tier 1

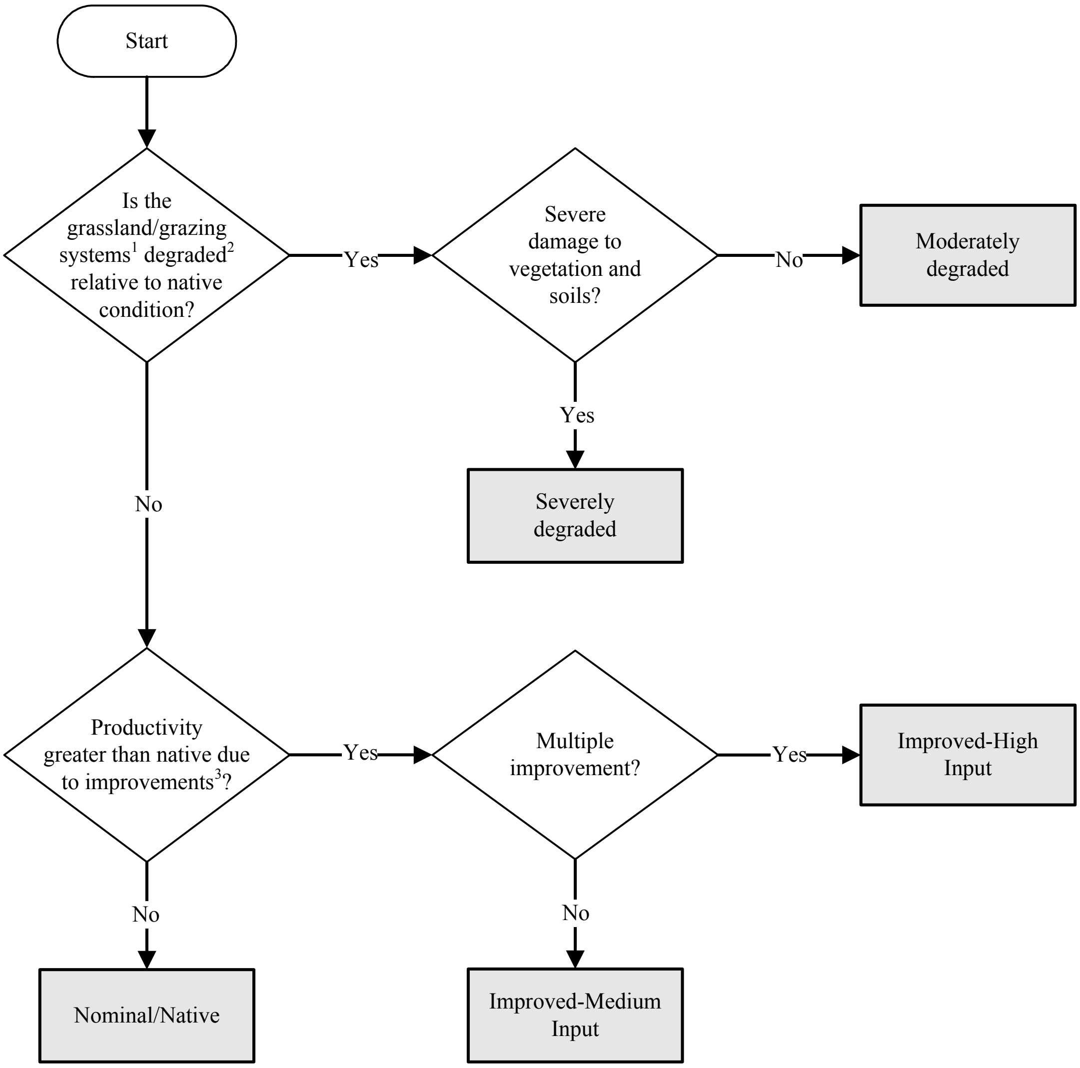
Grassland systems are classified by practices that influence soil C storage. In general, practices that are known to increase C input to the soil and thus soil organic C stocks, such as irrigation, fertilization, liming, organic amendments, more productive grass varieties, are given an improved status, with medium or high inputs depending on the level of improvement. Practices that decrease C input and soil organic C storage, such as long-term heavy grazing, are given a degraded status relative to nominally-managed seeded pastures or native grassland that are neither improved nor degraded. These practices are used to categorize management systems and then estimate the change in soil organic C stocks. A classification system is provided in Figure 6.1, which forms the basis for a Tier 1 inventory. Inventory compilers should use this classification to categorize management systems in a manner consistent with the default Tier 1 stock change factors. This classification may be further developed for Tiers 2 and 3 approaches.

The main types of land-use activity data include: i) aggregate statistics (Approach 1), ii) data with explicit information on land-use conversions but without specific geo-referencing (Approach 2), or iii) data with information on land-use conversion and explicit geo-referencing (Approach 3), such as point-based land-use and management inventories making up a statistically-based sample of a country's land area. (See Chapter 3 for discussion of Approaches). At a minimum, globally available land-use statistics, such as FAO's databases (http://www.fao.org/waicent/portal/glossary_en.asp), provide annual compilations of total land area by major land-use types. This would be an example of aggregate data (Approach 1).

Management activity data supplement the land-use data, providing information to classify management systems, such as stocking rates, fertilizer use, irrigation, etc. These data can also be aggregate statistics (Approach 1) or provide information on explicit management changes (Approach 2 or 3). It is *good practice* where possible for grassland areas to be assigned appropriate general management activities (i.e., degraded, native, or improved) or specific management activities (e.g., fertilization or grazing intensity). Soil degradation maps may be a useful source of information for stratifying grassland according to management (e.g., Conant and Paustian, 2002; McKeon *et al*., 2004). Expert knowledge is another source of information for management practices. It is *good practice* to elicit expert knowledge, where appropriate, using methods provided in Volume 1, Chapter 2 (Annex 2A.1, A protocol for expert elicitation).

National land-use and resource inventories based on repeated surveys of the same locations constitute activity data gathered using Approach 2 or 3, and have some advantages over aggregated pastoral and land-use statistics (Approach 1). Time series data can be more readily associated with a particular grassland management system and the soil type associated with the particular location can be determined by sampling or by referencing the location to a suitable soil map. Inventory points that are selected based on an appropriate statistical design also enable estimates of the variability associated with activity data, which can be used as part of a formal uncertainty analysis. An example of a survey using Approach 3 is the National Resource Inventory in the U.S. (Nusser and Goebel, 1997).

Figure 6.1 **Classification scheme for grassland/grazing systems. In order to classify grassland management systems, the inventory compiler should start at the top and proceed through the diagram answering questions (move across branches if answer is yes) until reaching a terminal point on the diagram. The classification diagram is consistent with default stock change factors in Table 6.2.**



Note:
1: Includes continuous pasture, hay lands and rangelands.
2: Degradation is equated with C input to the soil relative to native conditions, which may be caused by long-term heavy grazing or planting less productive plants relative to native vegetation.
3: Productivity refers explicitly to C input to soil (management improvements that increase input e.g., fertilization, organic amendment, irrigation, planting more productive varieties, liming, and seeding legumes).

Activity data require additional in-country information to stratify areas by climate and soil types. If such information has not already been compiled, an initial approach would be to overlay available land cover/land-use maps (of national origin or from global datasets such as IGBP_DIS) with soil maps of national origin or global sources, such as the FAO Soils Map of the World and climate data from the United Nations Environmental Program. A detailed description of the default climate and soil classification schemes is provided in Chapter 3, Annex 3A.5. The soil classification is based on soil taxonomic description and textural data, while climate regions are based on mean annual temperatures and precipitation, elevation, occurrence of frost, and potential evapotranspiration.

Tier 2
Tier 2 approaches are likely to involve a more detailed stratification of management systems (Figure 6.1) than in Tier 1, if sufficient data are available. This could include further subdivisions of grassland systems (i.e., moderately degraded, severely degraded, nominal and improved), and the input classes (medium and high input). It is *good practice* to further subdivide default classes based on empirical data that demonstrates significant differences in soil organic C storage among the proposed categories. In addition, Tier 2 approaches could involve a finer stratification of climate regions and soil types.

Tier 3
For application of dynamic models and/or a direct measurement-based inventory in Tier 3, similar or more detailed data on the combinations of climate, soil, topographic and management data are needed, relative to Tiers 1 and 2 methods, but the exact requirements will be dependent on the model or measurement design.

Organic soils

Tier 1
In contrast to the mineral soil method, grasslands on organic soils are not classified into management systems under the assumption that drainage stimulates oxidation of organic matter at about the same rate after exposure to aerobic conditions, regardless of the management system. However, in order to apply the method described in Section 2.3.3.1 (Chapter 2), managed grasslands do need to be stratified by soil type and climate region (see Chapter 3, Annex 3A.5, for guidance on soil and climate classifications).

Similar databases and approaches as those outlined for *Mineral Soils* in the Tier 1 section can be used for deriving area estimates. The land area, with organic soils that are managed grasslands, can be determined using an overlay of a land-use map on climate and soils maps. Country-specific data on drainage projects combined with soil maps and surveys can be used to obtain a more refined estimate of relevant areas of managed grassland on organic soils.

Tier 2
Tier 2 approaches may involve a stratification of management systems if sufficient data are available. This could include a division of grassland systems by drainage class, for example. Tier 2 approaches could also involve a finer stratification of climate regions.

Tier 3
Tier 3 approaches for organic soils will probably include more detailed data on climate, soil, topographic and management data, relative to the Tiers 1 and 2 methods, but the exact requirements will be dependent on the model or measurement design.

6.2.3.4 CALCULATION STEPS FOR TIER 1

Mineral soils

The steps for estimating SOC_0 and $SOC_{(0-T)}$ and net soil C stock change from *Grassland Remaining Grassland* are as follows:

Step 1: Organize data into inventory time periods based on the years in which activity data were collected (e.g., 1990 and 1995, 1995 and 2000, etc.)

Step 2: Determine the land-use and management by mineral soil type and climate region for land at the beginning of the inventory period, which can vary depending on the time step of the activity data (0-T; e.g., 5, 10 or 20 years ago).

Step 3: Select the native reference C stock value (SOC_{REF}), based on climate and soil type from Table 2.3, for each area of land being inventoried. The reference C stocks are the same for all land-use categories to ensure that erroneous changes in the C stocks are not computed due to differences in reference stock values among sectors.

Step 4: Select the land-use factor (F_{LU}), management factor (F_{MG}) and C input levels (F_I) representing the land-use and management system present at the beginning of the inventory period. Values for F_{LU}, F_{MG} and F_I are provided in Table 6.2.

Step 5: Multiply these values by the reference soil C stock to estimate the 'initial' soil organic C stock ($SOC_{(0-T)}$) for the inventory time period.

Step 6: Estimate SOC_0 by repeating Step 1 to 4 using the same native reference C stock (SOC_{REF}), but with land-use, management and input factors that represent conditions in the last (year 0) inventory year.

Step 7: Estimate the average annual change in soil organic C stock for the area over the inventory time period ($\Delta C_{Mineral}$).

Step 8: Repeat Steps 1 to 6 if there are additional inventory time periods (e.g., 1995 to 2000, 2001 to 2005, etc.).

A case example is given below for computing a change in grassland soil organic C stocks using Equation 2.25 (Chapter 2), default stock change factors and reference C stocks.

Example: The following example shows calculations for aggregate areas of grassland soil carbon stock change to a 30 cm depth. In a tropical moist climate on Ultisol soils, there are 1Mha of permanent grassland. The native reference carbon stock (SOC_{Ref}) for the climate/soil type is 47 tonnes C ha^{-1}. At the beginning of the inventory time period (1990 in this example) the distribution of grassland systems was 500,000 ha of unmanaged native grassland; 400,000 ha of unimproved, moderately degraded grazing land; and 100,000 ha of heavily degraded grassland. Thus, initial soil carbon stocks for the area were: 500,000 ha ● (47 tonnes C ha^{-1} ● 1 ● 1 ● 1) + 400,000 ha ● (47 tonnes C ha^{-1} ● 1 ● 0.97 ● 1) + 100,000 ● (47 tonnes C ha^{-1} ● 1 ● 0.7 ● 1) = 45,026,000 tonnes C. In the last year of inventory time period (2010 in this example), there are: 300,000 ha of unmanaged native grassland; 300,000 ha of unimproved, moderately degraded grazing land; 200,000 ha of heavily degraded grassland; 100,000 ha of improved pasture receiving fertilizer; and 100,000 of highly improved pasture receiving fertiliser together with irrigation. Thus, total soil carbon stocks in the inventory year are: 300,000 ha • (47 tonnes C ha^{-1} ● 1 ● 1 ● 1) + 300,000 ha ● (47 tonnes C ha^{-1} ● 1 ● 0.97 ● 1) + 200,000 ● (47 tonnes C ha^{-1} 1 ● 0.7 ● 1) + 100,000 ● (47 tonnes C ha^{-1} 1 ● 1.17 ● 1) + 100,000 ● (47 tonnes C ha^{-1} ● 1 ● 1.17 ● 1.11) = 45,959,890 tonnes C. The average annual stock change over the period for the entire area is: 45,959,890 – 45,026,000 = 933,890 tonnes/20 yr = 46,694.5 tonnes per year soil C stock increase. (Note: 20 years is the time dependence of the stock change factor, i.e., factor represents annual rate of change over 20 years).

Organic soils

The steps for estimating the loss of soil C from drained organic soils are as follows:

Step 1: Organize data into inventory time periods based on the years in which activity data were collected (e.g., 1990 and 1995, 1995 and 2000, etc.).

Step 2: Determine the amount of *Grassland Remaining Grassland* on drained organic soils in the last year of each inventory time period.

Step 3: Assign the appropriate emission factor (EF) for annual losses of CO_2 based on climatic temperature regime (from Table 5.6).

Step 4: Estimate total emissions by summing the product of area (A) multiplied by the emission factor (EF) for all climate zones.

Step 5: Repeat for additional inventory time periods.

6.2.3.5 UNCERTAINTY ASSESSMENT

Three broad sources of uncertainty exist in soil C inventories: 1) uncertainties in land-use and management activity and environmental data; 2) uncertainties in reference soil C stocks if using a Tier 1 or 2 approach (mineral soils only); and 3) uncertainties in the stock change/emission factors for Tier 1 or 2 approaches, model structure/parameter error for Tier 3 model-based approaches, or measurement error/sampling variability associated with Tier 3 measurement-based inventories. In general, precision of an inventory is increased and confidence ranges are smaller with more sampling to estimate values for the three broad categories, while reducing bias (i.e., improve accuracy) is more likely to occur through the development of a higher Tier inventory that incorporates country-specific information.

For Tier 1, uncertainties are provided with the reference C stocks in the first footnote in Table 2.3, emission factors for organic soils in Table 6.3, and stock change factors in Table 6.2. Uncertainties in land-use and management data will need to be addressed by the inventory compiler, and then combined with uncertainties for the default factors and reference C stocks (mineral soils only) using an appropriate method, such as simple error propagation equations. If using aggregate land-use area statistics for activity data (e.g., FAO data), the inventory agency may have to apply a default level of uncertainty for the land area estimates (±50%). However, it is *good practice* for the inventory compiler to derive uncertainties from country-specific activity data instead of using a default level.

Default reference C stocks and stock change factors for mineral soils and emission factors for organic soils can have inherently high uncertainties, particularly bias, when applied to specific countries. Defaults represent globally averaged values of land-use and management impacts or reference C stocks that may vary from region-specific values (Powers *et al*., 2004; Ogle *et al*., 2006). Bias can be reduced by deriving country-specific factors using a Tier 2 method or by developing a Tier 3 country-specific estimation system. The underlying basis for higher Tier approaches will be experiments in the country or neighbouring regions that address the effect of land use and management on soil C. In addition, it is *good practice* to further minimize bias by accounting for significant within-country differences in land-use and management impacts, such as variation among climate regions and/or soil types, even at the expense of reduced precision in the factor estimates (Ogle *et al*., 2006). Bias is considered more problematic for reporting stock changes because it is not necessarily captured in the uncertainty range (i.e., the true stock change may be outside of the reported uncertainty range if there is significant bias in the factors).

Uncertainties in land-use activity statistics may be reduced through a better national system, such as developing or extending a ground-based survey with additional sample locations and/or incorporating remote sensing to provide additional coverage. It is *good practice* to design a classification that captures the majority of land-use and management activities with a sufficient sample size to minimize uncertainty at the national scale.

For Tier 2 methods, country-specific information is incorporated into the inventory analysis for purposes of reducing bias. For example, Ogle *et al*. (2003) utilized country-specific data to construct probability distribution functions for US specific factors, activity data and reference C stocks for agricultural soils. It is *good practice* to evaluate dependencies among the factors, reference C stocks or land-use and management activity data. In particular, strong dependencies are common in land-use and management activity data because management practices tend to be correlated in time and space. Combining uncertainties in stock change/emission factors, reference C stocks and activity data can be done using methods such as simple error propagation equations or Monte-Carlo procedures to estimate means and standard deviations for the change in soil C stocks (Ogle *et al*., 2003; Vanden Bygaart *et al*., 2004).

Tier 3 models are more complex and simple error propagation equations may not be effective at quantifying the associated uncertainty in resulting estimates. Monte Carlo analyses are possible (Smith and Heath, 2001), but can be difficult to implement if the model has many parameters (some models can have several hundred parameters) because joint probability distribution functions must be constructed quantifying the variance as well as covariance among the parameters. Other methods are also available such as empirically-based approaches (Monte *et al*., 1996), which use measurements from a monitoring network to statistically evaluate the relationship between measured and modelled results (Falloon and Smith, 2003). In contrast to modelling, uncertainties in measurement-based Tier 3 inventories can be estimated directly from the sample variance, estimated measurement error and other relevant sources in uncertainty.

6.2.4 Non-CO_2 greenhouse gas emissions from biomass burning

Non-CO_2 emissions from biomass burning in *Grassland Remaining Grassland* result predominantly from `savannah burning`, which occurs mostly in tropical and sub-tropical regions. However, grassy and woody formations elsewhere in the world can also be subject to fire, mainly as a result of management practices, and the resulting non-CO_2 emissions should also be reported.

CO_2 emissions from biomass burning in *Grassland Remaining Grassland* are not reported since they are largely balanced by the CO_2 that is reincorporated back into biomass via photosynthetic activity, within weeks to few years after burning.

Non-CO_2 emissions (particularly CO, CH_4, N_2O and NO_x) that result from incomplete combustion of biomass in managed grassland should be reported, regardless of their nature (natural or anthropogenic fire). The amount of biomass burnt in any one fire may change from region to region, as well as vary seasonally. The efficiency of combustion and the corresponding fraction of the biomass converted into non-CO_2 greenhouse gases may also vary.

Countries should report non-CO_2 emissions from biomass burning in *Grassland Remaining Grassland* using annual data, instead of an average of activity data for a given period. This allows the reporting to capture interannual fluctuations due to climatic events (such as El Niño), or natural climatic variability (unusually dry years, when disturbances from fire may be more frequent). Generally, the estimates are highly uncertain due to the lack of reliable and accurate data on the mass of fuel available for combustion, and combustion and emission factors.

The general method for estimating greenhouse gas emissions in *Grassland Remaining Grassland* is described in Equation 2.27 in Chapter 2. Emissions from biomass burning should be estimated from the above-ground biomass, and DOM pools. With burning, below-ground biomass is assumed to remain constant after disturbance, or transferred to the soil pool. Default values for Tier 1 method or components of a Tier 2 method are provided in Section 2.4 of Chapter 2.

6.2.4.1 CHOICE OF METHOD

Figure 2.6 in Chapter 2 presents a decision tree that guides the selection of the appropriate Tier level to report non-CO_2 emissions from biomass burning. If biomass burning in *Grassland Remaining Grassland* is not a key category, countries may choose to report non-CO_2 emissions using Tier 1 method, which is based on highly aggregated data and default combustion and emission factors. However, if biomass burning in *Grassland Remaining Grassland* is a key category, countries should strive for improving inventory and reporting approaches by applying the highest Tier possible, given national circumstances.

Tier 1

Equation 2.27 should be applied when choosing to report under a Tier 1 method. Tier 1 is based on highly aggregated data and default combustion and emission factors. If data on *Mass of Fuel Available for Combustion* (M_B) are not available, countries should use the default data in Table 2.4 in Chapter 2 for the mass of fuel consumed. However, since the data in this table is provided by vegetation types and sub-categories, countries applying these default data should stratify the area of *Grassland Remaining Grassland* in their territory before choosing the appropriate default value (or values) to be applied.

Tier 2

Tier 2 extends Tier 1 by incorporating more disaggregated area estimates (per vegetation types, sub-categories) and country-specific estimates of combustion and emission factors for each stratum. The area burnt can be estimated using remotely sensed data of adequate spatial and temporal resolutions analysed according to a robust sampling design. The periodicity of data acquisition is crucial especially in the tropics, where burning occurs during a specific period in the year, which can extend over several months. It is important, when estimating the area burnt, to capture the month-to-month variation of the area burnt.

Tier 3

Tier 3 method should be based on models with algorithms to generate regional scale maps of area burnt using satellite data of multiple sources and of moderate spatial resolution. The results should be validated using high spatial resolution data augmented by field observations, and refined based on the validation results and feedback from operational users. A sampling approach can be designed to generate estimates of area burnt. Countries should stratify, as far as possible, the *Grassland Remaining Grassland* areas, and the corresponding combustion and emission factors. The Tier 3 method should provide estimates (fluxes) of the impact of biomass burning on all pools, including below-ground biomass.

6.2.4.2 CHOICE OF EMISSION FACTORS

Tier 1

Under a Tier 1 approach, default values are provided for combustion factors [fraction of fuel (above-ground biomass, litter and dead wood) consumed] in Table 2.6 in Chapter 2; and for emission factors in Table 2.5 in Chapter 2, for each non-CO_2 greenhouse gas. Estimates of above-ground biomass in savannas are provided in Table 6.4. The value in Table 2.4 should be used as the "fraction of fuel actually burnt" in Equation 2.27 in Chapter 2. Even though data for Tier 1 is usually highly aggregated, countries should seek to stratify the grassland area affected by biomass burning by broad vegetation type (shrubland, savanna woodland, savannah grassland), as well as according to the period of the burn (early dry season, or mid/late dry season). If the grassland is stratified by vegetation type and sub-category (e.g., savanna parkland, savanna woodland), countries can use the default values on biomass consumption provided in Table 2.4 in Chapter 2, which gives estimates of the product between fuel available and the fraction of biomass actually burnt (equivalent to the product of quantities M_B and C_f in Equation 2.27 in Chapter 2).

Tier 2

Countries using a Tier 2 approach should use country-specific combustion and emission factors developed for each broad grassland type (shrublands, savanna woodlands, savanna grassland) and sub-categories (if applicable).

Tier 3

Countries using a Tier 3 method should develop algorithms to estimate the area burnt, validating the products obtained with data from field observation and consultation with the product users.

6.2.4.3 CHOICE OF ACTIVITY DATA

Tier 1

For a Tier 1 method, the only activity data needed is the area affected by biomass burning in *Grassland Remaining Grassland*. If national data on burnt areas are not available, data from global fire maps can be used. However, note that any global fire product only represents a fraction of the total fires which take place both in time and space, due to inherent limitations of satellite sensors, which are the sources of the global map data. Alternatively, countries may also estimate the annual area burnt by multiplying the area of grassland in the territory by the estimated annual fraction of grassland burnt, and to apportion the area thus estimated between *Grassland Remaining Grassland* and *Grassland* converted to other land use.

Tier 2

This approach extends Tier 1 by incorporating more disaggregated data on areas affected by biomass burning. The grassland areas should be stratified according to different grassland vegetation types (shrublands, savanna grassland, savanna woodland, etc.) and by sub-category. National estimates of the area burnt should be produced. In the absence of reliable national data, countries can rely on global fire maps, but should strive to assess the particular sampling underlying the production of the fire maps, and, more importantly, whether the particular sample which is observed is affected by any systematic or unsystematic bias. Different data sources, which in general have different sampling strategies, should be used to estimate the total area burnt. Additionally, the burnt area should be compared to burnt areas with validation data sets.

Tier 3

Tier 3 requires high-resolution activity data disaggregated at sub-national to fine grid scales. Similar to Tier 2, the grassland area should be stratified by specific vegetation types and sub-categories to be used in models. If possible, spatially explicit area estimates are used to facilitate complete coverage of the grassland and ensure that areas are not over- or underestimated. Furthermore, spatially explicit area estimates can be related to locally relevant emission and combustion rates, improving the accuracy of estimates. The use of process-based models should provide a more accurate estimate of area burnt if the results are validated with field measurements. Sufficient representative measurements are needed for validation purposes.

6.2.4.4 UNCERTAINTY ASSESSMENT

There are several sources of uncertainty related to estimates of non-CO_2 emissions from biomass burning in *Grassland Remaining Grassland.* For example, savannas include a heterogeneous mosaic of grass, brush, thorn scrub, and open woodland. Fire behaviour varies greatly among these and hence, disaggregation of vegetative formations will lead to greater precision.

The fraction of fuel that is actually combusted during biomass burning (combustion factor) varies greatly, not only between ecosystems, but also between fires, between years, and as a function of cultural practices. Measurements from a given fire, year, and/or cultural setting cannot be extrapolated with confidence to other regions or years, or to biome scale (Robinson, 1989).

A major cause of uncertainty in estimating the contribution of biomass burning to emissions of trace gases is the extent of area burnt, intensity of the fire, and the rate of spread, especially in tropical ecosystems (Seiler and Crutzen, 1980; Matson and Ojima, 1990; Robinson, 1989). Precision estimates vary widely and depend essentially on the accuracy of the estimates of area burnt, proportion of the available fuel oxidized, and the biomass fuel available. Uncertainties of estimates of areas burnt can vary markedly depending on the methodology employed – for example, where very high resolution remote-sensing is used it may be of the order of 20%, whereas the use of global fire maps may result in uncertainties of up to two-fold. Uncertainties in estimates of greenhouse gas emissions over large regions from fire are likely to be at least 50%, even with good country-specific data, and at least two-fold where only default data are used.

6.3 LAND CONVERTED TO GRASSLAND

Land Converted to Grassland includes Forest Land or other land-use categories converted to Grassland within the last 20 years. Greenhouse gas inventory for the land-use category *Land Converted to Grassland* (LG) involves estimation of changes in carbon stock from five carbon pools (i.e., above-ground biomass, below-ground biomass, dead wood, litter, and soil organic matter), as well as emissions of non-CO_2 gases. The principal sources of emissions and removals of greenhouse gases in this category are associated with land-use change and management.

The carbon implications of the conversion from other land uses (mostly Forest Land, Cropland, and to lesser degree Wetlands and seldom Settlements) to Grassland is less clear cut than the case of conversion to Cropland. Literature on the main conversion type (from Forest Land to Grassland in the tropics) provides evidence for net gains as well as net losses in soil carbon, and the effect of management on the soil carbon changes of grassland after conversion is critical (see, for example, Veldkamp, 2001) as well as the pre-conversion stocks. Conversion of land from other uses and from natural states to Grassland can result in net emissions or net uptake of CO_2 from both, biomass and soil. The conversion process may also result in emissions from biomass burning.

The decision tree in, Figure 1.3 (Chapter 1) provides guidance for selecting the appropriate tier level for the implementation of estimation procedures for *Land Converted to Grassland*.

6.3.1 Biomass

This section provides guidelines for estimating carbon stock changes in biomass due to the conversion of unmanaged land to managed grassland, as well as conversion from other land uses to grassland, including *Forest Land Converted to Grassland* and Cropland converted to pasture and grazing lands. The changes in carbon stock in biomass from land conversion to grassland result from the removal of existing vegetation and replacement with grassland vegetation. This differs from the concepts underlying carbon stock changes in biomass of *Grassland Remaining Grassland* where changes are tied to management practices.

Conversion of land to grassland often results in the transfer of carbon from one pool to another. All transfers must be accounted for and gains and losses from these pools during the transition to a new steady state must be accounted when reporting lands converted to grasslands. For example, when converting a forest to a pasture, trees are felled and a portion of the above-ground biomass is transferred to the dead organic matter pool, a portion of the below-ground biomass is transferred to the soil organic matter pool, etc.

Estimating changes in carbon stocks in biomass for lands converted to grassland requires a two-phase approach. There is often an abrupt change in biomass associated with the land-use change, particularly when the change is deliberate and associated with land preparation operations (e.g., clearing and burning). This abrupt change is treated as Phase 1, and is estimated at the year of conversion. The second phase (Phase 2) accounts for gradual biomass loss and gain during a transition period to a new steady-state system. At some point in time, the grassland ecosystem should approach an equilibrium, when it is then considered under the category *Grassland Remaining Grassland* and accounted for under that category. A 20-year transition period following conversion is the default period for remaining in the transitional category, but countries can determine the appropriate transition period at their discretion. The values of coefficients determining the rate of emissions may depend on the transition period used.

To account for the transition period, lands converted to grasslands should be treated as annual cohorts. That is, land converted at a given year should be accounted for with Phase 1 methods in the year of conversion, and with Phase 2 methods for the subsequent 19 years. At the end of the 20-year period, the land area for that given year is added to the land area being accounted under the *Grassland Remaining Grassland* category.

It is likely that a number of lands converted to grassland will not have an abrupt transition (e.g., Cropland that is abandoned and that reverts to Grassland). In this case, Phase 1 methods will not be appropriate and there will be a gradual transition in biomass pools to a new equilibrium. When this type of conversion occurs, the whole conversion accounting can be treated with Phase 2 methods.

It is *good practice* to apportion transfers of carbon between pools when there is an abrupt transition. The immediate impacts of land conversion activities on the five carbon stocks can be summarized in a “disturbance matrix”. The disturbance matrix describes the retention, transfers and releases of carbon in the pools in the original ecosystem following conversion to grassland. A disturbance matrix defines for each pool the proportion that remains in that pool and the proportion that is transferred to other pools. A small number of transfers are possible, and are outlined in the disturbance matrix in Table 2.1 in Chapter 2. If the rate of land conversion is more or less constant, the assumption that all carbon in theses pools was lost at the time of conversion would be a reasonable first approximation. Where the rate of land conversion varies over time, it is *good practice* to account for the transfer and release of carbon among the different carbon pools and ensure that all carbon is accounted.

In cases where there is an immediate and abrupt carbon stock change in biomass due to conversion to grasslands, the effect of this conversion will be estimated using Equation 2.16 in Chapter 2. During the transition period, pools that gain or lose C often have a non-linear loss or accumulation curve that can be represented through successive transition matrices. If the true shapes of the curves are known, these curves can be applied to each cohort that is under transition during the reporting year to estimate the annual emission or removal by the specific pool. If the shape of the curve is unknown, countries may simplify and use a linear decay function to estimate pool changes. Two methods are available to estimate these changes.

6.3.1.1 CHOICE OF METHOD

The decision tree in, Figure 2.2 (Chapter 2) provides guidance for selecting the appropriate tier level for the implementation of estimation procedures for biomass in *Land Converted to Grassland*. Estimation of changes in biomass requires an estimate of changes in above-ground vegetation and changes in below-ground biomass. Countries should use the highest tier possible given national circumstances. It is *good practice* to use a Tier 2 or Tier 3 approach if carbon emissions and removals in *Land Converted to Grassland* is a key category and if the sub-category of biomass is considered significant, based on principles outlined in Volume 1, Chapter 4 (Methodological Choice and Identification of Key Categories).

Tier 1

The change in biomass carbon stock on *Land Converted to Grassland* under Tier 1 should be estimated using Equation 2.15. The average carbon stock change is equal to the carbon stock change due to the removal of biomass from the initial land use (i.e., carbon in biomass immediately after conversion minus the carbon in biomass prior to conversion), plus carbon stocks from biomass growth following conversion. As a simplification for Tier 1, it is assumed that all biomass is lost immediately from the previous ecosystem after conversion (Equation 2.16) , even when there is no abrupt change, and residual biomass (B_{AFTER}) is thus assumed to be zero, (i.e., the land is cleared of all vegetation before grassland vegetation is established). Thus, there is no transfer of biomass from the biomass pool to the dead wood pool, for example. Default values for biomass prior to conversion can be found in the chapters relating to the respective land uses (e.g., default factors for Forest Land are to be found in the chapter dealing with biomass in Forest Land).

Additionally, it is assumed that grasslands achieve their steady-state biomass during the first year following conversion. Thus, for Tier 1, there are no stock changes associated with Phase 2, though the lands converted to grasslands should be retained in the conversion category for the 20 year transition period because the soil stocks will take longer to reach equilibrium. Emissions and uptakes from biomass during Phase 2 of the calculation are therefore zero. If there are significant management changes during the transition phase, countries can account for the impacts of this on C stocks in biomass using Tier 2 methods from *Grassland Remaining Grassland*. It is *good practice* to account for all *Land Converted to Grassland*. Thus, a separate calculation must be done for each type of conversion.

Tier 2

The Tier 2 calculations differ structurally in a number of ways from Tier 1. First, Tier 2 estimates use the two-phase approach described earlier. Tier 2 relies on some country-specific estimates of the biomass in initial and final land uses rather than the defaults, as in Tier 1. Area estimates for *Land Converted to Grassland* are disaggregated at higher resolution spatial scales than in Tier 1 to capture regional variations within the grassland formations of the country.

Second, for Tier 2 countries may modify the assumption that biomass immediately following conversion is zero. This enables countries to take into account land-use transitions where some, but not all, vegetation from the original land use is removed. In addition, under Tier 2, it is possible to account for biomass accumulation following grassland establishment over a several year period (rather than accounting all biomass stock change in the year of conversion) if data are available to estimate the time to full biomass establishment and the annual stock changes.

Third, under Tier 2, it is *good practice* to apportion transfers of carbon between pools. Grassland systems typically do not contain significant carbon in the dead wood or litter pools, but dead wood may persist for a number of years in young grasslands that are replacing forests or accumulate in scrublands as woody biomass senesces. If the rate of land conversion is more or less constant, the assumption that all carbon in theses pools was lost at the time of conversion would be a reasonable first approximation. Where the rate of land conversion varies over time, it is appropriate to try to account for the transfer and release of carbon from litter, dead wood, and soil carbon pools. It is therefore necessary to distinguish immediate losses due to the conversion activities from the losses that occur in the years following the land conversion.

The immediate and abrupt carbon stock change in biomass due to *Land Converted to Grassland* under Tiers 2 and 3 will be estimated using Equation 2.16 in Chapter 2, where B_{AFTER} is assumed to be zero. During the transition period, pools that gain or loose C often have a non-linear loss or accumulation curve that can be represented through successive transition matrices. For Tier 2, a linear change function can be assumed. For a Tier 3 approach based upon these methods, it is *good practice* to use the true shapes of the curves. These curves are to be applied to each cohort that is under transition during the reporting year to estimate the annual change in the biomass carbon pools.

For the estimation of changes in biomass carbon during the transition phase, two methods are suggested. The equations used are the same as those used for Tier 2 in *Grassland Remaining Grassland* section.

Gain-Loss Method *(see Equation 2.7 in Chapter 2):* This method involves estimating the area of each type of land conversion and the average annual transfer into and out of biomass stocks. This requires: (i) an estimate of the area under *Land Converted to Grassland* according to different climate or ecological zones or grassland types, disturbance regime, management regime, or other factors significantly affecting biomass carbon pools; (ii) the quantity of biomass accumulating in the biomass stocks; and (iii) the quantity of biomass lost from the biomass stocks on per hectare basis according to different grassland types.

Stock-Difference Method *(see Equation 2.8 in Chapter2):* This method involves estimating the area of *Land Converted to Grassland* and the biomass stocks at two periods of time, t_1 and t_2. The biomass stock changes for the inventory year are obtained by dividing the stock changes by the period (years) between two measurements. The Stock-Difference Method is feasible for countries that have periodic inventories, and is more suitable for countries adopting Tier 3 methods. This method may not be well suited to regions with very variable climates and may produce spurious results unless annual inventories can be made.

Tier 3

Tier 3 methods are used where countries have country-specific emission factors, and substantial national data. Country-defined methodology may be based on detailed inventories of permanent sample plots for their grasslands and/or models. For Tier 3, countries should develop their own methodologies and parameters for estimating changes in biomass. These methodologies may be derived from methods specified above, or may be based on other approaches. The method used needs to be clearly documented.

Tier 3 involves inventory systems using statistically-based sampling of biomass over time and/or process models, stratified by climate, grassland type and management regime. For example, validated species-specific growth models that incorporate management effects such as grazing intensity, fire, liming, and fertilization, with corresponding data on management activities, could be used to estimate net changes in grassland biomass over time. Models, together with periodic sampling-based biomass estimates, similar to those used in detailed forest inventories, could be applied to estimate stock changes to make spatial extrapolations for grassland areas.

Key criteria in selecting appropriate models include the ability to represent all of the ecosystem conversions and management practices that are represented in the activity data. It is critical that the model be validated with independent observations from country-specific or region-specific field locations that are representative of the variability of climate, soil and grassland management systems in the country.

If possible, spatially explicit area estimates should be used to facilitate complete coverage of the grassland and ensure that areas are not over- or underestimated. Furthermore, spatially explicit area estimates can be related to locally relevant carbon accumulation and removal rates, and restocking and management impacts, improving the accuracy of estimates.

6.3.1.2 CHOICE OF EMISSION/REMOVAL FACTORS

Tier 1

Tier 1 methods require estimates of the biomass of the land use before conversion and after conversion. It is assumed that all biomass is cleared when preparing a site for grassland use, thus, the default for biomass immediately after conversion is 0 tonne ha^{-1}. Default values for biomass can be found at:

- Forest Land prior to clearing: see Chapter 4 (Forest Land);
- For Cropland containing woody perennial crops: see Chapter 5 (Cropland); and
- For Cropland containing annual crops: Use default of 4.7 tonnes of carbon ha^{-1} or 10 tonnes of dry matter ha^{-1}. The error range associated with this default is ±75%.

Table 6.4 provides default values for biomass following conversion; however, there is wide variation within any region largely driven by rainfall and soil texture. These default values have high error rates and thus when better country-specific data are available, countries should use the best locally available data to estimate grassland biomass.

TABLE 6.4
DEFAULT BIOMASS STOCKS PRESENT ON GRASSLAND , AFTER CONVERSION FROM OTHER LAND USE

IPCC climate zone	Peak above-ground biomass[1] (tonnes d.m. ha^{-1})	Total (above-ground and below-ground) non-woody biomass[2] (tonnes d.m. ha^{-1})	Error [3]
Boreal – Dry & Wet[4]	1.7	8.5	± 75%
Cold Temperate – Dry	1.7	6.5	± 75%
Cold Temperate –Wet	2.4	13.6	± 75%
Warm Temperate – Dry	1.6	6.1	± 75%
Warm Temperate –Wet	2.7	13.5	± 75%
Tropical – Dry	2.3	8.7	± 75%
Tropical - Moist & Wet	6.2	16.1	± 75%

[1] Data for standing biomass are compiled from multi-year averages reported at grassland sites registered in the ORNL DAAC NPP database [http://www.daacsti.ornl.gov/NPP/].

[2] Total above-ground and below-ground biomass values are based on the peak above-ground biomass values, and the below-ground biomass to aboveground biomass ratios (Table 6.1).

[3] Represents a nominal estimate of error, equivalent to two times standard deviation, as a percentage of the mean.

[4] Due to limited data, dry and moist zones for the boreal temperature regime and moist and wet zones for the tropical temperature regime were combined.

Tier 2

It is *good practice* to use country-specific estimates for biomass stocks and emissions/removals due to land conversion, and also include estimates of on-site and off-site losses due to burning and decay following land conversion to grassland. These improvements can take the form of systematic studies of carbon content and emissions and removals associated with land uses and land-use conversions within the country or region and a re-examination of default assumptions in light of country-specific conditions.

Region-specific or country-specific data on biomass for young grasslands are needed for a Tier 2 approach. These can be obtained through a variety of methods, including estimating density (e.g., crown cover) of woody and herbaceous vegetation from air photos or high resolution satellite imagery and ground-based measurement plots. Species composition, density, and above-ground vs. below-ground biomass can vary widely for different grassland types and conditions and thus it may be most efficient to stratify sampling and survey activities by grassland types. General guidance on survey and sampling techniques for biomass inventories is given in Chapter 3 in Annex 3A.3.

Accurately capturing the dynamics of below-ground biomass is necessary for accounting for carbon stock changes when land is converted to grassland. In the case of abandonment of Cropland, below-ground biomass will increase continuously as ecosystem succession takes place. For lands converted from forest to pasture, there will be a gradual decomposition of below-ground forest biomass and a gradual increase of below-ground biomass of pasture grasses. Estimating below-ground biomass can be an important component of biomass surveys of grassland but field measurements are laborious and difficult and thus expansion factors to estimate below-ground biomass from above-ground biomass are often used.

Root-to-shoot ratios show wide ranges in values at both individual species (e.g., Anderson *et al.*, 1972*)* and community scales (e.g., Jackson *et al.*, 1996; Cairns *et al.*, 1997*)*. Thus, it is recommended to use, as far as possible, empirically-derived root-to-shoot ratios specific to a region or vegetation type. Table 6.1 provides default root-to-shoot ratios for major grassland ecosystems of the world; these data can be used as defaults when countries do not have more regionally specific information to develop country-specific ratios. Ratios for woodland/savannah and scrublands are also included for use by countries that include these lands in the grassland section of their inventory.

Tier 3
Tier 3 approaches consist of using a combination of dynamic models and inventory measurements of biomass stock changes. This approach does not employ simple stock changes or emission factors *per se*. Estimates of emissions/removals using model-based approaches are derived from the interaction of multiple equations that estimate the net change of biomass stocks within the models. Models can be used, together with periodic sampling-based stock estimates similar to those used in detailed forest inventories, to estimate stock changes or inputs and outputs (as in Tier 2 to make spatial extrapolations for grassland areas). For example, validated species-specific growth models that incorporate management effects such as grazing intensity, fire, and fertilization, with corresponding data on management activities, could be used to estimate net changes in grassland biomass over time.

6.3.1.3 CHOICE OF ACTIVITY DATA

All tiers require estimates of land areas converted to Grassland. The same area data should be used for biomass calculations, dead organic matter, and the soil carbon estimates. If necessary, area data used in the soils analysis can be aggregated to match the spatial scale required for lower order estimates of biomass; however, at higher tiers, stratification should take account of major soil types. Area data should be obtained using the methods described in Chapter 3. Cross-checks should be made to ensure complete and consistent representation of annually converted lands in order to avoid possible omissions or double counting. Data should be disaggregated according to the general climatic categories and grassland types. Tier 3 inventories will require more comprehensive information on the establishment of new grasslands, with refined soil classes, climates, and spatial and temporal resolution. All changes having occurred over the number of years selected as the transition period should be included with transitions older than the transition period (default 20 years) reported as a subdivision of *Grassland Remaining Grassland*. Higher tiers require greater detail but the minimum requirement for inventories to be consistent with the *IPCC Guidelines* is that the areas of forest conversion are identified separately. This is because forest will usually have higher carbon density before conversion. This implies that at least partial knowledge of the land-use change matrix, and therefore, where Approaches 1 and 2 from Chapter 3 are used to estimate land area are being used, supplementary surveys may be needed to identify the area of land being converted from Forest Land to Grassland. As pointed out in Chapter 3, where surveys are being set up, it will often be more accurate to seek to establish directly areas undergoing conversion than to estimate these from the differences in total land areas under particular uses at different times.

Tier 1
Estimates of areas converted to Grassland, from initial land uses (i.e., Forest Land, Cropland, Settlements, etc.) to final grassland type, are necessary. The methodology assumes that area estimates are based on a one-year time frame, after which they are transferred to the category *Grassland Remaining Grassland*. If area estimates are assessed over longer time frames, they should be converted to average annual areas to match the carbon stock values used. If countries do not have these data, partial samples may be extrapolated to the entire land base or historic estimates of conversions may be extrapolated over time based on the judgement of country experts. At a minimum, countries can rely on average deforestation rates and land-use conversions to grassland from international sources, including the FAO (See FAOSTAT website). Tier 1 approaches may use average annual rates of conversion and estimated areas in place of direct estimates.

Tier 2
It is *good practice* to use actual area estimates for all possible transitions from initial land use to final grassland type. Complete reporting can be accomplished either through analysis of periodic remotely sensed images of land-use and land-cover patterns, and/or periodic ground-based sampling of land-use patterns, or hybrid inventory systems.

Tier 3
Activity data used in Tier 3 calculations should provide a full accounting of all land-use transitions to grassland and be disaggregated to account for different conditions within a country. Disaggregation can occur along

political boundaries (county, province, etc.), biome area, climate zone, or on a combination of these parameters. In many cases countries may have information on multi-year trends in land conversion (from periodic sample-based or remotely sensed inventories of land use and land cover).

6.3.1.4 CALCULATION STEPS FOR TIERS 1 AND 2

The following summarizes steps for estimating change in carbon stocks in biomass (ΔC_B) using the default methods

Worksheets have been provided for completing Tier 1 estimates of emissions and removals from this category (see Annex 1 AFOLU Worksheets). For this calculation, Equation 2.15 is simplified. The assumption for Tier 1 is that ΔC_G and ΔC_L equal zero. Thus, the only term that requires calculation is the $\Delta C_{CONVERSION}$, which is calculated with Equation 2.16. For lands converted to Grassland, Equation 2.16 is computed twice, once for the herbaceous biomass and once for the woody biomass. This is done because each of these components has a different carbon fraction.

Tier 1

For Tier 1, only the abrupt change needs to be calculated. The simplifying assumption is that all stock changes occur in the year of conversion. Thus for conversions older than 1 year, but still in the transition period, the assumption is that there are no net changes in biomass C stocks.

Step 1: Determine the categories of land conversion to be used in this assessment and the representative areas. Tier 1 requires estimates of areas converted to Grassland, from initial land uses (i.e., Forest Land, Cropland, Settlements, etc.) to final grassland type. When calculating for lands in the transition phase, only the total area of land converted during the previous 20 years is required as the Tier 1 assumption is that all changes in C stocks in the biomass occur during the first year.

Step 2: Determine the activity categories to be used in this assessment and the representative areas. The activity category consists of definitions of the type of conversion and, if applicable, the nature of management of the previous land cover and grassland management (e.g., 'conversion of logged tropical seasonal forest to cattle pasture using exotic grasses').

Step 3: For each activity category, determine the biomass per hectare in herbaceous biomass and woody biomass (separately) prior to conversion. Where data on below-ground biomass are lacking, use below-ground to above-ground biomass ratios to estimate the below-ground component of the biomass. Default values can be found in the chapter that refers to the other land-use category.

Step 4: For each activity category, determine the biomass per hectare in herbaceous biomass and woody biomass (separately) following one year of conversion to grassland. Where data on below-ground biomass are lacking, use below-ground to above-ground biomass ratios to estimate the below-ground component of the biomass. Default values for herbaceous biomass can be found in Table 6.4.

Step 5: Determine the appropriate carbon fractions for herbaceous and woody biomass. The default values are 0.50 tonne C (tonne d.m.)$^{-1}$ for woody biomass and 0.47 tonne C (tonne d.m.)$^{-1}$ for herbaceous biomass.

Step 6: Estimate the net change of carbon stocks in woody and herbaceous biomass (separately) by subtracting the final biomass from the initial biomass and multiplying this difference by the representative area for the activity and by the carbon fraction of the biomass component. A negative value indicates an increase of biomass.

Step 7: Sum the changes in carbon stocks in woody and herbaceous biomass to determine the net change in biomass C stocks for each activity category. Sub-totals for each type of conversion should be computed and a grand total should be computed and entered at the bottom of the last column of the table.

Tier 2

Step 1: Determine the categories of land conversion to be used in this assessment and the representative areas. When calculating for lands in the transition phase, representative areas for each category at different stages of conversion are required.

Step 2: Abrupt changes

- Determine the activity categories to be used in this assessment and the representative areas. The activity category consists of definitions of the type of conversion and, if applicable, the nature of management of the previous land cover and grassland management (e.g., 'conversion of logged tropical seasonal forest to cattle pasture using exotic grasses').

- For each activity category, determine the biomass per hectare in herbaceous biomass and woody biomass (separately) prior to conversion. Where data on below-ground biomass are lacking, use below-ground to above-ground biomass ratios to estimate the below-ground component of the biomass.
- For each activity category, determine the biomass per hectare in herbaceous biomass and woody biomass (separately) following one year of conversion to grassland. Where data on below-ground biomass are lacking, use below-ground to above-ground biomass ratios to estimate the below-ground component of the biomass.
- Determine the appropriate carbon fractions for herbaceous and woody biomass. The default values are 0.50 tonne C (tonne d.m.)$^{-1}$ for woody biomass and 0.47 tonne C (tonne d.m.)$^{-1}$ for herbaceous biomass.
- Estimate the net change of woody and herbaceous biomass per hectare for each type of conversion by subtracting the final biomass from the initial biomass and multiplying this difference by the representative area for the activity and by the carbon fraction of the biomass component. A negative value indicates an increase of biomass.
- Sum the changes in carbon stocks in woody and herbaceous biomass to determine the net change in biomass C stocks for each activity category. Sub-totals for each type of conversion should be computed and a grand total should be computed.

Step 3: Transitional changes

- Determine the categories and cohorts to be used in this assessment and the representative areas. The category consists of definitions of the type of conversion and, if applicable, the nature of management of the previous land cover and grassland management (e.g., ‘conversion of logged tropical seasonal forest to cattle pasture using exotic grasses’).
- Determine the annual change rate for herbaceous and woody biomass (separately) by activity type using either the Gain-Loss Method or the Stock-Difference method (see below) for each cohort of lands that are currently in the transition phase between conversion and a new steady-state grassland system.
- Determine the herbaceous and woody biomass in the cohort during the previous year (usually taken from the previous inventory).
- Estimate the change in herbaceous and woody biomass for each cohort by adding the net change rate to the previous year’s stocks.

Gain-Loss Method (Equation 2.7 in Chapter 2)

- Determine the average annual increment of herbaceous and woody biomass (separately).
- Determine the average annual losses of herbaceous and woody biomass (separately).
- Determine the net change rate in herbaceous and woody biomass by subtracting the loss from the increment.

Stock-Difference Method (Equation 2.8 in Chapter 2)

- Determine the inventory time interval, the average stocks of herbaceous and woody biomass at the initial inventory, and the average herbaceous and woody biomass at the final inventory.
- Use these figures to estimate the net annual difference in herbaceous and woody biomass by subtracting the initial stock from the final stock and dividing this difference by the number of years between inventories. A negative value indicates a loss in the stock.
- A Tier 2 approach requires country-specific or ecosystem-specific expansion factors and the best available local data should be used (and documented).

6.3.1.5 UNCERTAINTY ASSESSMENT

Uncertainty analyses for *Land Converted to Grassland* are fundamentally the same as *Grassland Remaining Grassland*. Two sources of uncertainty exist in C inventories: 1) uncertainties in land-use and management activity and environmental data; 2) uncertainties in carbon increase and loss, carbon stocks and expansion factor terms in the stock change/emission factors for Tier 2 approaches, model structure/parameter error for Tier 3 model-based approaches, or measurement error/sampling variability associated with Tier 3 measurement-based inventories. See the uncertainty section in *Grassland Remaining Grassland* for additional discussion (Section 6.2.1.5).

6.3.2 Dead organic matter

In this section, changes in carbon stocks of dead organic matter pool (DOM) are presented for the land category *Land Converted to Grassland*. Cropland, Forest Land, Settlements, and other land-use categories could be potentially converted to Grassland. Methods are provided for two types of dead organic matter pools: 1) dead wood, and 2) litter. Chapter 1of this Volume provides detailed definitions of these pools. The features of dead wood and litter are described in Section 6.2.2.

Estimating changes in carbon stocks in DOM for *Land Converted to Grassland* requires a two-phase approach, similar to approach described in Biomass Section (Section 6.3.1). During the first phase, there is often an abrupt change in DOM associated with the land-use change, particularly when the change is deliberate and associated with land preparation operations (e.g., clearing and burning). The second phase accounts for decay and accumulation processes during a transition period to a new steady-state system. At some point in time, the grassland ecosystem should reach an equilibrium; at which time it can be considered *Grassland Remaining Grassland* and accounted for under that category. A 20-year transition period following conversion is the default period, but countries are free to determine the appropriate transition period at their discretion.

To account for the transition period, lands converted to grasslands should be treated as annual cohorts. That is, land converted in a given year should be accounted for under Phase 1 in the year of conversion, and under Phase 2 for the subsequent 19 years. At the end of the 20-year period, the land area for that given year is added to the land area being accounted under the *Grassland Remaining Grassland* category.

It is likely that many land uses will not have a dead wood or a litter pool, so that corresponding carbon pools prior to conversion can be assumed to be zero. Forest Land, agroforests, and Wetlands converted to Grassland, could have significant carbon in these pools, as well as forest areas around settlements that may have been defined as settlements based on nearby use rather than land cover.

It is also likely that a number of land areas converted to grassland will not have an abrupt transition (e.g. Cropland that is abandoned and that reverts to grassland). In this case, Phase 1 assumptions will not be appropriate and there will be a gradual transition in DOM pools to a new equilibrium. When this type of conversion occurs, the whole conversion accounting can be treated as Phase 2.

Conversion of lands to grasslands often involves clearing and burning. As land is cleared, DOM may be removed for fuelwood or other uses. Countries may try to quantify these removals and account for the carbon in other sectors (e.g. Energy). Additionally, burning the remaining vegetation does not completely remove the DOM and some is converted to charcoal. At higher tiers, countries may wish to account for this transfer to a long-term storage pool.

6.3.2.1 CHOICE OF METHOD

The decision tree in Figure 2.3 in Chapter 2 provides assistance in the selection of the appropriate tier level for the implementation of estimation procedures. Estimation of changes in carbon stocks in DOM requires an estimate of changes in stocks of dead wood and changes in litter stocks. Each of the DOM pools (dead wood and litter) is to be treated separately, but the method for each pool is the same.

Tier 1

A Tier 1 approach involves estimating the area of each type of land conversion using only the major conversion categories (e.g., Forest Land to Grassland). The immediate and abrupt carbon stock change (Phase 1) in dead wood and litter due to conversion of other lands to Grassland under Tier 1 is estimated using Equation 2.23 where C_0 equals zero and T_{on} equals 1. The Tier 1 default assumes removal of all dead wood and litter during conversion and that there is no dead wood or litter that remains or accumulates in *Land Converted to Grassland*. Countries where this assumption is known to be false (e.g., where slash and burn agriculture is widely practiced) are encouraged to use a higher tier when accounting for lands converted to Grassland. Additionally, it should be assumed that grasslands achieve steady-state biomass during the first year following conversion. Thus, for Tier 1, there is no emissions or removals associated with Phase 2, though the lands converted to Grassland should be retained in the conversion category for the 20-year transition period because the soil stocks will take longer to reach equilibrium.

There are no default values available for dead wood or litter in most systems. For forests, there are no global default values for dead wood, but there are values for litter (Table 2.2 in Chapter 2). Countries should make best estimates and use local data from forestry and agricultural research institutes to provide best estimates of the dead wood and litter in the initial system prior to conversion.

Tier 2

Tier 2 approaches require greater disaggregation than that used in Tier 1. Activity data should be reported by ecological zone and management regimes.

As explained in the biomass section (Section 6.3.1), the immediate impacts of land conversion activities on the five carbon pools can be summarized in a "disturbance matrix". The disturbance matrix describes the retention, transfers and releases of carbon in the pools in the original ecosystem following conversion to Grassland. A disturbance matrix defines the proportion of the carbon stock that remains in that pool and the proportion that is transferred to other pools. A small number of transfers are possible, and are outlined in the disturbance matrix in Table 2.1 in Chapter 2. Use of a disturbance matrix ensures consistency of the accounting of all carbon pools.

The immediate and abrupt carbon stock change in dead wood due to conversion of other lands to Grassland under Tiers 2 and 3 will be estimated using Equation 2.23. During the transition period, pools that gain or lose C often have a non-linear loss or accumulation curve that can be represented through successive transition matrices. For Tier 2, a linear change function can be assumed; a Tier 3 approach based upon these methods should use the true shapes of the curves. These curves should be applied to each cohort that is under transition during the reporting year to estimate the annual change in the dead wood and litter carbon pools.

For the calculation of changes in dead wood and litter carbon during the transition phase, two methods are suggested:

Gain-Loss Method (Equation 2.18 in Chapter 2): This method involves estimating the area of each type of land conversion and the average annual transfer into and out of dead wood and litter stocks. This requires an estimate of area under *Land Converted to Grassland* according to different climate or ecological zones or grassland types, disturbance regime, management regime, or other factors significantly affecting dead wood and litter carbon pools and the quantity of biomass transferred into dead wood and litter stocks as well as the quantity of biomass transferred out of the dead wood and litter stocks on per hectare basis according to different grassland types.

Stock-Difference Method (Equation 2.19 in Chapter 2): The Stock-Difference Method involves estimating the area of *Land Converted to Grassland* and the dead wood and litter stocks at two periods of time, t_1 and t_2. The annual dead wood and litter stock changes for the inventory year are obtained by dividing the stock changes by the period (years) between two measurements. This method is feasible for countries, which have periodic inventories. This method may not be well suited to regions with very variable climates and may produce spurious results unless annual inventories can be made.

Tier 3

For Tier 3, countries should develop their own methodologies and parameters for estimating changes in DOM. These methodologies may be derived from either of the methods specified above, or may be based on other approaches. The method used needs to be clearly documented. The Stock-Difference Method described above may be suitable for countries adopting Tier 3 methods. Tier 3 methods are used where countries have country-specific emission factors, and substantial national data. Country-defined methodology may be based on detailed inventories of permanent sample plots for their grasslands and/or models.

6.3.2.2 CHOICE OF EMISSION/REMOVAL FACTORS

Carbon fraction: The carbon fraction of dead wood and litter is variable and depends on the stage of decomposition. Wood is much less variable than litter and a value of 0.50 tonne C (tonne d.m.)$^{-1}$ can be used for the carbon fraction. Litter values in grasslands range from 0.30 to 0.50 tonne C (tonne d.m.)$^{-1}$. When country-specific or ecosystem-specific data are not available, countries should use a carbon fraction value of 0.40 tonnes C (tonne d.m.)$^{-1}$.

Tier 1

For Tier 1, it is assumed that the dead wood and litter carbon stocks in lands converted to grasslands are all lost during the conversion and that there is no accumulation of new DOM in the grassland after conversion. Countries experiencing significant conversions of other ecosystems to grasslands are encouraged to develop domestic data to quantify this impact and report it under Tier 2 or 3 methodologies.

Tier 2

It is *good practice* to use country-level data on dead wood and litter for different grassland categories, in combination with default values if country or regional values are not available for some conversion categories. Country-specific values for the transfer of carbon from live trees and grasses that are harvested to harvest residues and decomposition rates, in the case of the Gain-Loss Method, or the net change in DOM pools, in the case of the Stock-Difference Method, can be derived from domestic expansion factors, taking into account the grassland type, the rate of biomass utilization, harvesting practices and the amount of damaged vegetation during harvesting operations. Country-specific values for disturbance regimes should be derived from scientific studies.

Tier 3

National level disaggregated DOM carbon estimates should be determined as part of a national grasslands inventory, national level models, or from a dedicated greenhouse gas inventory programme, with periodic sampling according to the principles set out in Chapter 3, Annex 3A.3. Inventory data can be coupled with modelling studies to capture the dynamics of all grassland carbon pools.

Tier 3 methods provide estimates of greater certainty than lower tiers and feature a greater link between individual carbon pools. Some countries have developed disturbance matrices that provide a carbon reallocation pattern among different pools for each type of disturbance. Other important parameters in a modelled DOM carbon budget are decay rates, which may vary with the type of wood, climatic conditions, and site preparation procedures (e.g., controlled broadcast burning, or burning of piles).

6.3.2.3 CHOICE OF ACTIVITY DATA

All tiers require estimates of land areas converted to Grassland. The same area data should be used for biomass calculations, dead organic matter, and the soil carbon estimates. If necessary, area data used in the soils analysis can be aggregated to match the spatial scale required for lower order estimates of biomass; however, at higher tiers, stratification should take account of major soil types. Area data should be obtained using the methods described in Chapter 3. Cross-checks should be made to ensure complete and consistent representation of annually converted lands in order to avoid possible omissions or double counting. Data should be disaggregated according to the general climatic categories and grassland types. Tier 3 inventories will require more comprehensive information on the establishment of new grasslands, with refined soil classes, climates, and spatial and temporal resolution. All changes having occurred over the number of years selected as the transition period should be included with transitions older than the transition period (default 20 years) reported as a subdivision of *Grassland Remaining Grassland*. Higher tiers require greater detail but the minimum requirement for inventories to be consistent with the *IPCC Guidelines* is that the areas of forest conversion are identified separately. This is because forest will usually have higher carbon density before conversion. This implies that at least partial knowledge of the land-use change matrix, and therefore, where Approaches 1 and 2 from Chapter 3 are used to estimate land area are being used, supplementary surveys may be needed to identify the area of land being converted from Forest Land to Grassland. As pointed out in Chapter 3, where surveys are being set up, it will often be more accurate to seek to establish directly areas undergoing conversion, than to estimate these from the differences in total land areas under particular uses at different times.

Chapter 3 provides general guidance on approaches for obtaining and categorizing area by different land-use classes. For estimating emissions and removals from this source, countries need to obtain area estimates for conversions to grassland, disaggregated as required to correspond to the available emission factors and other parameters.

6.3.2.4 CALCULATION STEPS FOR TIERS 1 AND 2

For Tier 1, only the abrupt change needs to be calculated and this is done using Equation 2.23 where C_0 equals zero and T_{on} equals 1. The Tier 1 default assumes removal of all dead wood and litter during conversion and that there is no dead wood or litter that remains or accumulates in *Land Converted to Grassland*. Thus, for conversions older than 1 year but still in the transition period, the assumption is that there are no net changes in biomass C stocks.

Tier 1

Step 1: Determine the categories of land conversion to be used in this assessment and the representative areas. Tier 1 requires estimates of areas converted to Grassland from initial land uses (i.e., Forest Land, Cropland, Settlements, etc.) to final grassland type. When calculating for lands in the transition phase, only the total area of land converted during the previous 20 years is required as the Tier 1 assumption is that there is no accumulation of C stocks in the DOM during the first year. Note that all grasslands older than 20 years should be accounted for in *Grassland Remaining Grassland*. Thus, grassland areas that are 21 years old, must be transferred to this category.

Step 2: Determine the activity categories to be used in this assessment and the representative areas. The activity category consists of definitions of the type of conversion and, if applicable, the nature of management of the previous land cover and grassland management (e.g., 'conversion of logged tropical seasonal forest to cattle pasture using exotic grasses').

Step 3: For each activity category, determine the C stock per hectare in dead wood and litter (separately) prior to conversion. Default values, if they exist, can be found in the chapter that refers to the other land-use category.

Step 4: For each activity category, the C stock per hectare in dead wood and litter (separately) following one year of conversion to grassland is assumed to be 0.

Step 5: Determine the appropriate carbon fractions for dead wood and litter biomass. The default values are 0.50 tonne C (tonne d.m.)$^{-1}$ for dead wood and 0.40 tonne C (tonne d.m.)$^{-1}$ for litter.

Step 6: Estimate the net change of carbon stocks in dead wood and litter (separately) by subtracting the final stock from the initial stock and multiplying this difference by the representative area for the activity and by the carbon fraction of the biomass component.

Step 7: Sum the changes in carbon stocks in dead wood and litter to determine the net change in DOM C stocks for each activity category. Sub-totals for each type of conversion should be computed and a grand total should be computed and entered at the bottom of the last column of the table.

Tier 2

Step 1: Determine the categories of land conversion to be used in this assessment and the representative areas. When calculating for lands in the transition phase, representative areas for each category at different stages of conversion are required.

Step 2: Abrupt changes

- Determine the activity categories to be used in this assessment and the representative areas. The activity category consists of definitions of the type of conversion and, if applicable, the nature of management of the previous land cover and grassland management (e.g., 'conversion of logged tropical seasonal forest to cattle pasture using exotic grasses').
- For each activity category, determine the mass per hectare of dead wood and litter (separately) prior to conversion.
- For each activity category, determine the mass per hectare of dead wood and litter (separately) following one year of conversion to grassland.
- Determine the appropriate carbon fractions of dead wood and litter. The default values are 0.50 tonne C (tonne d.m.)$^{-1}$ for dead wood and 0.40 tonne C (tonne d.m.)$^{-1}$ for litter.
- Estimate the net change of C stock in dead wood and litter (separately) for each type of conversion by subtracting the final stocks from the initial stocks and multiplying this difference by the representative area for the activity and by the carbon fraction of the biomass component. A negative value indicates an increase of DOM.
- Sum the changes in carbon stocks in dead wood and litter to determine the net change in C stocks for each activity category. Sub-totals for each type of conversion should be computed and a grand total should be computed.

Step 3: Transitional changes

- Determine the categories and cohorts to be used in this assessment and the representative areas. The category consists of definitions of the type of conversion and, if applicable, the nature of management of the previous land cover and grassland management (e.g., 'conversion of logged tropical seasonal forest to cattle pasture using exotic grasses').
- Determine the annual change rate for dead wood and litter (separately) by activity type using either the Gain-Loss Method or the Stock-Difference Method (see below) for each cohort of lands that are currently in the transition phase between conversion and a new steady-state grassland system.
- Determine the dead wood and litter in the cohort during the previous year (usually taken from the previous inventory).
- Estimate the change in dead wood and litter for each cohort by adding the net change rate to the previous year's stocks.

Gain-Loss Method (Equation 2.18 in Chapter 2)

- Determine the average annual inputs of dead wood and litter (separately).
- Determine the average annual losses of dead wood and litter (separately).
- Determine the net change rate in dead wood and litter by subtracting the loss from the increment.

Stock-Difference Method (Equation 2.19 in Chapter 2)

- Determine the inventory time interval, the average stocks of dead wood and litter at the initial inventory, and the average dead wood and litter at the final inventory.
- Use these figures to estimate the net change in dead wood and litter by subtracting the initial stock from the final stock and dividing this difference by the number of years between inventories. A negative value indicates a loss in the stock.
- A Tier 2 approach requires country-specific or ecosystem-specific expansion factors and the best available local data should be used (and documented).

6.3.2.5 UNCERTAINTY ASSESSMENT

Uncertainty analyses for *Land Converted to Grassland* are fundamentally the same as *Grassland Remaining Grassland*. Two sources of uncertainty exist in C inventories: 1) uncertainties in land-use and management activity and environmental data; 2) uncertainties in carbon increase and loss, carbon stocks and expansion factor terms in the stock change/emission factors for Tier 2 approaches, model structure/parameter error for Tier 3 model-based approaches, or measurement error/sampling variability associated with Tier 3 measurement-based inventories. See the uncertainty section in *Grassland Remaining Grassland* for additional discussion (Section 6.2.2.5).

6.3.3 Soil carbon

Grassland management involving drainage will generate emissions from organic soil, regardless of the previous land use. However, the impact on mineral soils is less clear-cut for lands converted to Grassland. Literature on one of the dominant conversion types globally (from Forest Land to Grassland in the tropics) provides evidence for net gains as well as net losses in soil C, and it is known that the specific management of the grassland after conversion is critical (e.g., Veldkamp, 2001).

General information and guidance for estimating changes in soil C stocks are provided in Chapter 2, Section 2.3.3 (including equations), and this section needs to be read before proceeding with a consideration of specific guidelines dealing with grassland soil C stocks. The total change in soil C stocks for *Land Converted to Grassland* is estimated using Equation 2.24 for the change in soil organic C stocks for mineral soils and organic soils; and stock changes associated with soil inorganic C pools (if estimated at Tier 3). This section provides specific guidance for estimating soil organic C stock changes. There is a general discussion in Section 2.3.3 in Chapter 2 on soil inorganic C and no additional information is provided here.

To account for changes in soil C stocks associated with *Land Converted to Grassland*, countries need to have, at a minimum, estimates of the areas of *Land Converted to Grassland* during the inventory time period, stratified by climate region and soil type. If land-use and management data are limited, aggregate data, such as FAO statistics, can be used as a starting point, along with country expert knowledge of the approximate distribution of land-use types being converted and the management of those lands. If the previous land uses and conversions are unknown, SOC stocks changes can still be estimated using the methods provided in *Grassland Remaining Grassland*, but the land base area will likely be different for grasslands in the current year relative to the initial year in the inventory. It is critical, however, that the total land area accounted across all land-use sectors be equal over the inventory time period (e.g., if 3 Million ha of Forest Land and Cropland are converted to Grassland during the inventory time period, then Grassland will have an additional 3 Million ha in the last year of the inventory, while Cropland and Forest Land will have a corresponding loss of 3 Million ha in the last year). *Land Converted to Grassland* is stratified according to climate regions, management, and major soil types, which could either be based on default or country-specific classifications. This can be accomplished with overlays of suitable climate and soil maps, coupled with spatially-explicit data on the location of land conversions.

6.3.3.1 CHOICE OF METHOD

Inventories can be developed using a Tier 1, 2 or 3 approach, with each successive Tier requiring more details and resources than the previous one. It is possible that countries will use different tiers to prepare estimates for the separate sub-categories of soil C (i.e., soil organic C stocks changes in mineral soils and organic soils; and stock changes associated with soil inorganic C pools). Decision trees are provided for mineral soils (Figure 2.4) and organic soils (Figure 2.5) in Chapter 2 to assist inventory compilers with selection of the appropriate tier for their soil C inventory.

Mineral soils

Tier 1

Using Equation 2.25 (Chapter 2), the change in soil organic C stocks can be estimated for mineral soils accounting for the impact of land-use conversion to Grassland. The method is fundamentally the same as the one used for *Grassland Remaining Grassland*, except pre-conversion C stocks are dependent on stock change factors for another land use. Specifically, the initial (pre-conversion) soil organic C stock ($SOC_{(0-T)}$) and stock in the last year of inventory time period (SOC_0) are computed from the default reference soil organic C stocks (SOC_{REF}) stock change factors (F_{LU}, F_{MG}, F_I). Note that area of exposed bedrock in Forest Land or the previous land use are not included in the soil C stock calculation (assume a stock of 0). Annual rates of stock changes are estimated based on the difference in stocks (over time) for the first and last year in the inventory time period divided by the time dependence of the stock change factors (D, default is 20 years).

Tier 2

The Tier 2 method for mineral soils also uses Equation 2.25, but involves country-specific or region-specific reference C stocks and/or stock change factors and more disaggregated land-use activity and environmental data.

Tier 3

Tier 3 methods will involve more detailed and country-specific models and/or measurement-based approaches along with highly disaggregated land-use and management data. It is *good practice* that Tier 3 approaches, estimating soil C change from land-use conversions to Grassland, employ models, data sets and/or monitoring networks that are capable of representing transitions over time from other land uses, including Forest Land, Cropland, and possibly Settlements or other lands. If possible, it is also recommended for Tier 3 methods to be integrated with estimates of biomass removal and the post-clearance treatment of plant residues (including woody debris and litter), as variation in the removal and treatment of residues (e.g., burning, site preparation) will affect C inputs to soil organic matter formation and C losses through decomposition and combustion. It is important that models be evaluated with independent observations from country-specific or region-specific field locations that are representative of the interactions of climate, soil, and grassland management on post-conversion change in soil C stocks.

Organic soils

Tier 1 and Tier 2

Land Converted to Grassland on organic soils within the inventory time period is treated the same as *Grassland Remaining Grassland* on organic soils, i.e., they have a constant emission factor applied to them, based on climate regime, and C losses are computed using Equation 2.26 (Chapter 2). Additional guidance on the Tier 1 and 2 approaches are given in the *Grassland Remaining Grassland* section (Section 6.2.3.1).

Tier 3

Similar to mineral soils, a Tier 3 approach will involve more detailed and country-specific models and/or measurement-based approaches along with highly disaggregated land-use and management data (*see Mineral Soils* above for additional discussion).

6.3.3.2 CHOICE OF STOCK CHANGE AND EMISSION FACTORS

Mineral soils

Tier 1

For unmanaged land, as well as for managed Forest Land, Settlements and nominally managed Grassland with low disturbance regimes, soil C stocks are assumed equal to the reference values (i.e., land use, disturbance (forests only), management and input factors equal 1), while it will be necessary to apply the appropriate stock change factors to represent other systems such as improved and degraded grasslands, as well as all cropland systems. Default reference C stocks are given in Chapter 2, Table 2.3. See the *Choice of Stock Change and Emission Factors* in the appropriate land-use chapter for default stock change factors (Forest Land in Section 4.2.3.2, Cropland in 5.2.3.2, Grassland in 6.2.3.2, Settlements in 8.2.3.2, and Other land in 9.3.3.2).

Note that it is *good practice* to use the management factor (F_{LU}) for set-asides (Table 5.5) if dealing with cultivated annual Cropland converted into Grassland (i.e., until the land is re-classified as *Grassland Remaining Grassland*) because recently converted annual cropland systems will typically gain C at a rate similar to set-aside lands. Moreover, the Tier 1 set-aside factors were derived from empirical data to explicitly represent the expected gain during the first 20 years for lands removed from cultivation. If countries decide to assume a faster increase in C that raises levels to native conditions within 20 years, a justification should be provided in the documentation.

Tier 2

Estimation of country-specific stock change factors is probably the most important development for the Tier 2 approach. Differences in soil organic C stocks among land uses are computed relative to a reference condition, using land-use factor (F_{LU}). Input factor (F_I) and management factor (F_{MG}) are then used to further refine the C stocks of the new grassland system. Additional guidance on how to derive these stock change factors is given in *Grassland Remaining Grassland*, Section 6.2.3.2 as well as other general guidance in Section 2.3.3.1 (Chapter 2). See the appropriate section for specific information regarding the derivation of stock change factors for other land-use sectors (Forest Land in Section 4.2.3.2, Cropland in 5.2.3.2, Settlements in 8.2.3.2, and Other land in 9.3.3.2).

Reference C stocks can also be derived from country-specific data in a Tier 2 approach. However, reference values must be consistent across land-use sectors (i.e., Forest Land, Cropland, Grassland, Settlements, Other land), which requires coordination among the various teams conducting soil C inventories for AFOLU.

Tier 3

Constant stock change rate factors *per se* are less likely to be estimated in favor of variable rates that more accurately capture land-use and management effects. See Section 2.3.3.1 in Chapter 2 for further discussion.

Organic soils

Tier 1 and Tier 2

Land Converted to Grassland on organic soils within the inventory time period is treated the same as *Grassland Remaining Grassland* on organic soils. Tier 1 emission factors are given in Table 6.3, while Tier 2 emission factors are derived from country-specific or region-specific data.

Tier 3

Constant emission rate factors *per se* are less likely to be estimated in favor of variable rates that more accurately capture land-use and management effects. See Section 2.3.3 in Chapter 2 for further discussion.

6.3.3.3 CHOICE OF ACTIVITY DATA

Mineral soils

Tier 1 and Tier 2

For purposes of estimating soil carbon stock change, area estimates of *Land Converted to Grassland* should be stratified according to major climate regions and soil types. This can be based on overlays with suitable climate and soil maps and spatially-explicit data of the location of land conversions. A detailed description of the default climate and soil classification schemes is provided in Chapter 3. See corresponding sections dealing with each land-use category for sector-specific information regarding the representation of land-use/management activity data (Forest Land in Section 4.2.3.3, Cropland in 5.2.3.3, Grassland in 6.2.3.3, Settlements in 8.2.3.3, and Other land in 9.3.3.3).

An important issue in evaluating the impact of *Land Converted to Grassland* on soil organic C stocks is the type of land-use and management activity data. Activity data gathered using Approach 2 or 3 (see Chapter 3 for discussion about Approaches) provide the underlying basis for determining the previous land use for land categorized as *Land Converted to Grassland*. In contrast, aggregate data (Approach 1) only provide the total amount of area in each land use at the beginning and end of the inventory period (e.g., 1985 and 2005). Thus, unless supplementary information can be gathered to infer the pattern of land-use change (as suggested in Chapter 3) Approach 1 data are insufficient to determine specific transitions between land-use categories. Therefore, the previous land use before conversion to grasslands will be unknown. Fortunately, this is not problematic using a Tier 1 or 2 method because the calculation is not dynamic and assumes a step change from one equilibrium state to another. Therefore, with aggregated data (Approach 1), changes in soil organic C stocks may be computed separately for each land-use category and then combined to obtain the total stock change for all land uses combined. The soil C stock change estimate will be equivalent to results using Approach 2 (or 3) activity data (i.e., a full land-use change matrix), but evaluation of C stock trends will only be relevant after combining the stock estimates for all land uses (i.e., stocks will increase or decrease with the changes in land area within individual land uses, but this will offset by gains or losses in other land uses, and thus not an actual stock change in the soil pool for a country. Thus, with aggregate (Approach 1 data) it is important to achieve coordination among all land sector to ensure the total land base is remaining constant over time, given that some land area will be lost and gained within individual sectors during each inventory year due to land-use change.

Note that it will not be possible to determine the amount of cultivated annual croplands converted to grasslands with aggregated activity data (Approach 1). Therefore, grassland stock change factors will be applied, without consideration for the slower rate of C gain in recently converted annual croplands, which may lead to an over-estimation of C gain over a 20-year time period, particularly using the Tier 1 method (see Choice of Stock

Change and Emission Factors for additional discussion). This caveat should be acknowledged in the reporting documentation, and it is *good practice* for future inventories to gather additional information needed to estimate the area of grassland recently converted from croplands, particularly if soil C is a key source category.

Tier 3

For application of dynamic models and/or a direct measurement-based inventory in Tier 3, similar or more detailed data on the combinations of climate, soil, topographic and management data are needed, relative to Tier 1 or 2 methods, but the exact requirements will be dependent on the model or measurement design.

Organic soils

Tier 1 and Tier 2

Land Converted to Grassland on organic soils within the inventory time period is treated the same as *Grassland Remaining Grassland* on organic soils, and guidance on activity data is discussed in Section 6.2.3.3.

Tier 3

Similar to mineral soils, Tier 3 approaches will likely require more detailed data on the combinations of climate, soil, topographic and management data, relative to Tier 1 or 2 methods, but the exact requirements will be dependent on the model or measurement design.

6.3.3.4 CALCULATION STEPS FOR TIER 1

Mineral soils

The steps for estimating SOC_0 and $SOC_{(0-T)}$ and net soil C stock change of *Land Converted to Grassland* are as follows:

Step 1: Organize data into inventory time periods based on the years in which activity data were collected (e.g., 1990 and 1995, 1995 and 2000, etc.)

Step 2: Determine the land-use and management by mineral soil types and climate regions for land at the beginning of the inventory period, which can vary depending on the time step of the activity data (0-T; e.g., 5, 10 or 20 years ago).

Step 3: Select the native reference C stock value (SOC_{REF}), based on climate and soil type from Table 2.3, for each area of land being inventoried. The reference C stocks are the same for all land-use categories to ensure that erroneous changes in the C stocks are not computed due to differences in reference stock values among sectors.

Step 4: Select the land-use factor (F_{LU}), management factor (F_{MG}) and C input levels (F_I) representing the land-use and management system present before conversion to grassland. Values for F_{LU}, F_{MG} and F_I are given in the respective section for the land-use sector (Cropland in Chapter 5, Grassland in Chapter 6, Settlements in Chapter 8, and Other land in Chapter 9).

Step 5: Multiply these values by the reference soil C stock to estimate 'initial' soil organic C stock ($SOC_{(0-T)}$) for the inventory time period.

Step 6: Estimate SOC_0 by repeating Steps 1 to 4 using the same native reference C stock (SOC_{REF}), but with land-use, management and input factors that represent conditions (after conversion to grassland) in the last (year 0) inventory year.

Step 7: Estimate the average annual change in soil organic C stock for the area over the inventory time period ($\Delta C_{Mineral}$)

Step 8: Repeat Steps 1 to 6 if there are additional inventory time periods (e.g., 1995 to 2000, 2001 to 2005, etc.).

A numerical example is given below for afforestation of cropland soil.

Using Equation 2.25 (Chapter 2), default stock change factors and reference C stocks, a case example is given below for estimating changes in soil organic C stocks associated with *Land Converted to Grassland*.

Example: For tropical moist, volcanic soil that has been under long-term annual Cropland, with intensive tillage and where crop residues are removed from the field, carbon stocks at the beginning of the inventory time period (1990 in this example), $SOC_{(0-T)}$ are 70 tonnes C ha^{-1} ● 0.48 ● 1 ● 0.92 = 30.9 tonnes C ha^{-1}. Following conversion to improved (e.g., fertilised) pasture, carbon stocks in the last year of inventory (2010 in this example) (SOC_0) are 70 tonnes C ha^{-1} ● 0.82 ● 1.17 ● 1 = 67.2 tonnes C ha^{-1}. Thus the average annual change in soil C stock for the area over the inventory time period is calculated as (67.2 tonnes C ha^{-1} – 36.9 tonnes C ha^{-1}) / 20 yrs =1.5 tonnes C ha^{-1} yr^{-1}. Note that the set-aside factor (0.82) from croplands was used for the F_{LU} because grasslands do not gain the full complement of the native C stock in 20 years. After the first 20 years, a factor of 1 would be used for F_{LU} in the Tier 1 approach.

Organic soils

Calculation steps are the same as described in Section 6.2.3.4 above.

6.3.3.5 UNCERTAINTY ASSESSMENT

Uncertainty analyses for *Land Converted to Grassland* are fundamentally the same as *Grassland Remaining Grassland*. Three broad sources of uncertainty exists: 1) uncertainties in land-use and management activity and environmental data; 2) uncertainties in reference soil C stocks if using a Tier 1 or 2 approach (mineral soils only); and 3) uncertainties in the stock change/emission factors for Tier 1 or 2 approaches, model structure/parameter error for Tier 3 model-based approaches, or measurement error/sampling variability associated with a Tier 3 measurement-based inventories. See the uncertainty section in *Grassland Remaining Grassland* for additional discussion (Section 6.2.3.5).

6.3.4 Non-CO_2 greenhouse gas emissions from biomass burning

Greenhouse gas emissions from *Land Converted to Grassland* occur from combustion of biomass and dead organic matter (DOM) in *Land Converted to Grassland*. Emissions are accounted for in the new land category. The most significant greenhouse gas emissions in this section arise from conversion of Forest Land to Grassland, but important emissions may also occur as a result of the conversion of Cropland to Grassland. It is very unlikely that Grassland originates from conversion of the other land-use categories (Settlements, Wetlands, or Other land).

In the tropics, it is common practice to burn repeatedly until most (or all) of the forest residues and DOM is cleared, and pasture can be established. In some places, up to three or four fires are necessary. Part of the above-ground forest biomass removed during the process of conversion of Forest Land to Grassland may be transferred to harvested wood products, and an amount may be removed from the site to be used as fuel wood (hence, burnt off-site). Whatever remains is normally burnt on-site.

Greenhouse gas emissions from biomass burning in unmanaged Forest Land, if followed by a land-use conversion, needs to be reported, since the converted land is considered to be managed land.

The conversion of Cropland to Grassland does not normally result in biomass burning. However, whenever it is practiced, countries should report the corresponding greenhouse gas emissions, on an annual basis.

The approach to be used to estimate non-CO_2emissions from biomass burning in *Land Converted to Grassland* is essentially the same as that presented for *Grassland Remaining Grassland*.

6.3.4.1 CHOICE OF METHOD

The decision tree in Figure 2.6 in Chapter 2 provides guidance on the choice of the Tier level to be applied by countries when reporting greenhouse gas emissions from *Land Converted to Grassland.*

The choice of method is directly related to the availability of national data on the area of converted land burnt, the mass of fuel available, and combustion and emission factors. When using higher tiers, country-specific data on the mass of available fuel is used to take account of the amount of biomass transferred to harvested wood product (if applicable), removed for fuel use and burnt off-site.

Countries should report using a Tier 2 or Tier 3 method whenever greenhouse gas emissions from biomass burning in *Land Converted to Grassland* is a key category.

6.3.4.2 CHOICE OF EMISSION FACTORS

Tier 1

The mass of fuel available for combustion (quantity M_B in Equation 2.27) is critical for estimating greenhouse gas emissions. Default data to support estimation of emissions under a Tier 1 approach are provided in Tables 2.4 to 2.6 in Chapter 2. Countries need to judge how their different vegetation types map onto the broad vegetation categories described in the default tables. For Tier 1, it should be assumed that all above-ground biomass and DOM in the previous land-use category is lost immediately after conversion. Default values for biomass prior to conversion can be found in the chapters relating to the respective land uses (e.g., default factors for Forest Land are to be found in the chapter dealing with biomass in Forest Land).

Tier 2

In a Tier 2 method, country-specific estimates of fuel combustion should be used. Data should be disaggregated according to forest types, in the case of *Forest Land Converted to Grassland*. Combustion and emission factors that better reflect the national conditions (climate zone, biome, burning conditions) should be developed and uncertainty ranges provided. In addition, unlike Tier 1 where it is assumed that all the carbon in above-ground biomass and DOM is lost immediately after conversion, in a Tier 2 method the transfers of biomass to harvested wood products and fuelwood (burnt off-site) should be estimated to provide a more reliable estimate of the mass of fuel available.

Tier 3

Under a Tier 3, all the parameters should be country defined.

6.3.4.3 CHOICE OF ACTIVITY DATA

The activity data needed to estimate greenhouse gas emissions from biomass burning refers to the area affected by this activity. Countries shall stratify the area converted to Grassland by Forest Land- and by Cropland-converted, since the amount of fuel available for burning may vary markedly from one category of land use to another.

Tier 1

Countries applying a Tier 1 approach should estimate the areas converted to Grassland from initial land uses (Forest Land, Cropland, etc.). The conversion should be estimated on a yearly basis. The estimates can be derived from several approaches: (1) applying a rate of conversion to Grassland to the total annual area converted (the rate can be estimated on the basis of historical knowledge, judgement of country experts, and/or from samples of converted areas and assessment of the final land use); or (2) using data from international sources, such as FAO, to estimate the area of Forest Land and Cropland annually converted, and using expert judgement to estimate the portion of this area converted to Grassland.

Tier 2

Countries should, wherever possible, use actual area estimates for all possible conversions to grassland. Multi-temporal remotely sensed data of adequate resolution should provide better estimates of land-use conversion than the approaches introduced in Tier 1. The analysis may be based on full coverage of the territory or on representative samples selected, from where estimates of the area converted to grassland in the entire territory can be derived.

Tier 3

The activity data in Tier 3 should be based on the Approach 3 method presented in Chapter 3, where the total annual area converted to Grassland (from Forest Land, Cropland, or other land-use categories) is estimated. The data should be disaggregated according to the type of biome, climate, political boundaries, or a combination of these parameters.

6.3.4.4 UNCERTAINTY ASSESSMENT

Tier 1

The sources of uncertainty in this method arises from many sources: (i) use of global or national average rates of conversion and coarse estimates of land areas converted to grassland; (ii) estimate of the area converted that is burnt as part of a management practice (disposal of the biomass in the initial land use to establish the agriculture land); (iii) mass of available fuel; and (iv) combustion and emission factors. Uncertainties associated with emission and combustion factors are provided, and those related to items (i) and (ii) can vary significantly depending on the method used in their estimation. As a result of these uncertainties, it is unlikely that the estimate of area burnt will be known to better than 20% and the emissions per unit area to within a factor of 2 using Tier 1 methods.

Tier 2
The use of area estimates produced from more reliable sources (remotely sensed data, sample approach) will improve their accuracy relative to Tier 1 and Approach 1 (of Chapter 3). These sources will also provide better estimates of the areas that are converted and burnt. Disregarding the biomass transferred to harvested wood product or removed from the site as fuelwood, and the biomass left on-site to decay, will also eliminate a bias (overestimation) in the estimates. Estimates of emission or combustion factors at national level, if accompanied by error ranges (in the form of standard deviation), will allow uncertainty associated with *Land Converted to Cropland* to be assessed.

Tier 3
The uncertainty associated with activity data in Tier 3 is likely to be smaller than that in Tier 1 or 2, and is dependent on the remote sensing and field surveys, modelling approach used, and the data inputs.

6.4 COMPLETENESS, TIME SERIES, QA/QC, AND REPORTING

6.4.1 Completeness

Tier 1
A complete Grassland inventory for Tier 1 has three elements: 1) carbon stock changes and non-CO_2 (CH_4, CO, N_2O, NO_x) emissions from biomass burning have been estimated for all *Land Converted to Grassland* and *Grassland Remaining Grassland* during the inventory time period; 2) inventory analysis addressed the impact of all management practices described in the Tier 1 methods; and 3) the analysis accounted for climatic and soil variation that affects emissions and removals (as described for Tier 1).

The latter two elements require assignment of management systems to grassland areas and stratification by climate regions and soil types. It is *good practice* for countries to use the same area classifications for biomass and soil pools in addition to biomass burning (to the extent that classifications are needed for these source categories). This will ensure consistency and transparency, allow for efficient use of land surveys and other data collection tools, and enable the explicit linking between changes in carbon stocks in biomass and soil pools, as well as non-CO_2 emissions from biomass burning.

For biomass and soil C stock estimations, a Grassland inventory should address the impact of land-use change (*Land Converted to Grassland*) and management. However, in some cases, activity data or expert knowledge may not be sufficient to estimate the effects of management practices, such as extent and type of silvopastoral management, fertilizer management, irrigation, grazing intensity, etc. In those cases, countries may proceed with an inventory addressing land use alone, but the results will be incomplete and omission of management practices must be clearly identified in the reporting documentation for purposes of transparency. If there are omissions, it is *good practice* to collect the additional activity data on management for future inventories, particularly if biomass or soil C is a key source category.

C stock changes may not be computed for some grassland areas if greenhouse gas emissions and removals are believed to be insignificant or constant through time, such as non-woody grasslands where there are no management or land-use changes. In this case, it is *good practice* for countries to document and explain the reason for omissions.

For biomass burning, non-CO_2 greenhouse gases should be reported for all controlled burns and wildfires on managed grasslands. This includes conversion of Forest Land to Grassland, where the amount of fuel available for burning is usually more significant than in the other land-use categories; emissions from burning of DOM and cleared tree biomass should be included in these estimates. Savannah burning also constitutes a large source of non-CO_2 emissions from biomass burning. Biomass burning should be reported where wildfire on unmanaged land is followed by transition to managed land during the inventory reporting period.

Estimation of the area actually burnt is critical to the reliable calculation of non-CO_2 greenhouse gas emissions. Remotely-sensed estimates of the area burnt need to be rigorously tested against ground data to ensure that areas burnt are accurately estimated. The use of regionally average statistics is likely to be highly unreliable for estimating the area burnt in a specific country.

In grasslands where fire management is changing the balance between grass and woody vegetation, the emissions of CO_2 in fire may not be balanced by the re-fixation of an equivalent amount of C into biomass in the short-term. In such situations, net release of CO_2 caused by burning should also be reported.

Tier 2

A complete Tier 2 inventory has similar elements as Tier 1, but incorporates country-specific data to estimate C stock change factors, reference soil C stocks, biomass density estimates (fuel load), and combustion and emission factors for biomass burning; to develop climate descriptions and soil categories; and to improve management system classifications. Moreover, it is *good practice* for a Tier 2 inventory to incorporate country-specific data for each component. Inventories are still considered complete, however, if they combine country-specific data with Tier 1 defaults.

Tier 3

In addition to Tiers 1 and 2 considerations, completeness of Tier 3 inventories will depend on the components of the country-specific evaluation system. In practice, Tier 3 inventories are likely to more fully account for emissions and removals for grasslands using more finely resolved data on climate, soils, biomass burning and management systems. It is *good practice* for inventory compilers to describe and document the elements of the country-specific system, demonstrating the completeness of the approach and data sources. If gaps are identified, it is *good practice* to gather additional data and further develop the country-specific system.

6.4.2 Developing a consistent times series

Tier 1

Consistent time series are essential for evaluating trends in emissions and removals. In order to maintain consistency, compilers should apply the same classifications and factors over the entire inventory time period, including climate, soil types, management system classifications, C stock change factors, reference soil C stocks, biomass density estimates (fuel load), combustion factors, and non-CO_2 emission factors. Defaults are provided for all of these components, so consistency should not be an issue. In addition, the land base should remain consistent through time, with the exception of *Land Converted to Grassland* or grassland converted to other land uses.

Countries should use consistent sources of activity data on land use, management and biomass burning, over the entire reporting time period where possible. Sampling approaches, if used, should be maintained for the duration of the inventory time period to ensure a consistent approach. If sub-categories are created, countries should keep transparent records of how they are defined and apply them consistently throughout the inventory.

In some cases, sources of activity data, definitions or methods may change over time with availability of new information. Inventory compilers should determine the influence of changing data or methods on the trends; and if deemed significant, emissions and removals should be re-calculated for the time series using methods provided in Chapter 5 of Volume 1.

For C stock changes, one key element in producing a consistent time series is to ensure consistency between carbon stocks for *Land Converted to Grassland* that were estimated in previous reporting periods and the state of those stocks reported for those lands that are remaining grasslands in the current reporting period. For example, if 10 tonnes of the above-ground live biomass was transferred to the dead organic matter pool from *Forest Land Converted to Grassland* in the previous reporting period, reporting in the current period must assume that the starting C stocks in the dead organic matter pool was 10 tonnes for those lands.

Tier 2

In addition to the issues discussed under Tier 1, there are additional considerations associated with introduction of country-specific information. Specifically, it is *good practice* to apply new factor values or classifications derived from country-specific information across the entire inventory and re-calculate the time series. Otherwise, positive or negative trends in C stocks or biomass burning emissions may be partly due to changes associated with inventory methods at some point in the time series, and not representative of actual trends.

It is possible that new country-specific information may not be available for the entire time series. In those cases, it is *good practice* to demonstrate the effect of changes in activity levels versus updated country-specific data or methods; guidance on recalculation for these circumstances is presented in Chapter 5 of Volume 1.

Tier 3

Similar to Tiers 1 and 2, it is *good practice* to apply the country-specific estimation system throughout the entire time series; inventory agencies should use the same measurement protocols (sampling strategy, method, etc.) and/or model throughout the inventory time period.

6.4.3 Quality Assurance and Quality Control

Tier 1

It is *good practice* to implement Quality Assurance/Quality Controls with internal and external review of grassland inventory data. Internal review should be conducted by the agency in charge of the inventory, while external review is conducted by other agencies, experts or groups who are not directly involved with the compilation.

Internal review should focus on the inventory implementation process to ensure that: 1) activity data have been stratified appropriately by climate regions and soil types; 2) management classifications/descriptions have been applied appropriately; 3) activity data have been properly transcribed into the worksheets or inventory computation software; and 4) C stock change factors, soil reference C stocks, biomass densities (fuel load), and biomass burning combustion and emission factors have been assigned appropriately. Quality Assurance/Quality Control measures may involve visual inspection as well as built-in program functions to check data entry and results. Summary statistics can also be helpful, such as summing areas by strata within worksheets to determine if they are consistent with land-use statistics. Total areas should remain constant over the inventory period, and areas by strata should only vary by land-use or management classification (climate and soil areas should remain constant).

External reviews need to consider the validity of the inventory approach, thoroughness of inventory documentation, methods explanation and overall transparency. It is important to evaluate if the total area of managed grassland is realistic, taking into account the total grassland area of the territory. Cross-checking area estimates across land-use categories (i.e., Forest Land, Cropland, Grassland, etc.) will also be necessary. Ultimately, the sum of the entire land base for a country, which includes each sector, must be equal across every year in the inventory time period.

For biomass burning, specific attention should be given to country-specific estimates of annual area burnt. When estimating area burnt from global datasets, it is important to validate the information using field data or high resolution remotely-sensed data.

Tier 2

In addition to the Quality Assurance/Quality Controls measures under Tier 1, the inventory agency should review the country-specific climate regions, soil types, management system classifications, C stock change factors, reference soil C stocks, biomass densities (fuel load), combustion factors and/or non-CO_2 emission factors for biomass burning. If using factors based on direct measurements, the inventory agency and external reviewers should review the measurements to ensure that they are representative of the actual range of environmental and management conditions, and were developed according to recognized standards (IAEA, 1992). If accessible, it is *good practice* to compare the country-specific factors with Tier 2 stock change, combustion and emission factors used by other countries with comparable circumstances, in addition to the IPCC defaults.

Given the complexity of emission and removal trends, specialists in the field should be involved in the external review to check country-specific factors and/or classifications.

Tier 3

Country-specific inventory systems will likely need additional Quality Assurance/Quality Control measures beyond those listed for Tiers 1 and 2, but this will depend on the systems that are developed. It is *good practice* to develop a Quality Assurance/Quality Control protocol that is specific to the country's advanced inventory system, archive the reports, and include summary results in reporting documentation.

6.4.4 Reporting and Documentation

Tier 1

In general, it is *good practice* to document and archive all information required to produce national inventory estimates. For Tier 1, inventory compilers should document activity data trends and uncertainties in grasslands. Key activities include land-use change, biomass burning, use of silvopastoral practices, grazing intensity, use of mineral fertilizers or organic amendments, irrigation practices, liming, inter-seeding with legumes or planting more productive species, and biomass burning (wildfires and controlled burns).

It is *good practice* to archive actual databases, such as census data, burning records and pastoral statistics, and procedures used to process the data (e.g., statistical programs); definitions used to categorize or aggregate activity data; and procedures used to stratify activity data by climate and soil types. The worksheets or inventory software should be archived with input/output files that were generated to produce the results.

In cases where activity data are not available directly from databases or multiple data sets were combined, the information, assumptions and procedures that were used to derive the activity data should be described. This documentation should include the frequency of data collection and estimation, and uncertainty. Use of expert knowledge should be documented and correspondences archived.

It is *good practice* to document and explain trends in biomass and soil C stocks, as well as biomass burning emissions in terms of the land-use and management activity. Changes in biomass stocks should be linked directly to land use, to changes in silvipastoral practices or woody plant encroachment; while trends in soil C stocks may be due to land use or shifts in key management activities as described above. Biomass burning emissions will depend on the extent and frequency of controlled burns and wildfires. Significant fluctuations in emissions between years should be explained.

Countries need to include documentation on completeness of their inventory, issues related to time series consistency or lack thereof, and a summary of Quality Assurance/Quality Control measures and results.

Tier 2

In addition to the Tier 1 considerations, inventory compilers should document the underlying basis for country-specific C stock change factors, reference soil C stocks, biomass density estimates (fuel load), combustion and emission factors for biomass burning, management system classifications, climate regions and/or soil types. Furthermore, it is *good practice* to archive metadata and data sources for information used to estimate country-specific values.

Reporting documentation should include the new factors (i.e., means and uncertainties), and it is *good practice* to include a discussion in the inventory report about differences between country-specific factors and Tier 1 defaults as well as Tier 2 factors from regions with similar circumstances as the reporting country. If different emission factors, parameters and methods are used for different years, the reasons for these changes should be explained and documented. In addition, inventory agencies should describe country-specific classifications for management, climate and/or soil types, and it is recommended that improvements to the inventory estimates based on the new classifications be documented. For example, grassland condition may be subdivided into additional categories beyond the Tier 1 classes (i.e., nominal, improved, degraded and severely degraded), but further subdivisions will only improve inventory estimates if the stock change or emission factors differ significantly among the new categories.

When discussing trends in emissions and removals, a distinction should be made between changes in activity levels and changes in methods from year to year, and the reasons for these changes need to be documented.

Tier 3

Tier 3 inventory needs similar documentation about activity data and emission/removal trends as lower tier approaches, but additional documentation should be included to explain the underlying basis and framework of the country-specific estimation system. With measurement-based inventories, it is *good practice* to document the sampling design, laboratory procedures and data analysis techniques. Measurement data should be archived, along with results from data analyses. For Tier 3 approaches using models, it is *good practice* to document the model versions and provide model descriptions, as well as permanently archive copies of all model input files, source code and executable programs.

Annex 6A.1 Estimation of default stock change factors for mineral soil C emissions/removals for Grassland

Default soil C stock change factors are provided in Table 6.2 that were computed from a global dataset of experimental studies for three general types of grassland condition: degraded, nominally managed, and improved grassland. An additional input factor was included for application to improved grassland. The management improvements considered here were limited to fertilization (organic or inorganic), sowing legumes or more grass species, and irrigation. Overgrazed grassland and poorly managed (i.e., none of the management improvements were applied) tropical pastures were classified as degraded grassland. Native or introduced grasslands that were unimproved were grouped into the nominal grassland classification. Grasslands with any single type of management improvement were classified as improved grassland with medium C input rates. For improved grassland in which multiple management improvements were implemented, C input rates were considered high.

Experimental data (citations provided in reference list) were analyzed in linear mixed-effects models, accounting for both fixed and random effects. Fixed effects included depth, number of years since the management change, and the type of management change (e.g., reduced tillage vs. no-till). For depth, we did not aggregate data but included C stocks measured for each depth increment (e.g., 0-5 cm, 5-10 cm, and 10-30 cm) as a separate point in the dataset. Similarly, we did not aggregate data collected at different points in time from the same study. Consequently, random effects were used to account for the dependence in times series data and among data points representing different depths from the same study. If significant, a country-level random effect was used to assess an additional uncertainty associated with applying a global default value to a specific country (included in default uncertainty). Factors were estimated for the effect of the management practice at 20 years for the top 30 cm of the soil. Variance was calculated for each of the factor values, and can be used with simple error propagation methods to construct probability distribution functions with a normal density.

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