CHAPTER 5

LAND-USE CHANGE & FORESTRY

5. LAND-USE CHANGE & FORESTRY

5.1 Overview

This chapter summarises methods for calculating greenhouse gas (GHG) emissions from human activities which:

1. change the way land is used (e.g., clearing of forests for agricultural use, including open burning of cleared biomass), or
2. affect the amount of biomass in existing biomass stocks (e.g., forests, village trees, woody savannas, etc.).

The biosphere is a strong determinant of the chemical composition of the atmosphere. This has been true since the existence of the biosphere, and hence well before the presence of humans. A rich variety of carbon, nitrogen, and sulphur gases are emitted and absorbed by the biosphere. There is, however, strong evidence that the expanding human use and alteration of the biosphere for food, fuel and fibre is contributing to increasing atmospheric concentrations of GHGs. The dominant gas of concern in this source category is carbon dioxide (CO_2), and much of the methodology discussion in this chapter is specific to CO_2. Other important direct GHGs, including methane (CH_4) and nitrous oxide (N_2O), and indirect GHGs,[1] including carbon monoxide (CO), oxides of nitrogen (NO_x, i.e., NO and NO_2), and non-methane volatile organic compounds (NMVOCs) are also produced from land-use change and forest management activities, particularly where burning is involved. Non-methane volatile organic compounds are emitted in significant quantities from biomass burning. These emissions could be estimated using the same approach provided for other non-CO_2 gases. However, the detailed methods and default information have not yet been developed and are not included in this version of the *Guidelines.* This is an area to be considered in future improvements to the *Guidelines*.

Estimates of CO_2 emissions due to land-use change vary considerably because humans interact with the land in a myriad of ways. Estimates vary due to uncertainties in annual forest clearing rates, the fate of the land that is cleared, the amounts of biomass (and hence carbon) contained in different ecosystems, the modes by which CO_2 is released (e.g., burning or decay) and the carbon released when soils are disturbed. The 1995 IPCC Scientific Assessment (IPCC, 1996) estimated the average annual flux due to tropical deforestation for the decade 1980-1989 to be 1.6±1.0 Pg C as CO_2 (CO_2-C). Carbon sequestration by tropical tree plantations was not explicitly included in these estimates but is thought to be relatively small: in 1980 these plantations were estimated to absorb only 0.03-0.11 Pg CO_2-C (Brown et al. 1986). Recent analyses have suggested that growth of existing forests in temperate and boreal regions may be a significant carbon sink, potentially as much as 0.7 Pg C annually. Analysts have suggested a number of complementary factors which could be causing these sinks, including regrowth of historically cleared forests, CO_2 fertilisation, and nitrogen fertilisation due to atmospheric deposition (e.g., IPCC, 1995; Kokorin and Nazarov, 1995a; Tans et al., 1990; Kauppi et al., 1992; and Dixon et al., 1994). Based upon the latest estimates of CO_2 sources, sinks and

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[1] "Indirect" greenhouse gases here refers to gases which, although not important GHGs in their own right, can influence the concentration of some GHGs, tropospheric ozone in particular.

atmospheric storage, the IPCC estimates a remaining terrestrial sink of 0.9 ± 0.5 Pg C/year to 1.4 ± 1.5 Pg C/year (Schimel et al., 1995; and Brown et al., 1996). This apparent imbalance in the carbon budget, which was previously referred to as a "missing sink," is believed to be due to CO_2 fertilisation, N fertilisation, climate change (e.g., temperature increase), more extensive regrowth or tree planting programmes in the tropics, and possibly other factors.[2] The precise mix and relative contribution of these processes to the remaining terrestrial sink is still a subject of research and debate; and this terrestrial sink will not necessarily remain the same size or even the same sign under conditions of climate change.

Emissions of non-CO_2 trace gases (CH_4, CO, N_2O, and NO_x) due to biomass burning are generally produced immediately and are considered as net emissions. NMVOC are not treated here. Gross emissions of CO_2 due to reductions in forest area may or may not be balanced by uptake of CO_2 and may occur over immediate or delayed time frames.[3] Similarly, increases in forest area or in the biomass density of existing forests will result in CO_2 uptake at varying rates and over delayed time frames. Only about 50-60 per cent of the carbon estimated to have been released in 1980 from forest conversion was a result of the conversion and subsequent biomass burning in that year. The remainder was a release due to oxidation (i.e., inherited emissions) of biomass harvested in previous years (Houghton, 1991). Other land-use changes, such as land flooding, result in continuous GHG emissions possibly for as long as the land remains in its altered state.

5.1.1 Background - Biomass Stocks and Carbon Fluxes

Vegetation withdraws CO_2 from the atmosphere through the process of photosynthesis. Carbon dioxide is returned to the atmosphere by the respiration of the vegetation (autotrophic) and the decay of organic matter in soils and litter (heterotrophic respiration). The gross fluxes are large; roughly a seventh of the total atmospheric CO_2 passes into vegetation each year (in the order of 100 Pg CO_2-C per year), and in the absence of significant human disturbance, this large flux of CO_2 from the atmosphere to the terrestrial biosphere is thought to be balanced by the return respiration fluxes.

Land-use change and the use of forests directly alters these fluxes, and their balance, and consequently the amount of carbon stored in living vegetation, litter, and soils. For example, forest clearing for agriculture by burning greatly increases the return flux of CO_2 and decreases for a while the photosynthetic flux. Burning is, after all, simply a rapid form of oxidation or decay. Subsequently, the CO_2 flux of the cleared area will reach a new steady state: the photosynthesis associated with agricultural production being balanced by the respiration of vegetation, the decay of on-site organic material, and the

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[2] For recent analyses of the effects of changing CO_2 concentrations and climate variables on terrestrial sinks, see, Cramer and Solomon, 1993; Smith and Shugart, 1993; Kokorin and Nazarov, 1995b; Mellilo et al., 1993; and Alcamo et al., 1994. For analysis of the possible effects of N fertilisation from atmospheric deposition, see Gifford, 1994, Rastetter et al., 1992 and Comins and McMurtrie, 1993. It is also possible that atmospheric deposition of air pollutants can damage forests, as discussed in Denniston, 1993, which would reduce the amount of carbon stored in forests. However, it is uncertain whether or not this is a significant effect at global or national scales.

[3] Delayed releases of non-CO_2 trace gases are an important research issue. These releases may be important , but are currently too uncertain to be included in calculations.

oxidation of the agricultural product when it is consumed, perhaps off site. However, the total amount of carbon stored in the terrestrial system will have been reduced because a forest contains more carbon than does a field of annual crops or pasture, and the removed carbon (i.e., the forest) was not put into long term storage pools. Consequently there is a net flux of CO_2 from the land (vegetation and soil) to the atmosphere. A natural first order assumption is that the net reduction in carbon stocks is equal to the *net* CO_2 flux from the cleared area.

Forest harvest does not necessarily result in a net flux to the atmosphere. It can produce a complex pattern of net fluxes that change direction over time. For instance, suppose that a forest is harvested, producing wood products and leaving some slash and debris. Initially, the CO_2 flux from the wood products that decay rapidly, plus the increased respiration flux of CO_2 associated with the oxidation of the slash, could exceed the flux from the atmosphere due to photosynthesis and the resulting carbon storage in the regrowing forest. Consequently, there is a net flux of CO_2 from the forest, forest floor and soil to the atmosphere. This would also be reflected in the carbon accounting: the amount of carbon in the original living vegetation, the litter, and the soils would be greater than the amount of carbon in the young regrowing forests, litter, soils and forest products pool. However, if some of the forest products are very long-lived, and if the forest regrows to its original level, then the integrated net flux must have been from the atmosphere to the terrestrial biosphere since the resulting total terrestrial carbon stocks (vegetation, litter, soils, and wood products) would be greater than before the forest harvest.

This characteristic, that changes in landuse today affect both present and future CO_2 fluxes associated with that specific landuse, is one feature of CO_2 emissions analysis that distinguishes landuse from fossil fuel consumption. Consequently, when one considers the issue of CO_2 flux associated with landuse today or in any base year, one must consider past land-use activities and their effects upon current fluxes of CO_2. Box 1 provides some illustrative numerical examples of carbon fluxes associated with land-use change over a series of years.

5.1.2 The Proposed Approach

The fundamental basis for the methodology rests upon two linked themes: i) the flux of CO_2 to or from the atmosphere is assumed to be equal to changes in carbon stocks in existing biomass and soils, and ii) changes in carbon stocks can be estimated by first establishing rates of change in land use and the practice used to bring about the change (e.g., burning, clear-cutting, selective cut, etc.). Simple assumptions are then applied about their impact on carbon stocks and the biological response to a given landuse. As noted above, there are large uncertainties in all current methods for estimating fluxes of CO_2 from forestry and land-use change. *Direct* measurements of changes in carbon stocks are extremely difficult since one must confront the difficulty of determining small differences in large numbers as well as the inherent heterogeneity of terrestrial systems. A more practical first order approach in many countries is to make simple assumptions about the effects of land-use change on carbon stocks and the subsequent biological response to the land-use change, and to use these assumptions to calculate carbon stock changes and hence the CO_2 flux. This observation is at the heart of the proposed approach.

Rates of change of land use are difficult to establish, although there are a variety of data on which to base land-use change estimates. The Technical Appendix to this chapter reviews sources of data on rates of tropical deforestation, the land-use change which currently makes the largest contribution to CO_2 flux. Finally, the assumptions regarding the response of vegetation and soils to different land uses and land-use change can be expressed in simple terms which can be altered for specific conditions in different countries or regions.

The methodology is designed to be comprehensive, i.e., to cover all of the main land-use change and forestry activities; and to be feasible to implement by all participating countries. It can be implemented at several different levels of complexity and geographic scales, depending on the needs and capabilities of national experts in different countries.

1. A simple, first order approach can be based on very aggregate default data and assumptions, derived from the technical literature, and provided throughout the text. Methods are presented in the context of national level aggregate calculations for a limited set of subcategories which can be supported by these default values. It is important to note that many of the default data provided in the land-use change and forestry chapter are highly uncertain. Many of the important values needed for the calculations are not well established or are highly variable from region to region, or within very small subregions within a given country. In many cases in which values are particularly uncertain (e.g., the fraction of cleared biomass burned on site), these weaknesses are discussed in the text. Where global average values are highly uncertain, they can be used for first order calculations or for comparison, but probably do not provide a basis for a credible final inventory. National experts in forestry and related fields should be consulted to determine the most appropriate values for use in national inventories.
2. A more accurate level can be achieved simply by substituting country-specific values for general defaults provided in the methodology. If appropriate and possible, locally available data can be used to carry out calculations at a more detailed geographic scale and/or subcategory level. Alternative levels of detail are discussed more fully in the next section. National experts are strongly encouraged to substitute more appropriate (i.e., country- or region-specific) and more detailed input data wherever they are available.
3. Forest inventory data can also be used with this methodology. It is important to note that some countries with highly developed forestry industries do in fact keep track of existing commercial forests through periodic detailed inventories. In these countries it is generally the ongoing management of existing forests rather than land-use changes which has the greatest impact on the exchange of GHG between the land and atmosphere. National experts who have very detailed, inventory based data, can re-format and analyse these data to derive equivalent average responses (e.g., annual biomass growth rates by ecosystem type) which can be aggregated up to categories matching the simple approach outlined here. This procedure is discussed in more detail in the *changes in forest and other woody biomass stocks* section below.

The intent is to provide a calculation and reporting framework which can accommodate users with vastly different levels of available data, yet allow them all to present the results on a comparable basis.

Box 1
ILLUSTRATIVE CALCULATIONS OF CARBON FLUXES

Consider the example of forest clearing for agriculture which results in a net flux to the atmosphere. For descriptive purposes we consider the following assumptions:

1) a 20 year time frame (e.g., 1970 to 1990);
2) one hectare is cleared each year (so that over the 20 year period, 20 hectares are cleared);
3) cleared land is used as pasture, which is established the year following the clearing;
4) after three years, cleared land is abandoned and it regrows linearly at 10tC/ha per year to 75 per cent its original biomass only in 15 years;
5) all of the vegetation is completely burned at the time of clearing and there are essentially no changes in soil or litter pools; and
6) there are 200 tonnes of carbon per hectare in the forest biomass and 5 tonnes carbon per hectare in the pasture.

In the first year, there is a 200 tonne net flux of carbon as CO_2 to the atmosphere. In the second there is a 195 tonne net flux; the clearing of the second hectare is partially balanced by the establishment of the first pasture. In the third, there is a net flux again of 195; the clearing of the third hectare is again partially balanced by the establishment of the second pasture; however, the first pasture is now again in a steady state (as a pasture). The fourth year the pattern is again the same, but in the fifth year the net annual flux drops to 185 as the first pasture is now abandoned and begins to recover to a secondary forest. In the sixth year, the flux drops to 175 as two hectares are recovering to a secondary forest. In this example, in 1989 one hectare would be converted to pasture (200 tonne flux of carbon to the atmosphere), one hectare would have become a pasture (5 tonne flux to the terrestrial biosphere), two hectares would be in steady state as pasture, and 15 hectares would be recovering to secondary forest with one hectare in its final year of recovery (150 tonne flux to the terrestrial biosphere). The gross flux of carbon from land clearing in 1989 would still be 200 tonnes to the atmosphere, but the net flux to the atmosphere in 1989 associated with land clearing would be 45 tonnes of carbon as CO_2. The 1990 flux would be the same since now the original one hectare of pasture would have reached a new steady state as a secondary forest.

Many variations on this example can be devised: e.g., conversion of some vegetation to charcoal, varying deforestation and regrowth rates. For instance, if the land clearing rates declined over the time period, the 1990 net flux could easily be from the atmosphere to the biosphere even though the net integrated flux over the time period was to the atmosphere.

There are other complexities such as the variety of land-use practices, different assumptions about biomass densities, recovery rates, the dynamics of the associated litter and soil pools, and so forth. However, the net flux to or from a particular site will always be reflected in the change of carbon stocks on site and/or in the products pools associated with the site. Thus, a methodology that determines carbon stock changes also provides estimates of the net fluxes of CO_2.

5.1.3 Priority Categories

In estimating the effects of landuse and land-use changes on the emissions of GHGs, it is reasonable to stage the calculation methods so that the most important components can be addressed first. Complexities and subtleties of the relationship of forestry and land-use change to fluxes of CO_2 and other gases can be incorporated in a consistent manner into subsequent calculations as knowledge advances and data improve. The methodology presented in this chapter focuses initially on a simple, practical and fair procedure for determining the biomass-derived CO_2 flux directly attributed to forest management and land-use change activities. This procedure must also account for the influence of inherited "emissions" or past land-use changes upon the contemporary CO_2 flux,[4] as well as trace gas emissions from biomass burning where this occurs in conjunction with land-use change.[5]

The general forest and grassland ecosystem categories are listed in Box 2. Detailed description of tropical forest types and regional forest formations are presented in Table 5-1.

On a global scale, the most important land-use changes that result in CO_2 emissions and removals are:

- **changes in forest and other woody biomass stocks -** the most important effects of human interactions with existing forests are considered in a single broad category, which includes commercial management, harvest of industrial roundwood (logs) and fuelwood, production and use of wood commodities, and establishment and operation of forest plantations as well as planting of trees in urban, village and other non-forest locations;[6]
- **forest and grassland conversion -** the conversion of forests and grasslands to pasture, cropland, or other managed uses can significantly change carbon stored in vegetation and soil;[7]
- **abandonment of croplands, pastures, plantation forests, or other managed lands** which regrow into their prior natural grassland or forest conditions.
- **changes in soil carbon.**

The method also addresses the immediate release of non-CO_2 trace gases (CH_4, CO, N_2O and NO_x) from the open burning of biomass from forest clearing.

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[4] Similarly, current land-use changes will affect future fluxes of CO_2.

[5] Burning of biomass residues can occur in other situations which are not land-use change, e.g., in the use of forests or other biomass stocks as a part of the ongoing management of these stocks without changing the land use. This should be treated in the same way as burning of cleared forests for calculation of non-CO_2 GHG from burning.

[6] Changes in forest and other woody biomass stocks are accounted for in each Inventory Year.

[7] Conversion of forests is also referred to as "deforestation" and it is frequently accompanied by burning.

BOX 2
FOREST AND GRASSLAND CATEGORIES

Ecosystem categories have been established based on conventions common in the literature. For the tropics, the categories are based mainly on the FAO system (FAO 1993a) to be consistent with the tables of default values provided, and used in the simple calculations presented in the Workbook. National experts are free, indeed encouraged, to use more detailed characterisations of ecosystems in their countries if the data are available and differences are important for carbon calculations. If more detailed categories are used, however, it is necessary to aggregate these up to match the broad specified categories in order to ensure consistency and comparability with national data across all participating countries. The categories are presented as follows:

Ecosystem Types

Tropical Ecosystems

Forests	Wet Moist with short dry season Moist with long dry season Dry Montane moist Montane dry
Grasslands/Shrublands	Mainly herbaceous and shrub savannas/ grasslands

Temperate Ecosystems

Forests	Broadleaf Coniferous
Grasslands	

Boreal Ecosystems

Forests	Coniferous Mixed broadleaf-coniferous Forest-tundra
Grasslands/Tundra	

Within each ecosystem category, subdivisions are recommended where data are available. For example, tropical forests are defined as ecosystems with a minimum of 10% crown cover of trees and/or bamboos, generally associated with wild flora, fauna and natural soil conditions, and not subject to agriculture practices. They can be divided into:

Closed forests - Characterised by crown cover higher than 40%

Open forest - Characterised by crown cover between 10 and 40%.

Degraded forests or grasslands - Forests or grasslands that are have been overused or poorly managed and are likely to have reduced biomass densities.

Protected forests or grasslands - Forests or grasslands that are designated as national parks or in other ways are legally protected.

TABLE 5-1
TYPES OF TROPICAL FORESTS AND REGIONAL FOREST FORMATIONS

Types of tropical forests[a]						
	Wet	Moist with short dry season	Moist with long dry season	Dry	Montane Moist	Montane Dry
	R ≥ 2000	2000>R>1000		R<1000	R>1000	R<1000
Forest	Mainly evergreen	Mainly moist deciduous	Mainly dry deciduous	Very dry deciduous	Mainly evergreen	Mainly dry deciduous
Typical regional forest formations:						
Africa	Lowland rain forests	Lowland evergreen to semi-ever-green forests	Dry deciduous forests and miombo woodlands	Deciduous forests and woodlands. Very dry savanna and steppe	Montane evergreen forests	Scrub forests and evergreen to semi-evergreen thickets
Asia	Tropical lowland evergreen rain forests	Dense semi-deciduous or deciduous forests	Dry deciduous forests	Low deciduous forests. Thorn forests	Tropical and wet and moist forests	Dry evergreen forests or pseudo-steppic vegetation
America	Ombrophilous forests	Evergreen seasonal forests.	Tropical and subtropical forests Cerrados or pantanal	Open deciduous forests	Tropical evergreen and/or seasonal forests	Dry deciduous forests or shrub savanna. Arid subdesertic matorrales
Open formations of the different climatic zones:						
Open Forest	Mainly evergreen degraded	Mainly moist deciduous	Mainly woodlands and tree savanna	Dry woodlands and tree savanna	Mainly degraded evergreen and seasonal	Mainly dry savannas

Note: R= annual rainfall in mm/yr

[a] The ecological conditions which characterise these main vegetation cover classes are:

Wet - Evergreen dense forests which receive more than 2000 mm per year rainfall evenly throughout the year.

Moist with short dry season - Deciduous forests, characterised by a short dry season (<4-5 months), and rainfall 1000-2000 mm per year.

Moist with long dry season - Woodlands and open forests, characterised by a long dry period (>5 months), and rainfall 1000-2000 mm per year.

Dry- Woodlands and tree savannas which receive less than 1000 mm per year of rainfall, very seasonally distributed.

Montane moist and dry- Main features of this zone are altitude above 1000 metres and rainfall above and below 1000 mm per year respectively.

5.1.4 Relationships among Categories

It is possible that some areas of land can fit the definitions of two categories - e.g., abandoned lands regrowing and changes in woody biomass stocks - simultaneously. In this situation, the most recent, significant human interaction should be used to allocate land into categories. Even though an area may have been abandoned and allowed to regrow, if it subsequently begins to be "managed" (e.g., as a significant source of fuelwood) it should be reclassified in the *changes in forest and other woody biomass stocks* category. It is important to recognise some key linkages and interactions both among components of the land-use change and forestry methods and with other calculations discussed in other chapters. Figure 5-1 illustrates a number of complicated relationships among these categories and also with biomass fuel combustion which is covered in the energy source category. Key linkages which should be understood are:

1. To estimate CO_2 emissions from *burning of cleared forests*, it is only necessary to know the total amount of biomass which is burned in the Inventory Year.

2. However, it is necessary to divide this burning into on-site and off-site (fuelwood) portions for two reasons:

   First, the type of burning affects the emissions of non-CO_2 trace gases such as CH_4 so that different emission factors may be applied to open burning on-site and to fuelwood use off-site.

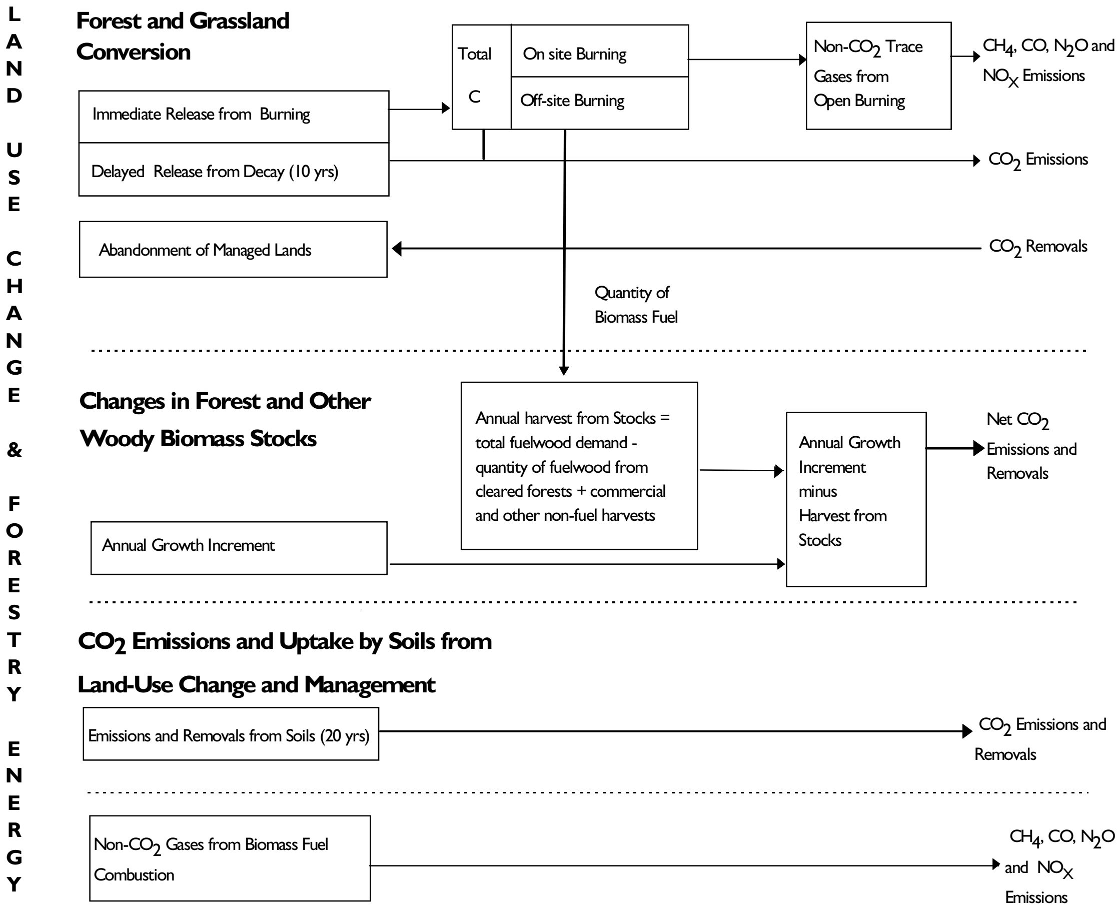
   Secondly, the amount of fuelwood removed from cleared forests must be deducted from the total biomass cleared to prevent double counting in the fuelwood consumption calculations. This is only an issue for those countries which must infer some or all of forest harvest from wood consumption surveys.

3. Fuelwood Consumption Information. Countries which have accurate and complete statistics on direct harvesting of all types of wood from biomass stocks, and all uses of biomass for fuel, should use locally available data. Many countries, however, have significant amounts of wood removed from forests, primarily for domestic fuel use, which are not accounted for in commercial harvest statistics. For these countries, a Fuelwood Consumption Accounting approach is provided which uses data from the FAO Yearbook of Forest Products.

   Fuelwood consumption information is used in two ways:

   – for estimating non-CO_2 trace gas emissions from biomass fuel combustion (in the Energy Section of the methodology); and
   – total wood consumption, corrected to deduct any wood which has come from forest clearing, is also a key input to the calculations of net CO_2 emissions or removals from *changes in forest and other woody biomass stocks*.

FIGURE 5-1 : RELATIONSHIPS AMONG CATEGORIES



5.1.5 Chapter Organisation

The remainder of this chapter presents methods for calculating GHGs from land-use change and forestry in two stages. The next section, *Basic Calculations*, presents initial simple calculations for each of three broad categories of forestry and changes in land use identified above. These categories also correspond directly to the subsections of the Land-use Change and Forestry Module of the *Workbook*.

The second stage, *Refinements in Calculations*, discusses a range of complexities and refinements which ideally could be included in such calculations, as data and understanding permit, in order to improve accuracy and completeness. These possible refinements include more detailed treatment of some aspects of the basic categories of land uses and land-use changes, as well as additional categories, which can affect carbon stocks and are potentially important for other GHGs. Issues discussed include the delayed release (or uptake) of non-CO_2 trace gases after burning of forests (either as a prescribed forest management tool or as a means of land-clearing), forest degradation, traditional shifting cultivation, and conversion of wetlands to other land uses or the reverse. These activities and other refinements can be incorporated in more detailed versions of the calculations.

A *Technical Appendix*, as mentioned, is also provided, which deals with sources of information on rates of land-use change, a critical activity data input for calculating GHG emissions.

5.2 Basic Calculations

5.2.1 Introduction

The basic calculations focus primarily on the land-use changes (causing changes in land cover) and land-use activities (forestry) that result in the largest, potential flux of CO_2 to the atmosphere or have the largest potential for sequestering carbon.

Two categories of land-use change are considered:

- forest and grassland conversion to agricultural lands
- abandonment of managed lands

In contrast to most GHG emission methodologies, estimating sources and sinks of CO_2 from land-use change requires the consideration of events over a long period of time. When forests are cleared or agricultural lands abandoned, the biological responses result in "commitments" of fluxes of carbon to or from the atmosphere for many years after the land-use change. This methodology is designed to produce an emissions estimate that is comparable to other elements of the inventory, fossil fuel emissions, for example. That is, it attempts to quantify the flux to or from the atmosphere *in the Inventory Year*. To do this, it is necessary to obtain estimates of land-use change activities for many years prior to the Inventory Year, and estimate the effects of these activities on the current year fluxes. The two selected categories are considered to be the most important land-use changes affecting CO_2 fluxes, but are not a comprehensive set. Many relevant land-use changes are excluded from the basic calculations. These are discussed in the last section of this chapter.

Relevant forestry (on-going land use) activity is combined in one very broad category, *changes in forest and other woody biomass stocks*, which is defined to include a wide variety of practices. Key examples are establishing and harvesting plantations, commercial forest management and harvesting, fuelwood gathering, and use of harvested wood.

Conceptually, this category is intended to account for all significant human interactions with forests and other woody biomass stocks which affect CO_2 fluxes to and from the atmosphere, but which do not result in a land-use change. It is intended to account, at least on a crude level, for all existing forests, but two comments are important here.

1. Natural, unmanaged (for wood products) forests are not considered to be either an anthropogenic source or sink, and are excluded from the calculations. However, in most countries of the world, a few undisturbed (by humans) forests exist, and they could still be sequestrating carbon as they regrow to a mature forest. The lack of consideration of these “undisturbed” forests in the tropics, for example, could lead to an underestimation of carbon sinks in this region. Tropical countries need to establish a permanent forest inventory monitoring network to determine if the “undisturbed” forests are sinks or not. Current research in the Amazon countries suggest some undisturbed forests are carbon sinks (Lugo and Brown, 1992; and Grace et al., 1995).

2. Forests regrowing naturally on abandoned lands are a net carbon sink attributable to past human activities and are accounted for separately. "Abandoned" lands are by definition assumed not to be subject to ongoing human intervention (of significance to carbon stocks) after abandonment.[8]

NOTE: Forests classified as natural, or abandoned/regrowing, can be excluded from the woody biomass stocks accounting only if there is no significant current human interaction with these forests. If they are being used as a source of fuelwood, or are being affected in other ways by ongoing human activities, they should be accounted for on an annual basis as part of *changes in forest and other woody biomass stocks*. In many countries, lands which are classified as natural or abandoned are in fact harvested informally. Thus, in some countries or regions with fuelwood shortages, little forest will actually fall into the natural or abandoned categories.

Several simplifying assumptions are made in the basic calculation methodology. A number of refinements are possible to improve on these basic calculations. One important option is to implement the basic calculations at a more detailed level of subcategories or geographic detail. National experts are strongly encouraged to do so if data are available. Box 3 discusses possibilities for adapting the methodology to various levels of detail, depending on the capabilities and data available to the user, and the relative importance of various components to the individual country.

Other possibilities for improving the accuracy and completeness of the basic calculations are possible. For example, the fate and amount of belowground biomass (roots, etc.) is currently ignored in the calculation. The section entitled *Refinements to Calculations*, later in this chapter, reviews a number of possible additions and refinements.

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[8] Abandoned lands which are regrowing naturally may be cleared again. In this case, they should shift again to cleared lands, probably with a lower value for preclearing biomass density than when they were first cleared.

BOX 3

ALTERNATIVE LEVELS OF DETAIL

For simplicity and clarity, this chapter discusses calculation of emissions at a national level and for a relatively small number of subcategories within each category of land-use change and forestry. The level of detail in the subcategories is designed to match the available sources of default input data, carbon contents and other assumptions. It is important, however, for users of these emissions methodology guidelines to understand that they are not only permitted but encouraged to carry out the GHG emissions inventory calculations at a finer level of detail, if possible. Many countries have more detailed information available about land-use change, forests and agriculture, than was used in constructing default values here. It may be important in such countries to carry out emissions calculations at finer levels in two ways:

1. Geographic detail at a regional, rather than a national, level

If data are available, experts may find that GHG 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 burned, etc.

2. Finer detail by subcategory

If data are available, experts may subdivide the recommended activity categories and subcategories to reflect important differences in ecology or species, land use or agricultural practices, bioenergy consumption patterns, etc.

In all cases, working at finer levels of disaggregation does not change the basic nature of the calculations, although additional data and assumptions will generally be required beyond the defaults provided in the chapter. Once GHG emissions have been calculated at whatever is determined by the national experts to be the most appropriate level of detail, results should also be aggregated up to the national level and the standard categories requested in the IPCC proposed methodology. 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 the IPCC to ensure transparency and replicability of methods. *Volume 1: Reporting Instructions* discusses these issues in more detail.

5.2.2 Changes in Forest and Other Woody Biomass Stocks

The category *changes in forest and other woody biomass stocks* as used in these basic calculations is very broad, potentially including a wide variety of land-use practices. This discussion focuses heavily on changes in forests, which globally account for the largest component of annual changes in biomass stocks. However, other types of biomass such as non-forest trees (e.g., in villages, cities, etc.) and woody shrubs in grasslands should be included when they are a significant component of total changes in biomass stocks, as is likely to be the case for some specific countries. A basic organising concept in this chapter is that all existing forests can be allocated into one of three categories.

1. Natural, undisturbed forests, where they still exist and are in equilibrium, should not be considered either an anthropogenic source or sink. They can therefore be excluded from national inventory calculations.

   NOTE: Many countries may have little or no forests or woody biomass stocks which are not affected significantly by humans. In areas with severe fuelwood shortages, for example, significant biomass - and hence carbon - may be removed for fuel annually even from "natural forests" and abandoned lands.[9]

2. Forests regrowing naturally on abandoned lands are a net carbon sink attributable to past human activities and are accounted for as discussed in a later section. While the current regrowth is considered a response to past anthropogenic activity, "abandoned" lands are by definition assumed not to be subject to ongoing human intervention (of significance to carbon stocks) after abandonment.

3. All other types of forest are included in the changes in forest and other woody biomass stocks category. That is, any forest which experiences periodic or on-going human interventions that affect carbon stocks should be included here. In the basic calculations, the chapter focuses primarily on a few types of human interactions with forests which are believed to result in the most significant fluxes of carbon. National experts are encouraged, however, to estimate emissions for any activity related to existing forests which is considered to result in significant carbon emissions or removals, and for which necessary data are available. Any such activities falling within our broad definition of *changes in forests and other woody biomass stocks* should be included in this category and reported to the IPCC as discussed in *Volume 1: Reporting Instructions*.

Some of the activities in the changes in forest and other woody biomass stocks category which can potentially produce significant carbon fluxes are:

- management of commercial forests - including logging, restocking, selective thinning, etc., as practised by commercial forest products industries
- establishment and management of commercial plantations[10]
- other afforestation, and reforestation programmes
- informal fuelwood gathering

This category also includes trees which may not traditionally be considered part of "forests". It can include village and farm trees if these are important for biomass and biofuel accounting in some developing countries. It can also include urban trees, trees

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[9] Also, as discussed in the chapter introduction, there are likely to be widespread human induced effects, e.g., CO_2 fertilisation and nitrogen deposition, which cause changes in virtually all terrestrial biological systems. In this sense, there may be no natural forests which are not subject to human induced GHG emissions or removals. However, at present, the understanding of these broad effects is so uncertain, and quantitative estimation so difficult, that they are not included in the basic calculations recommended for all national inventories.

[10] Plantations are forest stands that have been established artificially, to produce a forest product "crop". They are either on lands that previously have not supported forests for more than 50 years (afforestation), or on lands that have supported forests within the last 50 years and where the original crop has been replaced with a different one (reforestation) (Brown et al., 1986).

planted along highways, aircraft runways, etc., if these are considered significant for a particular country's biomass calculations. These dispersed trees do not contribute greatly to carbon fluxes to or from the atmosphere on a global scale. However, in some countries, they may be important in accounting for the total amount of wood used for fuel. Also, they may be of interest to some countries because of their potential use in response strategies. For these reasons, they are included in the basic calculation methods. National experts who feel they are important, and have the necessary locally available data, can include them.

In addition to trees in non-forest locations, in some countries, woody biomass from shrubs or other plants, in grasslands or other locations, may play a significant role in total fuelwood supply. If this is the case, the annual supply of biomass from these “non-trees” must be included in the overall fuelwood accounting. Otherwise the loss of biomass stocks in forests may be overstated.

As illustrated in the above list, the changes in forest and other woody biomass stocks category includes some tree planting activities which, strictly speaking, are land-use **changes**. Plantation establishment and other afforestation/reforestation programmes are examples. It is recognised that this is conceptually inconsistent as the category is intended to account for ongoing interactions with existing forests. However, from a pragmatic perspective, including these activities within the category can simplify the calculations. These subcategories are land-use changes which create new forest stocks. As soon as the land-use change occurs (i.e., the tree planting), the new land use becomes part of the *changes in forest and other woody biomass stocks* category which is accounted for on an annual incremental basis. Although it would be possible, it is not necessary to estimate the lagged effects of this change as is done with other land-use changes.[11] While including such a range of tree-related activities in one category may introduce some confusion, the calculation procedure is basically the same for all subcategories, and this allows the simplest possible set of emissions calculations.

As discussed above, if lands previously considered abandoned and regrowing, or natural forests, are being affected by human activity in the inventory year, they should be reclassified into the *changes in forest and other woody biomass stocks* category.

As discussed in the *Overview*, the methodology is designed to accommodate users at several levels of detail. This is especially important in the managed forests category. Possible levels include:

1. A simple first order approach, covering the main subcategories, with calculations based on simple default assumptions and default data provided.

   NOTE: An inventory of land-use change and forestry emissions developed on default values only is unlikely to be considered credible for any country which has significant emissions or activities in these areas.

2. Calculations at the same level of detail but substituting more appropriate data and assumptions from local sources.

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[11] There is one omission in this accounting which may be important for some countries. If plantations are established on previously unforested lands, there may be a long term accumulation of carbon in the soil as a result of the land-use change. This would not normally be picked up in the simple *changes in forest and other woody biomass stocks* calculations. It could be added if national experts have detailed data on the pre-plantation land uses, the soil carbon contents and rates of accumulation, etc.

3. Calculations following the same structure, but broken down to finer levels of detail to improve accuracy and utility of estimates, where locally available data can support this.

4. Estimates derived from much more detailed and precise inventory-based forest accounting methods. These results can be reformatted and **presented** in the form of calculations comparable to those used by the other national experts operating with less detailed data.

It is highly desirable that the methodology be relevant for countries which have access to much more detailed data on changes in forest stocks. Some countries with highly developed forestry industries do in fact keep track of existing commercial forests through periodic detailed surveys For such countries, it is possible to derive from survey results aggregate values comparable to the data and assumptions used in the simple approach, and present them in this common format. This will assist all interested parties in evaluating various national estimates on a comparable basis, and will thus be necessary to comply with requirements of *Volume 1: Reporting Instructions*. Box 4 provides some further discussion of these procedures.

BOX 4
ADAPTING DETAILED FOREST INVENTORY DATA TO THE IPCC FORMAT

A number of countries with highly developed commercial forestry industries routinely collect forest biomass data at a detailed inventory level which allows for relatively precise and direct assessment of the changes in biomass stocks, and equivalent carbon fluxes. National experts working with data of this kind should be able to derive from it values equivalent to those used in calculating emissions with the IPCC methodology.

Regardless of how detailed the data base used may be, the results ultimately must be presented in units (e.g. Gg) of carbon and CO_2 emitted or removed in a given average response category (e.g., annual biomass growth rates by ecosystem type). Similarly, the number of hectares of forest in various types can be aggregated up to categories matching the simple approach outlined here. The amount of biomass removed as commercial harvest or for other reasons, should also be relatively well established in such inventories. With these data, it should be possible to, in effect, work backwards to derive the necessary input assumptions and aggregate values. For example, national experts might start with a change in total biomass for specified forest types (and/or regions) over a specified time period. Then they could add the amounts of biomass removed through commercial harvest or for other reasons (e.g., thinning), to get the total growth of biomass over the period. This could then be divided by the number of kilohectares in the category (and the number of years, if a multi-year period) to get average annual growth rates by category. This would then provide all the values needed to reconstruct the calculations in a comparable form to those from countries with minimal data.

The national emission/removal estimates presented in this form would then be easily understood and compared by all other parties involved in the international climate change discussions. The intent is to provide a calculation and reporting framework which can accommodate users with vastly different levels of data available, yet allow them to present the results on a comparable basis.

Changes in forest and other woody biomass stocks may be either a source or a sink for carbon dioxide for a given year and country or region. The simplest way to determine which, is by comparing the annual biomass growth versus annual harvest, including the decay of forest products and slash left during harvest. Decay of biomass damaged or killed during logging results in short-term release of CO_2. For the purposes of the basic calculations, the recommended default assumption is that all carbon removed in wood and other biomass from forests is oxidised in the year of removal. This is clearly not strictly accurate in the case of some forest products, but is considered a legitimate, conservative assumption for initial calculations. Box 5 provides some further discussion of this issue.

BOX 5
THE FATE OF HARVESTED WOOD

Harvested wood releases its carbon at rates dependent upon its method of processing and its end-use: waste wood is usually burned immediately or within a couple of years, paper usually decays in up to 5 years (although landfilling of paper can result in longer-term storage of the carbon and eventual release as methane or CO), and lumber decays in up to 100 or more years. Because of this latter fact, forest harvest (with other forms of forest management) could result in a net uptake of carbon if the wood that is harvested is used for long-term products such as building lumber, and the regrowth is relatively rapid. This may in fact become a response strategy.

For the initial calculations of CO_2 emissions from changes in forest and other woody biomass stocks, however, the recommended default assumption is that all carbon in biomass harvested is oxidised in the removal year. This is based on the perception that stocks of forest products in most countries are not increasing significantly on an annual basis. It is the net change in stocks of forest products which should be the best indicator of a net removal of carbon from the atmosphere, rather than the gross amount of forest products produced in a given year. New products with long lifetimes from current harvests frequently replace existing product stocks, which are in turn discarded and oxidised. The proposed method recommends that storage of carbon in forest products be included in a national inventory only in the case where a country can document that existing stocks of long term forest products are in fact increasing.

If data permit, one could add a pool to Equation 1 (1) in the changes in forest and other woody biomass stocks calculation to account for increases in the pool of forest products. This information would, of course, require careful documentation, including accounting for imports and exports of forest products during the inventory period.

The net growth of biomass stocks (and accumulation of carbon) depends on the type of biomass stock and the intensity of harvesting. Well managed commercial forests, replacing natural forests, would over the long term be expected to have net emissions close to zero. In many cases, where historically cleared areas are regrowing under commercial management, with limited logging, the forest areas are currently a net sink. If forests (or parts of forests) are logged or harvested at a rate which exceeds regrowth, then there is a net loss of carbon.[12]

Establishment of plantations and other tree planting activities result in absorption of CO_2 from the atmosphere and storage of this carbon until the vegetation is burned or decays. Restocking of managed forests, planting of urban, village and farm trees, and establishing plantations on unforested lands, therefore, result in an uptake of carbon from the atmosphere, at least until the biomass is harvested and enters a decay pool, or the system reaches maturity. The effect of plantation establishment can be to create a net sink for carbon even if the plantation is harvested for products that are rapidly oxidised (e.g., fuelwood). If the plantations are harvested so that there is no net loss of biomass over time (i.e., harvested in a sustainable fashion), then the rate of carbon accumulation on land is positive (or at least non-negative) and tied directly to changes in the area of plantations and their average biomass.

The conversion of natural forests to plantations may result in an initial loss of biomass carbon due to an initial reduction in standing biomass. If plantations are established by first clearing existing forests, the initial loss should appear under *forest and grassland conversion* below. Reaccumulation of biomass in these plantations in subsequent years would be accounted for here under *changes in forest and other woody biomass* stocks. The approach accounts for all plantations in operation in the inventory year, including both previously planted and newly established plantations.

The method for calculating the net changes in biomass stocks is shown in Equation 1. For non-forest trees such as village and farm trees, accounting would be done on the basis of numbers of trees (e.g., in thousands) rather than for hectares of land. The calculations would be the same, except that average annual growth would be expressed in tonnes dm per thousand trees rather than per hectare.

The recommended unit of calculation is tonnes of dry biomass, and it is necessary to convert to carbon for emissions estimation. A general default value of 0.50 tonnes-C/tonne dry biomass is recommended for all biomass calculations. If more accurate conversion values are available for the particular system, these should of course be used.

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[12] In addition, logging provides access to previously inaccessible forests, thereby facilitating degradation of forests by activities such as fuelwood collection, habitation, and agricultural activity.

EQUATION 1

(1) hectares of land in a particular category (e.g., plantations)
x
average annual growth per hectare in biomass
=
gross annual growth increment.
total biomass increment is the sum of all relevant categories.

(2) total harvest by category (including fuelwood gathering)
x
expansion ratio to treat slash
=
gross annual biomass loss.
total harvest and other biomass loss is the sum of all relevant categories of harvest.

(3) total annual growth increment - total annual biomass loss
=
annual biomass change (positive or negative).

Growth Increments

Estimates of average annual accumulation of dry matter as biomass per hectare are presented for forests naturally regrowing by broad category in Table 5-2. These values can be used as default values for growth rates in similar managed forest categories if no other information is available. For forests which are more intensely managed (e.g., with periodic thinning, restocking, etc.) annual growth increments could be quite different. Values for some typical plantation species are presented in Table 5-3 and can be used as default values. As discussed in notes in these tables, average growth rates represent a great deal of variability within regions and even from site to site. It is always strongly recommended that locally available data be used or developed if possible in national inventory calculations.

TABLE 5-2
ANNUAL AVERAGE ABOVEGROUND BIOMASS UPTAKE BY NATURAL REGENERATION
(tonnes dm/ha)

Tropical Regions		Forest Types					
		Moist Forests		Seasonal Forests		Dry Forests	
		0-20 Years	20-100 Years	0-20 Years	20-100 Years	0-20 Years	20-100 Years
	America	8.0	0.9	5.0	0.5	4.0	0.25
	Africa	11	1.0	7.0	0.7	4.0	0.25
	Asia	11	1.0	7.0	0.7	4.0	0.25

Note: Growth rates are derived by assuming that tropical forests regrow to 70% of undisturbed forest biomass in the first twenty years. All forests are assumed to regrow to 100% of undisturbed forest biomass in 100 years. Assumptions on the rates of growth in different time periods are derived from Brown and Lugo (1990).

		0-20 Years	20-100 Years	
Temperate Forests				
	Evergreen	3.0	3.0	
	Deciduous	2.0	2.0	
Boreal Forests		1.0	1.0	

Note: Temperate and boreal forests actually require considerably longer than 100 years to reach the biomass density of a fully mature system. Harmon et al. (1990), for example, report carefully designed simulations indicating that a 100-year old stand of Douglas fir would contain only a little over half the biomass of a 450-year old growth stand of the same species. There is also evidence that growth rates in temperate and boreal systems are more nearly linear over different age periods than is the case in tropical systems. Nabuurs and Mohren (1993) suggest that growth rates for several different species in temperate and boreal zones rise slowly to peak at ages of 30-55 years and decline slowly thereafter. This suggests that using the same default values for 0-20 year and 20-100 years may be a reasonable first approximation. Nabuurs and Mohren (1990) also illustrate that growth rates may vary as much as a factor of ten for stands of the same species and age, depending on site-specific conditions. The table values are very general representative global values from Houghton et al. (1983 and 1987).

ALL OF THESE REGIONAL AVERAGE GROWTH RATES SHOULD BE CONSIDERED INDICATIVE ONLY. IF FORESTS ARE A SIGNIFICANT PART OF A COUNTRY'S TOTAL GHG INVENTORY, LOCALLY AVAILABLE DATA OR EXPERT JUDGEMENT SHOULD BE SOUGHT TO DEVELOP VALUES REFLECTING CONDITIONS AND PRACTICES.

TABLE 5-3
AVERAGE ANNUAL ACCUMULATION OF DRY MATTER AS BIOMASS IN PLANTATIONS

Forest Type		Annual Increment in Biomass (tonnes dm/hectare/year)
Tropical	*Acacia* spp.	15.0
	Eucalyptus spp.	14.5
	Tectona grandis	8.0
	Pinus spp.	11.5
	Pinus caribaea	10.0
	Mixed Hardwoods	6.8
	Mixed Fast-Growing Hardwoods	12.5
	Mixed Softwoods	14.5
Temperate	Douglas fir	6.0
	Loblolly pine	4.0

Sources: Derived from Brown et al., 1986. Farnum et al., 1983.

Note: These are average accumulation rates over expected plantation lifetimes; actual rates will vary depending on the age of the plantation. The data for the temperate species are based on measurements in the United States. Data on other species, and from other regions, should be supplied by individual countries (as available). Additional temperate estimates by species and by country can be derived from data in ECE/FAO (1992), assuming that country averages of net annual increment for managed and unmanaged stands are reasonable approximations for plantations.

Biomass Loss

Two approaches can be used to estimate biomass harvest and other losses from managed forests. Depending on the data collection and typical forestry practices in a given country, it may be appropriate to use either approach alone, or use both if the two approaches complement each other. This judgement must be made by national experts in each country.

Commercial Harvest Statistics. The first, and obvious, approach is to use statistics on amounts of biomass actually removed from forests. In countries where commercial harvests of various kinds make up a large majority of total biomass losses, and statistics are well maintained, this may be the only approach needed. Country-specific estimates of commercial harvest statistics are provided in annual FAO Forest Products Yearbooks (1993b), and periodic Assessments (e.g., FAO, 1993a), and are also generally available from national governments.

In using commercial harvest statistics, users must pay careful attention to the units involved. Commercial harvest statistics are often provided for the commercial portion of biomass only, in cubic metres (m^3) of roundwood. If this is the case, values will need to be converted to tons of dry biomass, and total biomass removed including slash. Some general default values for converting volume data to tons are 0.65 t dm/m^3 for deciduous trees and 0.45 t dm/m^3 for conifers. See Box 6 for more detailed information. To account for the biomass lost beyond the commercial wood portion, expansion ratios can be applied. Some general default values from the literature are 1.75 for undisturbed forests and 1.90 for logged forests.[13] There is considerable variability in these conversion values and expansion ratios, so it is highly desirable to use more specific locally available data. Also, some commercial harvest data may be reported as equivalent total biomass (i.e., expansion ratios already applied). It is important to check carefully the information in the original harvest data to ensure that expansion ratios are used only where appropriate.[14]

BOX 6
VARIABILITY IN DENSITIES OF TREE SPECIES

There is considerable variation in average densities for different tree species. While the broad average default values given in the text can be used for initial calculations, it is much better to use actual measured average values if available, or literature values specific to the dominant species in a particular forest. Dixon et al. (1991), for example, give densities for over 150 individual species, which range from 0.31 to 0.86 g/cm^3. Other sources of wood densities include USDA Forest Service (1987), Cannell (1984), Schroeder (1992), Dewar and Cannell (1992), UN ECE/FAO (1992), Nabuurs and Mohren (1993) and Hamilton (1985).

Fuelwood Consumption Accounting. In many countries, however, commercial harvest statistics will only partly account for wood removals. Significant quantities may be removed from forests on an informal basis (i.e., they are never accounted for in commercial statistics). In these cases FAO statistics of fuelwood consumption can be used to supplement the commercial harvest data.

Any wood which was extracted from cleared forests and used for fuel will already have been accounted for in the *forest and grassland conversion* calculations above. This amount should be subtracted from total wood consumed directly for fuel and for traditional charcoal making, to determine the amount which must have come from remaining managed forests. The result of this calculation can then be combined with any commercial harvest amounts to produce a total amount of biomass lost from managed forests.

There is an implicit assumption that slash is not accumulating. The instantaneous release of CO_2 from the current year's slash that is explicit in Equation 1 (2) is a simple mathematical device to treat slash oxidation from previous years under the assumption that the slash pool is not changing. The expansion ratio for slash in Equation 1 (2) could be modified to address the destruction of belowground biomass left after harvest. Treatment of carbon released from belowground biomass (e.g., roots) is discussed in the "Refinements in Calculations" section of this chapter.

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[13] Volume to mass conversions and expansion factors are taken from Brown et al., 1989 which reports on tropical forests. However, the values are in the range of those reported by ECE/FAO (1992) for temperate forests.

[14] If significant amounts of non-commercial biomass (slash) are burned on site during harvest, then emissions from this burning should be treated as described for burning associated with forest or grassland conversion in the next section. A portion of the burned carbon would be stored as unburned charcoal, and non-CO_2 gases should also be calculated.

The amount of biomass removed from forests and other woody biomass stocks in the inventory year should be subtracted from the annual growth in these stocks for the same year to arrive at the annual change in biomass stocks, positive or negative [Equation 1 (3)]. This result should be converted to a change in C (using the general default value of 0.50 t C/t dm, if necessary), and to CO_2 (using the ratio 44/12). A positive value for CO_2 in stocks is a CO_2 removal from the atmosphere while a negative value is an emission. For reporting purposes, the sign should be changed to conform to the convention that emissions are positive and removals are negative (i.e., negative emissions).

5.2.3 Forest and Grassland Conversion

CO_2 release

This category includes conversion of existing forests and natural grasslands to other land uses, such as agriculture. The calculation of carbon fluxes due to forest and grassland conversion is in many ways the most complex of the emissions inventory components. Responses of biological systems vary over different time-scales e.g., biomass burning occurs at less than one year scale, decomposition of wood at the decade scale, and loss of soil carbon at several decades scale. Thus, it is necessary to consider forest clearing activity over three different time-scales and to sum the results to estimate the total flux in the current year. Also, as with all categories of forest management and land-use change activity, it is necessary to determine *net* CO_2 flux.

Forests can be cleared to convert land to a wide variety of other uses, including agriculture, highways, urban development, etc.[15] In all cases there is a net carbon release to the atmosphere which should be accounted for in this calculation. The predominant current cause of forest clearing is conversion to pasture and cropland in the tropics. This is accomplished by an initial cutting of undergrowth and felling of trees. The biomass may then be combusted in a series of on-site burns or taken off site to be burned as fuel, or perhaps used for forest products. A portion of the biomass remaining on site as slash is not completely combusted and remains on the ground where it decomposes slowly.[16] Some of the decay of remaining carbon left on the ground is probably accomplished by termites, which produce both CO_2 and CH_4.[17] However, the CH_4 release from cleared, unburned biomass is very difficult to quantify and is ignored for purposes of the basic calculation, where all of the carbon in biomass which decays is assumed to be released as CO_2. Of the portion burned on site, a small fraction of the carbon remains as charcoal, which resists decay for well over 100 years or more. There is a great deal of uncertainty

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[15] Conversion of tropical forests to pasture and cropland accounts for the largest share of global forest clearing and resulting CO_2 emissions. The discussion and default information focus on this case, as it is most important that national inventories account for the largest contributions to emissions first. Forest clearing for other purposes (e.g., urban development) should also be accounted for to the extent possible. As less default information is provided for these cases, this will require national experts to provide input data.

[16] Decomposition rates of woody slash generally depend on several factors including humidity, temperature, and chemical composition (e.g., nutrient content and secondary chemicals).

[17] This issue is discussed in the section on possible refinements to the methodology.

about the fraction of carbon which remains unburned in charcoal under these conditions and also about the ultimate fate of this charcoal.[18] The remainder is released instantaneously to the atmosphere. For biomass removed for fuelwood, the fate is very similar. A small fraction of the carbon remains in unburned charcoal which effectively provides long term storage, while the majority of the carbon is released to the atmosphere.

For conversion of grasslands to crop or pasture lands, the default assumption is that there is no change in aboveground biomass between the pre-conversion natural grassland and the post-conversion crops or pasture. This assumption can be varied if there are locally available data that show a net change (see Box 7).

Forest and grassland conversion also results in CO_2 emissions through soil disturbance, particularly when the conversion is to cultivated or tilled lands. When forests are converted to croplands, a fraction of the soil carbon may be released as CO_2, primarily through oxidation of organic matter. This can be a long term process which continues for many years after the change in land use occurs. The calculations in Section 5.3 allow for estimation of loss in soil carbon due to land conversions.

Calculations

Emissions of CO_2 due to forest and grassland conversions are calculated through a sequence of steps treating:

- the net change in aboveground biomass carbon
- the portion of this change that is burned in the first year (either on- or off-site) versus the amount left to decay over a longer time period
- for the burned portion, loss to the atmosphere versus long-term storage in charcoal
- current emissions from decay of biomass cleared over the previous decade
- current releases of carbon from soils due to conversions (decomposition of soil organic matter).

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[18] The portion of burned carbon that remains on the ground as charcoal is highly uncertain. Measurements following burning of a forest for conversion to pasture indicate that 2.6 per cent of the pre-burn aboveground carbon, or 8.5 per cent of the burned carbon, is converted to charcoal (Fearnside et al., 1990a). According to Fearnside et al. (1990b), pastures are typically burned two to three times over about a 10-year period. Under such a scenario, the latter burns probably result in combustion of some of the charcoal formed during the first burn and formation of additional charcoal. Fearnside et al. (1990b) estimate that about 4.6 percent of the pre-burn aboveground carbon, or 10.1 percent of the burned carbon, is converted to charcoal under this scenario. Based on results of observations in the Brazilian Amazon (Fearnside et al., 1990a) and in a Florida pine forest (Comery, 1981), Crutzen and Andreae (1990) adopt charcoal values of 5 percent of the pre-burn aboveground carbon and 10 percent of the burned carbon for clearing in the tropics. Recent estimates of charcoal produced suggest that these values may be too high and will be re-assessed in future revisions to the *Guidelines.*

BOX 7

ABOVEGROUND BIOMASS IN GRASSLANDS

Conversion of a grassland to cultivated land may result in net CO_2 emissions to the atmosphere due to soil disturbance and resultant oxidation of soil carbon. In the simple default calculations, it is assumed that there is no net reduction in standing biomass because aboveground biomass densities of grasslands are approximately the same as that of croplands and pasture. Therefore any changes in this aboveground pool due to the land-use change are likely to be generally small in comparison with other changes in carbon stocks in terrestrial systems. Consequently, changes in aboveground biomass are ignored in the basic calculation. As with all default assumptions, users are encouraged to vary this one if they believe it is inaccurate for their conditions. Some grasslands can contain significantly more or less standing biomass than the default estimate of 10 tonnes dry matter/hectare for grasslands. If national experts have data locally available and differences are significant, these values should be used. In this case, the assumption of no net change in aboveground biomass would not be valid. The net change in aboveground biomass in this situation would be determined with exactly the same procedure as used in the forest clearing case.

Net change in aboveground biomass

First, the amount of aboveground biomass that is cleared in the emissions Inventory Year[19] is calculated by multiplying the annual forest area (or savannas, grasslands, etc., if appropriate) converted to pasture or cropland or other land uses by the net change in aboveground biomass. This calculation is carried out for each relevant forest/grassland type and, if appropriate, by region within a country.[20] The *net change* is the difference between the density (t dm/ha) of aboveground biomass on that forest/grassland prior to conversion, and the density of aboveground living biomass (t dm/ha) remaining as living vegetation, after clearing. The after clearing value includes the biomass that regrows on the land in the year after conversion and any original biomass which was not completely cleared.

Tables 5-4 to 5-6 provide a range of values for aboveground biomass in forests prior to clearing, which can be used as default data if more appropriate and accurate data are not

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[19] For simplicity of explanation, the discussion refers to the Inventory Year as though data for a single year were the desired input. However, as noted in the overview, for land use and forestry emissions estimates, it is recommended that data averaged over several years be used in place of annual data. E.g., forest inventories are often done at five or ten year periods - this would then be the period over which data would be averaged to obtain the annual flux.

[20] Defining regions will require balancing data availability, biological and land-use heterogeneity, and practical considerations such as the available time and effort. Furthermore, developing adequate land use and land-use change data is a central issue. In the case of land clearing, these data would likely be obtained from a combination of departments of land management, agriculture, and forestry. These data will come at a variety of scales in time and space, and producing consistent records will be a challenging task to all countries. In time, new internationally-based remote sensing programmes could greatly facilitate this task; this is discussed in the technical appendix.

available in a given country.[21] For aboveground biomass after clearing, it is necessary to account for any vegetation (i.e., crops, pasture, or forest) that replaces the vegetation that was cleared. A reasonable figure for crops or pasture is 10 tonnes of dry biomass per hectare (Houghton et al., 1987; see also Box 7). Higher estimates of biomass of replacement crops is expected when perennials plants such as coffee, tea, cocoa, coconut, etc., are established. Where replacement by perennials is common (e.g., in many Asian countries), every effort should be made to obtain representative values. The recommended default assumption is that all of the original aboveground biomass is destroyed during clearing. If locally available data indicate that some fraction of the original biomass is left living after clearing, this should be added to the after clearing value.

TABLE 5-4
AVERAGE ABOVEGROUND BIOMASS ESTIMATES
FOR TROPICAL FORESTS BY CLIMATIC ZONE
(TONNES DM/HA)

Tropical forests

	Wet	Moist with short dry season	Moist with long dry season	Dry	Montane Moist	Montane Dry
	R > 2000	2000>R>1000		R<1000	R>1000	R<1000
Africa	300	140	60-90[a]	20-55 [a]	105	40
Asia:						
Continental	225	185	100	75	190	no data
Insular	275	175	no data	little to no forest exists	255	no forest exists
America	295	no data	90	105	150	50

R= annual rainfall in mm/yr

Sources: Estimates were derived from a model in a geographic information system and calibrated with reliable forest inventory data (Iverson et al., 1994) or from direct measurements ([a] P. Frost, pers. comm., 1996). Multi-date inventories were brought to a common year of about 1980. The estimates do not distinguish between primary or secondary forests but represent values averaged over the whole forested area in a given climatic zone in a given tropical region. These average values can include forests in all successional states, from mature or undisturbed to young secondary. Additional country-specific biomass estimates are presented in Table 5-5. Data are from Brown et. al. (1993) for Asia; Brown and Gaston (1995) for Africa; and S. Brown (pers. comm., 1995) for America.

REGIONAL DEFAULT ESTIMATES FOR BIOMASS DENSITY MAY BE USED AS AN INITIAL STARTING POINT OR FOR COMPARISON PURPOSES. HOWEVER, IN ANY COUNTRY FOR WHICH FOREST CONVERSION OR REGROWTH IS A SIGNIFICANT SOURCE OR SINK, LOCAL EXPERTS AND MEASUREMENTS SHOULD BE CONSULTED TO DEVELOP MORE ACCURATE VALUES REFLECTING LOCAL CONDITIONS.

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[21] As in the case of land-use data, developing appropriate biomass data is a challenging task. In theory, it can be obtained directly by destructive sampling but this is unrealistic for adequate coverage for even small countries. An alternative approach is to use inventory data where one exploits volumetric data on merchantable timber and uses a sequence of expansion factors to convert this to total stemwood, total above ground biomass, and total biomass. See the references to Tables 5-3 and 5-4.

TABLE 5-5
ABOVEGROUND BIOMASS ESTIMATES FOR VARIOUS TROPICAL FOREST TYPES BY COUNTRY
(TONNES DM/HA)

Country	Forest Type	Climatic Zone	Aboveground Biomass
Africa			
Benin	Closed forest	Dry	175
	Tree savanna	Dry	96
Botswana[a]	Mixed tree savanna	Dry-long dry season	19
Burkina Faso (National)	Degraded tree savanna	Dry- long dry season	20
Cameroon	Primary	Very moist	310
Gambia (National)	Gallery forest	Moist- dry season	140
	Closed woodland	Dry	97
	Open woodland	Dry	50
	Tree savanna	Dry	28
Ghana	Closed forest	Moist-short dry season	395
Guinea (National)	Mixed; closed Open, secondary	Moist-long & short dry	135
Mozambique	Dense forest	Moist- long dry	120
	Dense forest	Moist- long dry	130
	Dense forest	Dry- long dry season	70
Zambia[a]	Woodland-miombo	Moist-long dry season	91
	Woodland-miombo	Dry-long dry season	81
Zimbabwe[a]	Woodland-miombo	Dry-long dry season	29
Asia			
Bangladesh	Closed -large crowns	Very moist	206-210
	Closed -small crowns	Very moist	150
	Disturbed closed	Very moist	190
	Disturbed open	Very moist	85
Cambodia	Dense	Moist-short dry	295
	Semi-dense	Moist-short dry	370
	Secondary	Moist-short dry	190
	Open	Moist-short dry	160
	Open	Moist-long dry	70
	Well to poorly stocked	Moist-long dry	100-155
	Evergreen		
	Deciduous	Moist-long dry	120
India	High to low volume	Dry	44-81
	Closed		
	Forest fallow	Dry	16

TABLE 5-5 (CONT.)
ABOVEGROUND BIOMASS ESTIMATES FOR VARIOUS TROPICAL FOREST TYPES BY COUNTRY
(TONNES DM/HA)

Country	Forest Type	Climatic Zone	Aboveground Biomass
Asia - (cont)			
Malaysia-Peninsular (National)	Superior/moderate hill	Very moist	245-310
	Poor hill	Very moist	180
	Upper hill	Very moist	275
	Disturbed hill	Very moist	200
	Logged hill	Very moist	180
	Forest fallow	Very moist	140
	Freshwater swamp	Very moist	220
	Disturbed freshwater swamp	Very moist	285
	Logged freshwater swamp	Very moist	185
Malaysia- Sarawak	Mixed dipterocarps-dense stocking, flat to undulating terrain	Very moist	325-385
	Mixed dipterocarps-dense stocking, mountainous	Very moist	330-405
	Mixed dipterocarps- medium stocking, flat to mountainous	Very moist	280-330
Myanmar	Evergreen	Moist-short dry	60-200
	Mixed deciduous	Moist-short dry	45-135
	Indaing forest	Moist-short dry	10-65
Philippines	Old-growth dipterocarp	Very moist	370-520
	Logged dipterocarp	Very moist	300-370
Sri Lanka	Evergreen-high yield	Very moist	435-530
	Evergreen-medium yield	Very moist	365-470
	Evergreen-low yield	Very moist	190-400
	Evergreen-logged	Very moist	255
	Secondary	Very moist	280
Thailand	Degraded dry evergreen	Moist-long dry	85
America -	All forests are located in the wet/very moist climatic zone except where indicated.		
Bolivia	Closed forest		230
Brazil	Closed forest		315
Ecuador	Closed forest		182
French Guyana	Closed forest		309
	Riparian forest		275
	Savanna forest		205
Guatemala	Closed forest		242

TABLE 5-5 (CONT.)
ABOVEGROUND BIOMASS ESTIMATES FOR VARIOUS TROPICAL FOREST TYPES BY COUNTRY
(TONNES DM/HA)

Country	Forest Type	Climatic Zone	Aboveground Biomass
America - (cont.)	All forests are located in the wet/very moist climatic zone except where indicated.		
Guyana	Closed forest		254
	Logged forest		190
	Wallaba forest-seasonal		145
	Mixed forest		275
	Low mixed forest		192
	Liana forest		125
	Wallaba forest		148
	Wallaba forest on white sands		405
Nicaragua	Orifino forest		240
	Lowland mixed		235
	Mature forest		240
	Secondary		183
Panama	High density-mixed		239-366
	Low density-mixed		169-245
	Campnosperma forest -high density		860
	Campnosperma forest -low density		470
	High density-mixed		186-252
	Low density-mixed		118-143
Peru	Primary		210
	Lightly logged		192
	Heavily logged		125
	Late secondary		140
	Young secondary		20
	Flooded secondary		195
	Low forest		155
Surinam	Upland forest		255
	Small crown-upland		136
	Savanna forest		195
	Riparian forest		217
	Liana forest		120
	Wallaba forest		250
Venezuela	Semi-deciduous-dry		78
	Closed forest		230

Source: All biomass estimates were derived from either reliable forest inventory data for subnational to national forest areas (sources of inventories and details of methods used to convert to biomass are given in Brown, (1996) or from direct measurements, ([a] P. Frost, pers. comm., 1996).

TABLE 5-6
DRY MATTER IN ABOVEGROUND BIOMASS IN TEMPERATE AND BOREAL FORESTS
(TONNES DM/HA)

Temperate Forests	Coniferous	220 - 295
	Broadleaf	175 - 250
Boreal Forests	Mixed broadleaf/coniferous	40 - 87
	Coniferous	22 - 113
	Forest-tundra	8 - 20

Source:
Temperate forest estimates from Whittaker and Likens (1973) and Houghton et al. (1983). Total biomass estimates were converted to aboveground biomass by multiplying by 0.83 (Leith and Whittaker, 1975). Boreal forests biomass estimates are from Bazilevich, (1993); Finnish Forest Research Institute, (1995); Kokorin and Nazarov, (1995a); and Isaev et al. (1993). Alternative estimates of aboveground biomass per hectare, by country, for coniferous species and non-coniferous species, can be derived using statistics provided in ECE/FAO (1992). Most temperate and boreal countries have their own national estimates of biomass densities for forests which should be used. These default values are very rough estimates and are provided for comparison only.

Immediate emissions from burning

The biomass that is cleared has one of three immediate fates:

1. a portion may be burned on site;
2. a portion may be removed from the conversion site and used as fuelwood or for products;
3. a portion is converted to slash, and decays on site to CO_2 over a decade or so. Some estimates in the literature suggest that a global average of about 50 per cent of the cleared biomass is burned in the first year with the remaining 50 per cent left to decay (e.g., Houghton, 1991; and Crutzen and Andreae, 1990). This value could be used as a default for first order calculations if the user does not have access to more appropriate local information. It is important to recognise that this average is dominated by practices in tropical America which has the largest current rate of deforestation. There are certainly wide variations in burning practices between and within regions. It is **highly recommended** that, for final inventories, users provide their own values reflecting practices and burning conditions in the regions of interest, rather than using the global default value. To calculate the gross amount of carbon released in the current year to the atmosphere it is necessary to consider the burned portions and the decaying portion over different time horizons.

When a forest is cleared for pasture or agriculture use not all trees are cut; some of them are left standing live. The carbon in these remaining trees needs to be considered in emission calculations.

To estimate the CO_2 released by the burning of cleared aboveground vegetation, estimate (a) the fraction of the affected biomass that is subjected to burning (the remaining, disturbed biomass is slash) and (b) the fraction of the burned biomass that is oxidised. The fraction of burned biomass which does not oxidise remains as charcoal. The amount of biomass oxidised is converted to carbon units to estimate the carbon flux from burning.[22] A reasonable average for converting from dry biomass to carbon content is to multiply dry biomass by 0.50.[23] Of the portion of cleared biomass which is burned, some of this may be burned in the field to facilitate clearing, and some may be removed and used as fuel. The portion which is burned in the field is used subsequently for calculating the non-CO_2 trace gas emissions from open burning of cleared biomass, in the next section. The amount removed for fuel is important for calculations of fuel wood extracted from *forest and other woody biomass stocks* as described earlier in these basic calculations.

Emissions from decay

The aboveground biomass which remained on site but was not burned is estimated to oxidise in roughly a decade, and this historical release associated with land clearing must be considered. The 10-year period is a recommended default value, as a reasonable historical horizon in light of the twin realities of data availability and biological dynamics (see Houghton, 1991; and Crutzen and Andreae, 1990). This can be varied if the user has data or a strong rationale to suggest that a longer or shorter average decay time is more representative of local conditions. The "committed" flux calculation simply accounts for the current oxidising of material left unburned during the specified historical decay period.

The decay phenomenon can be simply characterised for emissions estimation purposes. Each year, some portion of the cleared aboveground biomass is left as slash, and we assume that 10 per cent of this decomposes each year, based on the default 10 year period. Therefore, the total carbon being released to the atmosphere in the Inventory Year is a function of the land clearing rate for each of the past 10 years, and the portion of the aboveground carbon remaining on site but not combusted each year. The current year emissions from decay of biomass cleared in a historical year would be 10 per cent of the total decay. The total current emissions from decay of historically cleared biomass would then be the sum of the current estimated emissions from biomass cleared in each of the ten historical years.

To simplify the calculations, the methodology uses decade average values for the land clearing and portion left to decay. Working with average values, one would divide the total emissions from decay by 10 to get the contribution of one "average" historical year's clearing to current emissions, then multiply by 10 to account for ten historical years' clearing which could be expected to affect current emissions. Obviously the division by 10 and multiplication by 10 cancel each other and can be ignored. Therefore, the flux in the Inventory Year from aboveground vegetation decay due to current and historical land clearing is simply expressed in Equation 2.

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[22] As discussed elsewhere in these *Guidelines* this method counts the carbon actually emitted as CO and CH_4 as though it were carbon dioxide. Later in this chapter, these emissions of CO and CH_4 will also be estimated separately.

[23] The range most cited is 0.43-0.58; hence it is suggested that 0.5 is the appropriate default assumption.

EQUATION 2

average annual land clearing over the period (default of 10 years)

x

the average quantity of aboveground dry biomass per hectare remaining on site as slash but not burned (either oxidised or converted to charcoal)

x

carbon content of dry biomass

=

flux in the Inventory Year from historical land clearing of the aboveground vegetation

Soil carbon release

For calculating the annual CO_2 flux associated with the loss of soil organic carbon following forest clearing or grassland conversion, the methodology is described in Section 5.3 for all types of transitions, and will not be described further here.

Burning of Forests: Non-CO_2 Trace gases

Where there is open burning associated with forest clearing (or other land-use change), it is important to estimate the emissions of methane (CH_4), carbon monoxide (CO), nitrous oxide (N_2O), and oxides of nitrogen (NO_x, i.e., NO and NO_2). The approach is essentially the same as that used for non-CO_2 trace gases for all burning of unprocessed biomass, including savanna burning and field burning of crop residues. For these activities there is a common approach in the proposed methodology in that crude estimates of trace gas emissions can be based on ratios to the total carbon released by burning. The carbon trace gas releases (CH_4 and CO) are treated as direct ratios to total carbon released. To handle nitrogen trace gases, ratios of nitrogen to carbon in biomass are used to derive total nitrogen released from burning, and then emissions of N_2O and NO_x are based on ratios to total nitrogen release. Table 5-7 provides suggested default values for trace gas emission ratios.[24] These are presented with ranges which emphasise their uncertainty. However, the basic calculation methodology requires that users select a best estimate value.[25]

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[24] The emission ratios used in this section are derived from Crutzen and Andreae, (1990), Delmas, (1993) and Lacaux et al., (1993). They are based on measurements in a wide variety of fires, including forest and savanna fires in the tropics and laboratory fires using grasses and agricultural wastes as fuel. Research will need to be conducted in the future to determine if more specific emission ratios, e.g., specific to forest fires, can be obtained. Also, emission ratios vary significantly between the flaming and smouldering phases of a fire. CO_2, N_2O, and NO_x are mainly emitted in the flaming stage, while CH_4 and CO are mainly emitted during the smouldering stage (Lobert et al., 1990). The relative importance of these two stages will vary between fires in different ecosystems and under different climatic conditions, and so the emission ratios will vary. As inventory methodologies are refined, emission ratios should be chosen to represent as closely as possible the ecosystem type being burned, as well as the characteristics of the fire.

[25] Emissions inventory developers are encouraged to provide estimates of uncertainty along with these best estimate values where possible, or to provide some expression of

All of the crude biomass burning calculations have two steps: 1) estimating total carbon released, and 2) applying emission ratios to estimate emissions of the non-CO_2 trace gases. In the case of burning of cleared forests (and other land conversion if appropriate), step 1 has been carried out in the previous section which included the estimation of carbon emissions from the portion of biomass from conversions which is burned **on site** in the Inventory Year. The total carbon release from this on site burning (not including any carbon released from decay or soils) provides the basis for the Inventory Year release of non-CO_2 trace gases. To complete the calculations, it is necessary only to add step 2 of the calculation – the release of non-CO_2 trace gases from current burning.

TABLE 5-7
EMISSION RATIOS FOR OPEN BURNING OF CLEARED FORESTS

Compound	Ratios	
CH_4	0.012	(0.009 - 0.015) [a]
CO	0.06	(0.04 - 0.08) [b]
N_2O	0.007	(0.005 - 0.009) [c]
NO_x	0.121	(0.094 - 0.148) [c]

Sources: [a] Delmas, 1993
[b] Lacaux et al., 1993
[c] Crutzen and Andreae, 1990

Note: Ratios for carbon compounds, i.e., CH_4 and CO, are mass of carbon compound released (in units of C) relative to mass of total carbon released from burning. Those for the nitrogen compounds are expressed as the ratios of emission (in units of N) relative to total nitrogen released from the fuel.

Once the total carbon released from on site burning of cleared biomass has been estimated, the emissions of CH_4, CO, N_2O, and NO_x can be calculated (Crutzen and Andreae, 1990). The total carbon released due to burning is multiplied by the emission ratios of CH_4 and CO relative to emissions of total carbon to yield total emissions of CH_4 and CO (each expressed in units of C). The emissions of CH_4 and CO are multiplied by 16/12 and 28/12, respectively, to convert to full molecular weights.

To calculate emissions of N_2O and NO_x, first the total carbon released is multiplied by the estimated N/C ratio of the fuel by weight (0.01 is a general default value for this category of fuel (Crutzen and Andreae, 1990)) to yield the total amount of nitrogen (N) released. The total N released is then multiplied by the ratios of emissions of N_2O and NO_x relative to the total N released from the fuel to yield emissions of N_2O and NO_x (expressed in units of N). To convert to full molecular weights, the emissions of N_2O and NO_x are multiplied by 44/28 and 46/14, respectively.[26]

The trace gas emissions from burning calculation are summarised as follows:

- CH_4 Emissions = (carbon released) x (emission ratio) x 16/12

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the level of confidence associated with various point estimates provided in the inventory. Procedures for reporting this uncertainty or confidence information are discussed in the *Reporting Instructions.*

[26] The molecular weight ratios given above for the emitted gases are with respect to the weight of nitrogen in the molecule. Thus for N_2O the ratio is 44/28 and for NO_x it is 46/14. NO_2 has been used as the reference molecule for NO_x.

- CO Emissions = (carbon released) x (emission ratio) x 28/12
- N_2O Emissions = (carbon released) x (N/C ratio) x (emission ratio) x 44/28
- NO_x Emissions = (carbon released) x (N/C ratio) x (emission ratio) x 46/14

5.2.4 Abandonment of Managed Lands

If managed lands, e.g., croplands and pastures, are abandoned, carbon may re-accumulate on the land and in the soil. In this section, only the carbon accumulation in biomass is considered; accumulation in the soil, as organic carbon, is dealt with in Section 5.3. The response of these converted systems to abandonment depends upon a complex suite of issues including soil type, length of time in pasture or cultivation, and the type of original ecosystem. It may be that some of the abandoned agricultural lands are too infertile, saline, or eroded for regrowth to occur. In this case, either the land remains in its current state or it may further degrade and lose additional organic material (i.e., carbon in the biomass and the soils). Therefore, to calculate changes in carbon flux from this activity, the area abandoned should first be split into parts: lands that re-accumulate carbon naturally, and those that do not or perhaps even continue to degrade.

In the basic calculation, only those that begin to return to an approximation of their previous natural state are considered. Those that remain constant with respect to carbon flux can be ignored. Likewise, the CO_2 flux to the atmosphere for those lands that continue to degrade is likely to be small on a global basis and hence is ignored in the initial application of basic calculations. In some countries, abandoned lands which degrade may be a significant problem and could be an important source of CO_2 emissions. Where lands continue to degrade, both aboveground biomass and soil carbon may decline rapidly, e.g., due to erosion. However, carbon in eroded soil could be re-deposited in rivers, lakes, or other lands downstream. For countries which have significant areas of such lands this issue should be considered in a more refined calculation.

Abandoned lands must be evaluated in the context of the various natural ecosystems originally occupying them. In addition, the effect of previous patterns of abandonment should be considered while recognising the desire for simplicity and practicality. The process of recovery of aboveground biomass generally is slower than the human-induced oxidation of biomass. With this in mind and in consideration of possible data sources it is recommended that abandoned lands be evaluated in two time horizons. A twenty year historical time horizon is suggested to capture the more rapid growth expected after abandonment. A second time period – from 20 years after abandonment up to roughly 100 years – may be considered if data are available.[27]

The calculation, by original ecosystem is straightforward. To estimate gains in biomass carbon stocks the total area abandoned (total over the previous 20 years including the Inventory Year) is multiplied by the average annual uptake of carbon in the aboveground biomass. If landuse data are available to support calculations over a longer time horizon, national experts may want to consider adding a pool of forests and grasslands that are

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[27] It is clear that most forest systems will take longer than 100 years to return to the level of biomass contained in an undisturbed state. If data are available, it is possible to calculate carbon sinks from regrowth on lands abandoned more than 100 years prior to the Inventory Year. As a practical matter, however, it is unlikely that such data will be available in most countries, or that the magnitude of annual carbon accumulation would be large. Therefore, it is not generally recommended to carry these calculations back more than the specified period of 100 years.

regrowing from abandonment that occurred more than 20 years ago. The growth rates of aboveground biomass in these forests would be slower than those of forests regrowing from abandonment that occurred less than 20 years ago. The same calculations can be repeated for lands abandoned for more than 20 years and up to about 100 years prior to the Inventory Year.

Table 5-2 presents estimates of average annual aboveground biomass accumulation in vegetation in various regrowing forest ecosystems following abandonment of cultivated land or pasture[28]. These general growth rates, averaged over large regions and many specific ecosystem types, should be considered only approximations as applied to the particular lands regrowing in a given region or country. If more accurate data on these growth rates are locally available, they should be used. If lands are regenerating to grassland, then the default assumption is that no significant changes in aboveground biomass occur. This can be varied based on locally available data. Accumulation of aboveground dry biomass can be converted to carbon using a general default conversion value for biomass of 0.5 t C/t dm.

5.3 CO_2 Emissions and Uptake by Soils from Land-Use Change and Management

5.3.1 Overview

The principal sources/sinks of CO_2 in soils are associated with changes in the amount of organic carbon stored in soils. Release of CO_2 also occurs from inorganic sources, either from naturally occurring carbonate minerals or from applied lime. CO_2 flux from weathering of native carbonate minerals is not a significant source in most agricultural soils, with the possible exception of irrigated arid and semi-arid soils (Schlesinger, 1986). This section focuses on a methodology to estimate net fluxes of CO_2 due to changes in soil organic carbon stocks. CO_2 releases from liming applications are also dealt with.

Fundamentally, changes in organic carbon content are a function of the balance between inputs to soil of photosynthetically-fixed carbon and losses of soil carbon via decomposition. Soil erosion can also result in the loss (or gain) of carbon locally, but the net effect of erosion on carbon losses as CO_2 for large areas on a national scale is unclear and demands separate consideration.

For soils, both the quantity and quality of organic matter inputs and the rate of decomposition of soil organic carbon will be determined by the interaction of climate, soil and landuse/management (including land-use history). In native ecosystems, climate and soil conditions are the primary determinants of the carbon balance, because they control both production and decomposition rates. In agricultural systems, landuse and management act to modify both the input of organic matter via residue production, crop selection, fertilisation, harvest procedures, residue management and the rate of decomposition (by modifying microclimate and soil conditions through crop selection, soil tillage, mulching, fertilisation, irrigation and liming).

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[28] Values given in Table 5-2 assume linear regrowth of aboveground biomass in each of the two time periods (0-20 years and 21-100 years). In reality, as shown in Brown and Lugo (1990), the regrowth in tropical forests is closer to a logistic function. The calculation could be improved by breaking the 20 year period into finer segments, assuming availability of data, to determine a weighted average.

Estimates of CO_2 fluxes can be made in two ways: (1) by direct measurement of CO_2 flux, and (2) indirectly, through balance estimates of the net change in carbon stocks of the soil.

Direct estimates of CO_2 influx, through photosynthesis, and CO_2 efflux, through decomposition and respiration, are difficult to obtain for several reasons: both exhibit large diurnal, short-term and seasonal variations requiring near continuous measurements to derive annual estimates; different components of the overall fluxes operate on very different time scales (e.g., plant respiration vs. mineralisation of recalcitrant organic matter); and the magnitudes of influxes and effluxes of CO_2 are large relative to their difference. The most practical means of directly measuring net CO_2 fluxes for whole ecosystems is by using micrometeorological techniques, which are costly and time-consuming. Such measurements for agricultural ecosystems are scarce.

Balance estimates of CO_2 emissions from soils due to land use are based primarily on field studies of changes in soil carbon occurring over several years, from repeated measures of soil carbon in experimental plots or in sites representing a chronosequence, e.g., sites that had experienced a change in land use or management at different times prior to sampling. Such information, coupled with laboratory experiments, has been used to develop statistical and simulation models of soil carbon change as a function of climate, soil and land-use and management factors. At the present time, we deem a carbon balance-based approach as the most feasible alternative.

5.3.2 Description of a Carbon Balance Methodology

The most rigorous approach to estimating net changes in soil carbon would be to calculate inputs and outputs of carbon for a particular ecosystem and from the difference calculate the annual net change in carbon storage. To integrate the various factors determining the quantity and quality of carbon entering the soil as well as the decomposition rates of soil organic carbon, a simulation model can be used. This kind of an approach has recently been used at large spatial scales (i.e., regional and country-level) to estimate changes in carbon stocks in agricultural soils in the United States (Donigian et al., 1994, Lee et al., 1993, Paustian et al., submitted) and Canada (Smith et al., in press, Dumanski et al., submitted). Similar applications have been made at regional and global scales to evaluate potential responses of soil carbon to global climate change (Jenkinson et al., 1991, King et al., 1996, Potter et al., 1993, VEMAP, 1996). However, these applications have used relatively complex research models, requiring large numbers of simulation runs and sophisticated computer resources such as geographic information systems to manage large amounts of input data. Moreover, the models have not been extensively tested for many agricultural systems, particularly in the tropics. Thus, it is our opinion that a "model-based" approach would not be feasible at the present time. However, we feel this kind of an approach is a priority for further development and could be incorporated in future inventory methodologies.

The current method employs an accounting approach based on estimating soil carbon stocks and areas for major categories of agricultural land-use/management systems. A similar approach has been used in an assessment of the carbon balance for the agricultural sector in the former Soviet Union (Kolchugina and Vinson, 1996). The fundamental principle in this approach is that after many years under a particular form of land use, soil carbon levels tend towards an equilibrium state where carbon inputs from plant residues and losses of carbon through decomposition roughly balance. A new steady state balance is more rapidly reached in hot humid climates but the time to equilibrium can be much slower in cool and/or dry climates. Hence net fluxes of CO_2 can be associated with changes in soil carbon stocks as a unit area of land transitions from one form of land use and management to another.

Since climate and soil type are major determinants of the kinds of management systems employed, as well as the potential stocks of soil carbon and their responses to management, the inventory approach is based on a classification according to eight major climate regions and six major soil types.

5.3.3 Climate Categories

Eight broad climatic regions are defined for inventory purposes. Climate will have an overriding effect on land use, management and cropping practices and a significant effect on soil carbon levels. Major soil taxonomic groups will to some degree co-vary with climate regions. The eight climate regions chosen are: 1) cold temperate, dry, 2) cold temperate, moist, 3) warm temperate, dry, 4) warm temperate, moist, 5) tropical, dry 6) tropical moist (with long, dry season), 7) tropical moist (with short, dry season), and 8) tropical, wet. These regions were chosen largely on the basis of major constraints on crops and cropping practices.

The cold thermal regime in the temperate zone represents areas with short growing seasons dominated by spring-sown cereals (e.g., wheat, barley, rye), root crops and perennial forages. The warm temperate zone is characterised by warmer summers and milder winters, which are favourable for over-wintering cereals (e.g., winter wheat) and for heat-demanding crops such as maize and soybeans. In the tropical zone, low temperatures are not generally a constraint on crop growth.

The moisture regimes are intended to coincide with major differences in management as a function of moisture availability. In the dry temperate zone, moisture limits the potential for continuous cropping, thus summer fallowing is widespread and drought-tolerant crops are required. Irrigation, where available, is an important management practice. In the temperate, moist zone, precipitation is sufficient for cropping every year, summer fallowing is not generally practised and irrigation is mainly used for speciality crops. Moisture regimes in the tropics can be roughly classified by amounts of precipitation and length of the dry season. The dry tropics receive less than 1000 mm of precipitation, with a highly seasonal distribution and prolonged dry seasons. Agricultural systems are mainly extensive and subsistence-based, with grazing being an important component. Diverse and highly productive systems exist where irrigation is possible. The moist tropics are divided into two classes, both having annual precipitation in the range of 1000-2000 mm, but with classes having a prolonged dry season (> 5 months) versus short dry seasons (<5 months). Management systems become increasingly intensive as precipitation increases and is more evenly distributed. The wet tropics are classified as areas receiving >2000 mm per year. In this zone, production systems are mainly limited by fertility factors due to the preponderance of highly weathered soils.

5.3.4 Soil Categories

A stratification of up to six major soil groups is proposed, based on major differences in their inherent carbon stocks and their response to management. The soil groups chosen are:

TABLE 5-8
SOIL TYPE CLASSIFICATIONS

Soil Type	Examples for major FAO soil taxonomic groups	Examples for major USDA soil taxonomic groups
High clay activity mineral soils	Vertisols, Chernozems, Phaeozems, Luvisols	Vertisols, Mollisols, high-base status Alfisols
Low clay activity mineral soils	Acrisols, Nitosols, Ferralsols	Ultisols, Oxisols, acidic Alfisols
Sandy soils	Arenosols, sandy Regosols	Psamments
Volcanic soils	Andosols	Andisols
Aquic soils (wet soils)	Gleysols	Aquic suborders
Organic soils	Histosols	Histosols

The strong effect of texture and clay mineralogy on organic matter contents has been well demonstrated in both temperate and tropical regions. Thus we distinguish four major soil groups according to these criteria. Soils with high clay activity are defined as having appreciable contents of high activity clays (e.g., 2:1 expandable clays such as montmorillonite) which are implicated in the long-term stabilisation of soil organic matter, particularly in many carbon-rich temperate soils (Martel and Paul, 1974). Soils with low clay activity are defined as soils with low activity clays (e.g., 1:1 non-expandable clays such as kaolinite and gibbsite and hydrous oxide clays of iron and aluminium) which have a much lower ability to stabilise organic matter (Trumbore, 1993) and faster responses to changes in the soil's carbon balance (Tiessen et al., 1994). Among these are included highly-weathered acid soils of subtropical and tropical regions. Sandy soils are defined as soils having less than 8 per cent clay and greater than 70 per cent sand, which generally have poor structural stability and a low capacity to stabilise carbon. These coarse-textured soils can occur in many of the major taxonomic soil classes. The Andosol soil group includes soils derived from volcanic materials, with allophane as the primary colloidal mineral. These soils are generally rich in carbon and highly fertile.

The other two soil groups are distinguished on the basis of drainage and soil water status. Aquic soils are defined as mineral soils which have developed in poorly-drained, wet environments resulting in reduced decomposition rates and high organic matter contents. If artificially drained for agriculture they are subject to large losses of carbon. Histosols or peat soils are organic soils which form under water-saturated conditions where decomposition is greatly reduced. They can lose massive amounts of carbon over a sustained period upon drainage and cultivation.

5.3.5 Soil Carbon Responses to Agriculturally-Related Practices

Land-use practices affect soil carbon stocks by modifying carbon inputs to soil as well as the decomposition rate of soil organic matter. The most important kinds of management practices, from the standpoint of their effects on carbon levels, are briefly described.

Land clearing from native vegetation

The clearing of native vegetation (e.g., forests, savanna, grassland, wetlands) to agriculture almost invariably leads to a reduction in soil carbon as a result of decreased carbon inputs and enhanced decomposition from the disturbed soil. This has been well documented for temperate (Haas et al., 1957; Kononova, 1966; Dalal and Mayer, 1986; Paul and van Veen, 1978) as well as tropical (Nye and Greenland, 1960; Detwiler, 1986; Brown and Lugo, 1990) environments. Generally, the majority of the losses occur within the first few (< 10) years, particularly in the tropics (Detwiler, 1986), although slower declines in soil carbon can continue for many decades in organic matter rich soils, particularly in temperate regions (Tiessen et al., 1982; Rasmussen and Rohde, 1988). Erosion (by wind and water) can be a significant factor in carbon losses (and redistribution) locally, but the present inventory methodology does not account for effects of erosion on net CO_2 fluxes. Currently conversion of native vegetation to agricultural uses is occurring almost exclusively in the tropics.

The magnitude of soil carbon decline can vary according to native vegetation, climate, soil type, land clearing method, and subsequent management. Several reviews of the literature (Schlesinger, 1986; Mann 1986; Detwiler 1986) show losses of 20-40 per cent or more of the original soil carbon stock following cultivation. Mann (1985) reported an average of 40 per cent lower carbon contents in cultivated vs. uncultivated soils (0-15 cm), from a sample of more than 300 temperate forest- and grassland-derived soils. Davidson and Ackerman (1993) analysed soil carbon inventories, from paired comparisons including both concentration and bulk density changes. They reported average reductions in soil carbon stocks of about 40 per cent for the surface (A) horizon and about 30 per cent for the top 30 cm.

Clearing of native vegetation and conversion directly to pasture can result in lower carbon losses compared to clearing for cultivation. After initial decreases following forest clearance, soil carbon may even increase under pasture to levels comparable to pre-clearance levels within 10 years (Cerri et al., 1991; Eden et al., 1991; Lugo and Brown, 1993). With improved management (fertiliser and moderate grazing), high soil carbon levels may be sustainable over longer periods. However, unmanaged and overgrazed pastures are likely to decline in productivity and be subject to erosion and soil degradation, and subsequent decreases in soil carbon (Eden et al., 1991).

Conversion of cultivated land to perennial vegetation and shifting cultivation

In most cases, land that has been cultivated for many years is depleted in organic matter relative to its original state. If converted to perennial vegetation, either through land abandonment and natural succession or as an active management decision (e.g., conversion to pasture, land set-asides for conservation practices), soil carbon levels generally increase. An exception is where the land has been degraded to the extent that productivity is permanently impaired in which case soil carbon levels may decline further.

In the temperate zone, considerable areas of formerly cultivated lands have been abandoned or converted to grassland and forest, particularly in North America and

Europe. Agricultural set-aside programmes have also been implemented in North America and Europe during recent years. The rate of increase and the level at which soil carbon is eventually stabilised on these lands will depend on productivity levels and soil conditions. Low rates of carbon accrual, 0.05-0.15 tonnes C/ha/yr over 25-50 year periods, have been reported for abandoned fields in semi-arid regions of the United States and Canada (Dormaar and Smoliak, 1985; Burke et al., 1995). For land set aside planted to perennial grasses and then left unmanaged, Paustian et al. (submitted) estimated rates of carbon increase ranging from 0.05-0.30 tonnes C/ha/yr, for semi-arid to sub-humid regions in the central United States. Higher rates of 0.25-0.50 tonnes C/ha/yr, averaged over an 80 year period, have been reported for abandoned fields under more mesic conditions, in the UK (Jenkinson , 1971a). For managed conversions to improved pastures, much higher rates of 0.75-1.0 tonnes C/ha/yr, for 15-20 years, have been achieved (Tyson et al., 1990; Haynes et al., 1991). Improved management of subtropical and tropical grasslands, with the incorporation of legumes, fertilisation and control of burning have been shown to increase soil carbon levels (Greenland, 1995). Recent data also suggest the potential for substantial C sequestration in tropical grasslands with the use of deep-rooting exotic grasses (Fisher et al., 1994).

In the tropics, abandonment of land occurs as an integral phase of shifting cultivation. Shifting cultivation systems are characterised by a cycle of forest or bush clearing, followed by a few years of cropping and then abandonment to natural revegetation (fallow). Soil carbon is rapidly lost during the cropping phase and re-accumulates during fallow. In a study of six slash-and-burn chronosequences in Southern Cameroon, Woomer et al. (submitted) report the loss of 8 tonnes C/ha from soils (0-40 cm) within two years of forest conversion. Soil organic matter losses continued into the early fallow but the initial levels of 77 tonnes C/ha were re-established within the secondary forest after approximately 18 years. The mean soil carbon stocks maintained under shifting cultivation depend on the carbon lost during the cropping phase, the rate of accumulation under fallow and the length of fallow (Nye and Greenland, 1960). The length of the fallow period varies depending on climate, soil, vegetation type, land scarcity, and human population pressure.

Recovery of soil carbon during the fallow phase can be rapid (Greenland and Nye, 1959). In North-east Brazil, Tiessen et al. (1992) reported recoveries to native soil carbon levels after about 10 years of bush fallow (following a 5-6 year cultivation cycle), by which time vegetation had not nearly attained native size or composition. Global estimates of carbon fluxes assume that 75 per cent (Houghton et al., 1987) to 90 per cent (Palm et al., 1986) of the original carbon stocks from deforested soils are recovered with forest succession. Abandonment which leads to the establishment of degraded or unimproved grasslands, such as the extensive areas of Imperata in South-east Asia, has been assumed to result in incomplete recovery (50 per cent) of original carbon stocks (Palm et al., 1986). However, other data suggest little difference between soil carbon inventories under Imperata vs. secondary forest (van Noordwijk et al., submitted). The discrepancies in data on the carbon content of Imperata grasslands may be partly due to differences in fire frequency. Imperata grasslands without fire build up reasonable stocks of soil carbon, but frequent burning may lead to serious soil degradation. The rapid invasion of Imperata into crop fields after forest conversion in the humid parts of Asia probably slows down further carbon losses, as compared to other areas where cultivation is continued. Lugo et al. (1986) found carbon stocks for pastures derived from abandoned cultivated lands in Puerto Rico to have similar or higher levels than in secondary forests. Differences in soil fertility are also important in that infertile soils are less prone to a build up of soil C upon abandonment. Large spatial variability in soils, varying sample depths, patchiness of vegetation regrowth and whether or not litter mats are included in soil C inventories make it difficult to compare field studies.

Tillage

Intensive soil tillage is recognised as a significant factor causing soil organic matter declines in cultivated soils. Intensive tillage, particularly with soil inversion (e.g., moldboard ploughing), enhances decomposition by releasing organic matter protected within soil aggregates and by increasing soil temperature. Reduced tillage, and particularly no-till practices, have been shown to promote higher levels of organic matter in many systems, where productivity and organic matter inputs are not adversely affected. An analysis of 28 paired comparisons from no-till versus full tillage treatments in 19 long-term experiments in Canada, Europe and the United States showed mean increases under no-till of 0-30 % C, with an average of about 10 per cent (Paustian et al., 1997). The duration of the experiments ranged from 5 to 20 years. These data were normalised to compare equivalent soil mass (to below the depth of ploughing ca. 20-30 cm), in order to eliminate effects of changes in bulk density and differences in organic matter distribution with depth.

Experiments in the tropics have also demonstrated the potential for no-till systems to maintain higher soil carbon levels compared to conventional cultivation (Lal, 1986a). Reduced soil erosion and lower soil temperatures with surface mulches under no-till are particularly important attributes of no-till systems in the tropics (Lal, 1986a; Fernandes et al., submitted). Higher levels of carbon in no-till compared to cultivated treatments have been reported in a number of studies (Agboola, 1981; Jou and Lal, 1979; Aina, 1979). Jou and Lal (1979) reported nearly two times higher carbon contents in no-till vs. ploughed treatments in the top 10 cm (and no significant differences below 10 cm) under maize.

Residue inputs, mulching, cover crops

Maintenance of soil carbon depends on an adequate return of organic substrates which serve as the raw material for organic matter formation. In most agricultural systems, the primary sources of new carbon are crop residues, including roots, root exudates, and unharvested above-ground plant parts (e.g., straw or stover). The amount of carbon returned in the form of residues depends on the total biomass yield (including roots and related materials) and the proportion of that biomass which is exported from the field. Of the carbon applied to soil in the form of crop residues, about one third typically remains after one year and about one fifth remains after five years under temperate conditions (Jenkinson, 1971b). The remainder is returned to the atmosphere as CO_2 via biological decomposition. The rate of decomposition, and the proportion of carbon retained by soil, is influenced by climate, soil conditions, placement (surface versus buried), and the composition of the residue (Andrén et al., 1989).

Some agricultural soils also receive significant inputs in the form of vegetation grown, at least in part, to provide additional carbon and other nutrients to the soil. For example, legumes are sometimes included in cropping systems as a 'green manure'. Similar benefits are derived from vegetative additions in 'alley-cropping' systems.

A third source of carbon is various by-products which are applied as soil amendments. The most noteworthy of these are animal manure, but some soils also derive appreciable carbon inputs from sewage sludge and various industrial by-products. Although such additions can significantly increase soil carbon, gains in the soil must, from an atmospheric balance perspective, be compared with alternative uses of the resources. For example, if sewage sludge decomposes more rapidly in soil than in storage, the net effect will be an additional flux of carbon to the atmosphere.

Management practices which promote greater rates of return of crop residues or other organic amendments will result in increased soil carbon stocks. According to current theories of soil organic matter dynamics, there should be a linear relationship between changes in carbon inputs and soil carbon levels (Greenland, 1995; Paustian et al., 1995);

this relationship is supported by a number of long-term field studies (Paustian et al., 1997). In temperate zone cropping systems, carbon inputs can be increased through residue retention, cover crops, reduced summer (bare) fallow, rotations with perennial forage crops, and all practices that increase crop production and residue yields. In the tropics, these practices and others, including improved fallows, mulching and agroforestry, can increase carbon additions to soil (Lal, 1986b).

5.3.6 Management Categories

The estimate of CO_2 fluxes is based on inventorying the areas and C stocks for land-use systems predominating within a particular climatic region. As described above, the most significant practices that differentiate land-use and management systems are:

- clearing of native vegetation with conversion to cultivated crops or pasture;
- land abandonment;
- shifting cultivation;
- differing residue addition levels;
- differing tillage systems; and
- agricultural use of organic soils.

Criteria for defining management systems are that the distribution of land areas between the selected systems have changed over the past 20 years and that the systems differ significantly in their soil carbon stocks.

The recommended procedure is that country experts define and document an appropriate classification of systems for use in their inventory. A classification of land-use systems is included which can serve as an example for development of country-specific classifications. (See Module 5 for detailed description of land-use systems.) These classes are intended to be sufficiently general that they may be applicable in most countries and include systems that are likely to have significantly different C stocks, based on soil C responses to agricultural practices. Non-agricultural systems (e.g., forest, grassland) should be subdivided into categories on the basis of differences in soil carbon stocks (as well as soil and climate regimes). Organic soils that have been converted to agricultural use are considered separately (see Section 5.3.9).

TABLE 5-9
EXAMPLES OF MAJOR LAND-USE/LAND MANAGEMENT SYSTEMS WITHIN THE MAJOR CLIMATE DIVISIONS

Climate Division	Land-use System
Cold temperate, dry	Rangeland (unimproved) Small grain with summer-fallow Small grain with continuous cropping - conventional tillage Small grain with continuous cropping - no till Small grain/forage rotations Hay/improved pasture Successional grasslands Irrigated croplands
Cold temperate, moist	Forest Small grain monocultures Grain/root crop/perennial forage rotations Permanent pasture Forest/grassland set-aside
Warm temperate, dry	Rangeland (unimproved) Small grain with summer fallow Small grain/legume rotations with summer fallow Small grain with continuous cropping - conventional tillage Small grain with continuous cropping - no till Small grain/forage rotations Successional grassland Irrigated cropland
Warm temperate, moist	Forest Pasture/hay Intensive grain production systems, stratified according to: - residue return rate (production level, frequency of perennial forages in rotation, cover crops) - tillage intensity (full inversion, reduced, no tillage) Speciality crops with low residue return Forest/grassland set-aside and reverted lands
Tropical, dry	Savanna Subsistence farming with drought-resistant grain crops Irrigated cropland
Tropical, moist (includes systems for both short and long dry season categories)	Forest/woodland Unimproved/degraded pasture Improved pasture Shifting cultivation/fallow rotation Mixed continuous cropping Mechanised continuous cropping Plantations Irrigated cropland (including rice)
Tropical, wet	Forest/Woodland Agroforestry/perennial multi-strata systems Upland food crop production Perennial monoculture plantations Shifting cultivation/fallow rotation Improved pasture Degraded pasture Wetland (paddy) rice

5.3.7 Suggested Methodology for CO_2 Flux from Agricultural Soils

Three potential sources of CO_2 emissions from agricultural soils are included in the inventory. These are 1) net changes in organic carbon stocks of mineral soil associated with changes in land use and management, 2) emissions of CO_2 from cultivated organic soils (i.e., Histosols) and 3) emissions of CO_2 from liming of agricultural soils.

5.3.8 Changes in Mineral Soil Carbon Stocks

Inventory calculation period

Net carbon fluxes are calculated on the basis of changes in carbon stocks over a twenty-year period. For example, to calculate the inventory for 1990, land areas under each climate/soil/land-use class (Table 5-9) in 1970 and in 1990 are determined. Soil carbon values are then assigned to each class, and the summed differences in the total carbon stocks provide an estimate of the current net soil CO_2 flux. For mineral soils, only the top 30 cm are considered, which typically has the highest concentration of carbon and the greatest response to changes in management and landuse. In most soils, management effects on soil carbon at depth are minimal compared to changes that occur in the topsoil (Sombroek et al., 1993) and consequently most information on soil carbon responses to different management practices are limited to the upper soil horizons (0-30 cm depth).

The choice of a twenty-year period represents a compromise. The response time of a system to a change in management will differ according to a number of factors. Soil carbon approaches a new equilibrium more rapidly in the tropics compared to temperate soils. The rate of response to different practices also varies. For example, most of the loss of soil carbon following land clearing occurs within <10 yrs (Davidson and Ackerman, 1993). A build up of soil carbon, for example following land abandonment (Jenkinson, 1971a) or with increases in residue inputs, tends to occur more slowly, i.e., the approach to a new equilibrium value is more rapid for degrading systems than for aggrading systems. Thus, the longer the inventory period the closer systems will approach new equilibrium carbon levels. In general, however, the most rapid changes in soil carbon occur during the first 10-20 yrs following a significant change in management practices or land use. Furthermore, a long inventory period has two disadvantages. One is that past land-use information is likely to be less accurate and less available for further in the past. The second is that the balance approach carries an implicit assumption that the rate of land-use and management change over the period is constant. If rates of change are not linear with respect to time, there will be a bias in the estimates that increases with increasing the length of the assessment period. Twenty years was selected as an appropriate time period to include most of the change in carbon stocks resulting from land conversions to agriculture and most other management-induced changes in the tropics. To account for longer response times, such as for land abandonment in the temperate zone, it is recommended that one or more 'successional' system, having different soil carbon stocks, be defined (e.g., abandoned land for <20yrs and abandoned land >20yrs).

Soil carbon stock estimates

Carbon stock estimates should include the total organic carbon content to a depth of 30 cm as well as the carbon content of the surface litter mat, if present (e.g., in forests, grasslands, and pastures). Woody litter resulting from forest clearance should not be double counted as it is included in the inventory procedures in Forest and Grassland conversion (Section 5.2.2). Fresh crop residue in cultivated systems should not be counted. In no-till cropping systems, the minimum (over the year) surface residue loading should be included in the organic carbon stock.

The recommended option for assigning carbon stocks according to land management classes (within one or more of the six soil types) is that these be determined by experts in the participating countries. Where available, information from country soil surveys, field studies and long term agricultural experiments, as interpreted by knowledgeable soil scientists and agronomists, will provide the best estimates for these values. However, we have also provided a default methodology for estimating carbon stocks within predefined land-use/management categories (see Management Categories above), using estimates for carbon stocks under native vegetation derived from the FAO/USDA global soil carbon inventory (Eswaran et al., 1993).

Calculation procedures for mineral soils

The calculations for net CO_2-C emissions from mineral soils are straightforward and examples of their application are given in Table 5-10. Negative numbers represent a net decline in soil carbon stocks, hence a net emission or source of carbon to the atmosphere; positive numbers represent a net sequestration or sink of carbon in soil, over the 20-yr inventory period. To derive current net annual emissions the final total should be divided by 20. For the example shown, there is a net increase of carbon storage of 11.9 Tg over the 20-yr inventory period, thus annual net CO_2-C emissions for this example would be -0.595 Tg/yr, or a carbon sink.

Note: It is critical that the total area included in the inventory at time (t) and time (t-20) be identical. The area should represent at least all the land area of the country which has been subject to any significant changes in land-use and/or management practices over the past 20 years. An additional check should be made that the total area within each soil type is constant over the inventory period.

TABLE 5-10
EXAMPLE OF CALCULATIONS FOR NET CHANGE IN CARBON STORAGE IN MINERAL SOILS FOR A COLD TEMPERATE DRY REGION COUNTRY -
FOR SIMPLICITY ONLY FOUR MANAGEMENT SYSTEMS ARE INCLUDED

Landuse	Soil type	Soil Carbon (t C /ha)	Land Area (t-20) (Mha)	Land Area (t) (Mha)	C Stock (t-20) (Tg)	C Stock (t) (Tg)	Net change in Soil Carbon (Tg per 20 yr)
		[A]	[B]	[C]	[A x B]	[A x C]	[A x C] - [A x B]
Grassland (unimproved)	High activity	50	3.5	3.6	175	180	5
	Sandy	10	2.0	2.0	20	20	0
	Aquic	70	0.5	0.4	35	28	-7
Grain/summer-fallow with conventional tillage	High activity	33	4.0	2.8	132	92.5	-39.6
	Sandy	7	0.5	0.5	3.5	3.5	0
	Aquic	35	0	0	0	0	0
Grain/continuous with conventional tillage	High activity	40	2.4	3.0	96	120	24
	Sandy	-	0	0	0	0	0
	Aquic	45	0	0.1	0	4.5	4.5
Hay/improved pasture	High activity	50	1.5	2.0	75	100	25
	Sandy	-	0	0	0	0	0
	Aquic	-	0	0	0	0	0
Total			14.4	14.4	536.5	548.4	11.9

Default calculation procedures

If soil carbon stock estimates according to land-use and soil type are not available we have provided a procedure for estimating these. Estimates are based on global soils information (Table 5-11) compiled by the World Soils Resources division of the Natural Resources Conservation Service of the US Department of Agriculture (USDA), based on FAO and USDA soils information (Eswaran et al., 1993). These values serve as a first approximation and should not be considered as a preferable substitute for actual country-level data. Approximate organic carbon stocks are for the top 30 cm, in tonnes C/ha, under native vegetation. Histosols (peat soils) are considered in a separate calculation.

TABLE 5-11
APPROXIMATE QUANTITIES OF SOIL ORGANIC CARBON UNDER NATIVE VEGETATION
(TONNES C /HA TO 0-30 CM DEPTH)

Region	High activity soils	Low activity soils	Sandy soils	Volcanic soils (Andisols)	Wetland soils (Aquic)
Cold temperate, dry	50	40	10	20	70
Cold temperate, moist	80	80	20	70	180
Warm temperate, dry	70	60	15	70	120
Warm temperate, moist	110	70	25	130	230
Tropical, dry	60	40	4	50	60
Tropical moist (long, dry season)	100	50	5	70	100
Tropical moist (short, dry season)	140	60	7	100	140
Tropical, wet	180	70	8	130	180

To estimate soil carbon stocks by different agricultural land-use and management practices, we have compiled a set of coefficients to scale the carbon contents according to major management factors (Table 5-12). Estimates for the scaling factors were based on information from field studies, where available, and expert opinion. The database for these estimates is scanty, particularly from the tropics, and we emphasise that this default procedure is only intended as a first approximation and not as a substitute for country-level data where available. Carbon stock estimates are derived according to the formula:

$$\text{Soil Carbon}_{\text{managed}} = \text{Soil Carbon}_{\text{native}} \times \text{Base factor} \times \text{Tillage factor} \times \text{Input factors}$$

The base factor represents changes in soil organic matter associated with conversion of the native vegetation to agricultural use. Tillage and input factors account for effects of various management practices of lands in agricultural use. Thus these later two factors can be used to capture changes in management trends that have occurred over the inventory period. For example, a long-term cultivated high clay activity soil, under intensive (full) tillage and with low carbon inputs (e.g., straw removal) would be estimated to have 63 per cent (0.7 x 1 x 0.9) of the carbon content in a comparable uncultivated (native) soil. The same soil under no-till with high residue inputs (e.g., cover crops) would be estimated to have a carbon level equivalent to 85 per cent (0.7 x 1.1 x 1.1) of the native soil. Portions of the table where tillage and input factors are not given denote instances where these factors are not applicable to a particular management system or where information was deemed insufficient to go beyond estimating a base factor.

TABLE 5-12[a]
COEFFICIENTS USED IN DEFAULT CALCULATION PROCEDURES FOR ESTIMATING CARBON STOCKS IN MINERAL SOILS

System	SG[b]	BF[c]	Tillage Factor[d]			Input Factors[e]				
			No-tillage	Reduced tillage	Full tillage	Low input	Medium input	High input	Mature fallow	Shortened fallow
Temperate										
Long-term cultivated	A,B,C,D	0.7	1.1	1.05	1.0	0.9	1.0	1.1/1.2		
Long-term cultivated	E	0.6	1.1	1.05	1.0	0.9	1.0	1.1/1.2		
Improved pasture	All soils	1.1				ND	ND	ND		
Set aside (<20 years)	All soils	0.8				ND	ND	ND		
Set aside (>20 years)	All soils	0.9				ND	ND	ND		
Tropical										
Long-term cultivated	A,B,C,D	0.6	1.1	1.0	0.9	0.9	1.0	1.1/1.2		
Long-term cultivated	E	0.5	1.1	1.0	0.8	0.9	1.0	1.1/1.2		
Wetland (Paddy) rice	All soils	1.1	ND	ND	ND	ND	ND	ND		
Shifting cultivation (including fallow)	All soils	0.8	ND	ND	ND	ND	ND	ND	1.0	0.8
Abandoned/ Degraded land	All soils	0.5								
Unimproved pasture	All soils	0.7				ND	ND	ND		
Improved pasture	All soils	1.1				ND	ND	ND		

[a] Filled portions of the table, where tillage and input factors are not given, denote instances where these factors are not applicable to a management system. Where tillage or input factors were not determined (ND), information was deemed insufficient to go beyond estimating a base factor.

SG = Soil Group, BF = Base Factor

[b] Soil groups A = High activity, B = Low activity, C = Sandy, D = Volcanic, E = Aquic

[c] For temperate cultivated soils, the average loss of 30% (0.7) is based on paired profile comparisons by Mann (1985, 1986) and Davidson and Ackerman (1993). Greater losses for cultivation of wet (aquic) soils, relative to other mineral soils, are assumed due to artificial drainage and enhanced decomposition when cultivated (van Noordwijk et al., submitted). Conversion to paddy rice is assumed to slightly increase carbon contents (Greenland, 1985). Carbon levels in improved pastures can exceed native levels with fertilisation and species selection (Fisher et al., 1994, Cerri et al., 1994, Grace et al., 1994). Carbon under shifting cultivation (including the fallow phase) and abandoned degraded lands are based on estimates from Palm et al. (1986), Tiessen et al. (1992) and Woomer et al. (submitted).

[d] Use of no-till is assumed to increase soil carbon by 10% over full tillage (full soil inversion) in temperate systems, based on analysis of long-term experiments in Australia, Canada, Europe and the United States (Paustian et al., 1997); greater effects, over full tillage, are assumed for tropical systems (Aina, 1979, Juo and Lal, 1979, Agboola, 1981). Reduced tillage (i.e., significant soil disturbance but without inversion) is assumed to yield small increases over full tillage (Paustian et al., 1997).

[e] Input factors apply to residue levels and residue management, use of cover crops, mulching, agroforestry, bare fallow frequency in semi-arid temperate systems. Low input applies to where crop residues are removed or burned, or use of bare fallow; medium input to where crop residues are retained; high input applies to where residue additions are significantly enhanced with addition of mulches, green manure, or enhanced crop residue production (1.1) or regular addition of high rates of animal manure (1.2), relative to the nominal (medium) case. Based on temperate zone studies analysed by Grace et al. (1994) and Paustian et al. (1997), and tropical studies by Jones (1971), Wilson et al. (1982), Sidhu and Sur (1993), Lal et al. (1979, 1980), Mazzarino et al. (1993), Kang and Juo (1986), Inoue (1991), van Holm (1993) and reviews by van Noordwijk et al. (submitted) and Fernandes et al. (submitted).

5.3.9 Calculation of CO_2 Fluxes from Organic Soils

Conversion of organic soils to agriculture is normally accompanied by artificial drainage, cultivation and liming, resulting in rapid oxidation of organic matter and soil subsidence. The rate of carbon release will depend on climate, the composition (decomposability) of the organic matter, the degree of drainage and other practices such as fertilisation and liming. Unlike the situation with mineral soils, where carbon levels approach some new equilibrium following changes in land use/management, carbon losses from organic soils can be sustained over long periods of time, in principle, until the organic soil layer has been completely lost. As decomposition proceeds, the more recalcitrant organic matter fractions, having slower decomposition rates, will accumulate. This would tend to reduce CO_2 emissions over time. However, a compensating factor is that with tillage, less decomposed organic matter from below will be continually incorporated into the surface layer as it decomposes and the soil subsides. This process will tend to maintain high rates of CO_2 loss until much of the organic horizon is exhausted. Because of the variability in depth of organic soils, which in many cases is poorly known (Eswaran et al., 1993), a calculation procedure which incorporates the dynamic changes in the depth and the quality of organic matter in these soils was deemed unfeasible at present. Existing data on CO_2 emission rates from organic soils are typically given as rates per unit land area and this approach is used in the current methodology.

Use of organic soils for upland crops (e.g., grain, vegetables) gives greater carbon losses than for conversion to pasture or forests, due to deeper drainage and more intensive management practices (e.g., liming, cultivation) (Armentano and Verhoeven, 1990). Armentano and Menges (1986) estimated annual loss rates under crops to be 2.2 tonne/ha/yr in boreal regions (Finland, Russia), 7.9-11.3 tonne/ha/yr in temperate climates (USA and Western, Central and Eastern Europe, China, Japan) and 21.9 tonnes C/ha/yr in Florida and coastal California. Other data from Russian sources (references V.D. Skalaban, personal communication) suggest somewhat lower losses from cultivated organic soils in the boreal zone, on the order of 0.4-1.2 tonnes C/ha/yr. Estimates for annual losses under introduced pastures/forests ranged from 15-70 per cent, with most around 25 per cent, of the rate under crops. The rates recommended for inventory purposes are derived from these values. For tropical systems, there are fewer data although it is expected that rates should be generally higher compared to temperate zone soils due to sustained higher temperatures. The rate used for cropland (20 tonnes C/ha/yr) is twice that for the warm temperate zone, which is similar to the rates reported for subtropical Florida (21.9 tonnes C/ha/yr). We assume that loss rates from conversions to pasture are 25 per cent of those under cropland within each climate region. For the inventory, values are calculated on an annual basis.

5.3.10 CO_2 Emissions from Liming Agricultural Soils

Liming is commonly used to ameliorate soil acidification. Among the compounds used are carbonate containing minerals such as limestone $CaCO_3$ and dolomite $CaMg(CO_3)_2$. When added to acid soil these compounds release CO_2 in the bicarbonate equilibrium reaction. The rate of release will vary according to soil conditions and the compound applied. However, in most instances where liming is practised, repeated applications are made every few years. Therefore, for purposes of the inventory, we assume that the addition rate of lime is in near equilibrium to the consumption of lime applied in previous years. Emissions associated with use of carbonate limes can thus be calculated from the amount and composition of the lime applied annually within a country.

5.3.11 Total CO_2 Emissions from Agricultural Soils

Total annual emissions of CO_2, are calculated from i) net changes in carbon storage in mineral soil, ii) CO_2-C emissions from organic soils and iii) CO_2-C emissions from liming.

5.4 Refinements In Calculations

5.4.1 Introduction

There are a number of areas in which the basic calculations could be improved at least theoretically. Simplifying assumptions have been made in many places in order to produce methods consistent with data likely to be available in many countries. The basic calculations focus only on the most important categories for emissions of CO_2 within a much larger set of land-use and forest management activities having some impact on GHG emission fluxes. Some activities are known to result in GHG fluxes, but cannot be quantified based on the available scientific research results. Many of these issues are summarised below to assist users in considering which, if any, of these possible refinements could be included in national inventories, either currently, or in the future as scientific understanding improves.

The first section deals with the subcategories already discussed in the basic calculations, but highlights a number of ways in which these calculations could be augmented. The second section discusses additional categories of land-use change or forest management which could be added to the categories in the basic calculations.

5.4.2 Possible Refinements or Additions to Basic Categories

CHANGES IN FOREST AND OTHER WOODY BIOMASS STOCKS

Prescribed Burning of Forests: Non-CO_2 Trace Gases

The issue of prescribed forest burning is complex for two reasons. First, there is the question of the rate of change that humans have induced and second, there is the question of releases of trace gas several years after the burning. Prescribed burning is a method of forest management by which forests are intentionally set on fire in order to reduce the accumulation of combustible plant debris and thereby prevent forest fires, which could possibly be even more destructive. This activity is primarily limited to North America and Australia (Seiler and Crutzen, 1980). Because carbon is allowed to re-accumulate on the land after burning, no net CO_2 emissions occur over time, although emissions of CH_4, CO, N_2O, and NO_x result from the biomass combustion.

Some of the issues associated with prescribed forest burning, particularly in the temperate and boreal world, remain important research topics. Some have suggested that prescribed forest burning may be increasing carbon stocks in forests and hence serving as a CO_2 sink, but at the same time adding other radiatively important non-CO_2

trace gases to the atmosphere. An important issue is the change in burning rate because of human activity. Is prescribed burning, and its consequent emissions, just a man-made replacement for what would have occurred naturally? What is the rate change? If we assume that this question, the rate of change, can be answered, then the issue of trace gas release for prescribed burning is similar to trace gas emissions following forest clearing. This process is under evaluation in the development of the *Guidelines.*

The second complicating issue which should be considered is the release of non-CO_2 trace gases in years after burning. This is also discussed under *forest and grassland conversion* below. The same uncertainties apply here, although this may be a less important area for prescribed burning, because the forests will be regrowing quickly, and possibly overcoming the conditions which could cause longer term trace gas emissions.

Carbon Stock in Dead Organic Matter (excluding soil) of Forests

The quantity of carbon in litter, woody debris, belowground remains, and dry standing stems is a significant carbon reservoir in many of the world's forests. The present methodology does not account for any of these components, which could represent important carbon sink in regrowing forests after abandonment or logging or additional carbon sources when burned during forest clearing or fires. The role of dead organic matter in forest carbon budgets should be considered in future work on inventory methods.

Forest and Grassland Conversion

Forest clearing is a very complex and diverse set of activities which can have many interactions with biospheric fluxes of greenhouse gases over long periods of time. The components of this set of interactions which are included in the previous section are those on which there is general agreement among experts of their importance and simple estimation procedures. A number of other possible elements have been discussed in the scientific literature, but are controversial or difficult to calculate at present.

Emissions from Burning of Forests

A number of aspects of emissions due to burning could be treated in more detail.

> *a. Subsequent burns in years after clearing.* In some cases, where forests are cleared for agricultural purposes, the land may be partially burned in the year of clearing, but may also be burned again in later years. Fearnside (1990b) indicates that pastures in the Brazilian Amazon are typically burned two or three times over about a 10 year period. This would cause a larger fraction of carbon in cleared biomass to be released to the atmosphere sooner than the approach now included in the basic calculations, and would certainly increase emissions of non-CO_2 trace gases from biomass burning.
>
> *b. Non-CO_2 trace gases released after burning*. Basic calculations address the main issues in trace gas production by burning, however, they do not treat all issues. For instance, the effect of past burning, particularly of forests, on trace gas exchanges must eventually be considered. Specifically, the instantaneous release of non-CO_2 trace gases when forests are burned is included in Land Clearing calculations. However, the longer-term release or uptake of these gases following forest burning is an important research issue and should eventually be included in refinements of calculations. The issue of the contemporary release of non-CO_2 trace gases associated with past burning is complex. For example, clearing by burning may stimulate soil nutrient loss. Measurements in temperate ecosystems (e.g., Anderson et al., 1988; and Levine et al., 1988) indicate that surface biomass burning enhances emissions of N_2O and NO_x from the soils for up to 6 months

following the burn; however, in other studies measurements of N_2O emissions at a cleared and burned tropical forest site in Brazil, begun five months after the burn and continuing for a year, were not significantly different from those taken from a nearby intact forest site (Luizão et al., 1989). The "historical" issue is obviously complex and further research is needed before an adequate methodology for emissions calculations can be proposed.

Delayed Release of Non-CO_2 Trace Gases after Land Disturbance.

Even when no burning is involved there may still be a release of trace gases. An experiment in a temperate forest in the north eastern United States found that clearcutting resulted in enhanced N_2O flux to the atmosphere via dissolution of N_2O in the soil water, transport to surface waters, and degassing from solution (Bowden and Bormann, 1986). An experiment in Brazil found that N_2O emissions from newly clearcut tropical forests were about three times greater than those from adjacent undisturbed forests (Keller et al., 1986). Conversion of tropical forests to pasture also has been found to result in elevated N_2O emissions relative to the intact forest soils (Luizão et al., 1989; and Matson et al., 1990). Another example involves the loss of a sink for CH_4 which, in effect, adds to the atmospheric burden of CH_4. Specifically, the loss of forest area (tropical or temperate) may also result in increased net CH_4 emissions to the atmosphere. Soils are a natural sink of CH_4 (i.e., soils absorb atmospheric CH_4), and various experiments indicate that conversion of forests to agricultural lands diminishes this absorptive capacity of soils (Keller et al., 1990; and Scharffe et al., 1990).

Conversion of natural grasslands to managed grasslands and to cultivated lands may affect not only the net emission of CO_2 but CH_4, N_2O, and CO emissions as well. For instance, the conversion of natural grasslands to cultivated lands has been found in the semi-arid temperate zone to also decrease CH_4 uptake by the soils (Mosier et al., 1991). It is not clear what the effect on N_2O would be, unless of course nitrogen fertilisation occurs. The effect of conversion of natural grasslands to managed grasslands on trace gas emissions has not been evaluated in the field, except for the effect of associated nitrogen fertilisation on N_2O emissions. Nitrogen fertilisation on managed fields may increase carbon accumulation on land, relative to the unfertilised system, and grazing by domestic animals may also affect trace gas fluxes. CO fluxes may be affected due to changes in soil temperature and moisture. These effects on trace gas fluxes, however, are highly speculative and remain a research issue.

Methane from Termites Attributable to Biomass Left to Decay

When forests are cleared, a portion of the cleared biomass may be left to decay on the ground. Frequently some of the biomass decay is accomplished by termites which emit both CH_4 and CO_2 during this process. Fearnside (1990b) estimates that 75 per cent of the unburned carbon is decomposed by termites, and of this 75 per cent, 99.8 per cent is released as CO_2 and 0.2 per cent is released as CH_4. Fearnside suggests that forest clearing results in increased termite populations and thereby enhances natural termite CH_4 emissions. However, as discussed by Collins and Wood (1984), data from Malaysia, Nigeria, and Japan indicate that clearing and cultivation in some forests reduces termite populations. The only incidence of termite abundance increase following clearing cited by Collins and Wood was entirely due to a fungus-growing termite, a type of termite which is unlikely to produce CH_4. Because of the uncertainty of the effect of clearing on termite populations and associated CH_4 release, no guidance on calculation of this component is included in the methodology.

Fate of Roots in Cleared Forests

The basic calculation ignores the fate of living belowground woody biomass (roots) after forest clearing. The amount of belowground biomass affected, and its fate, need to be considered as work continues beyond the basic calculations. This belowground biomass could be treated as slash but with perhaps a longer (for coarse roots) or shorter (for fine roots) decay times. Alternatively, it might be more reasonable to deal with the belowground biomass in conjunction with soil carbon calculations. This is an area for further development by the relevant expert groups, and also by national experts in individual countries who are encouraged to carry out experimental calculations. See Box 8 for further information on the estimation of the amounts of belowground biomass.

Aboveground biomass after conversion

In the basic calculation, a single default value (10 tonnes dm/ha) is recommended for aboveground biomass which regrows after forests are cleared for conversion to crops or pastures. This may be somewhat variable depending on the type of crop or other vegetation which regrows. National experts carrying out more detailed assessments may wish to account more precisely for this variability, especially when perennial tree crop are planted.

Abandoned Lands

The basic calculations account only for the portion of abandoned lands which regrow toward a natural state. There may be additional releases of carbon from abandoned lands which continue to degrade, e.g., because of erosion. Where data are available, analysts doing detailed assessments may wish to account for this phenomenon.

5.4.3 Other Possible Categories of Activity

Several other land-use activities affect the flux of CO_2 and other trace gases between the terrestrial biosphere and the atmosphere. Shifting cultivation may now be reducing the storage of carbon in forests, because of shorter fallow periods, and thereby becoming a net source of CO_2 to the atmosphere. Furthermore, lands under shifting cultivation may be converted to permanent agriculture which, of course, affects the biomass assigned to the land being converted. The changing areas and distribution of wetlands may be adding to or reducing the CH_4 burden of the atmosphere. These issues are complex; often the sign of the flux is not even known, and simple models may not give reasonable results. In this section, some of the issues and possible methodological approaches are recorded; however, an agreed-upon methodology is not yet at hand.

Box 8
Belowground Biomass

For forest clearing, carbon in belowground (root) biomass is ignored in the basic calculations, but should be considered. There are large uncertainties concerning the time horizon over which this biomass would oxidise. As noted in the text, it could be considered with decay of slash left aboveground from forest conversion. There is no recommended step-by-step methodology for calculating the carbon released from this source in the current guidelines. However, interested national experts are encouraged to carry out such calculations and report them to the IPCC using their own methods.

The following information about multipliers (root-to-shoot ratios - R/S, average and range of R/S) can be applied to total aboveground biomass to estimate the belowground biomass.

Tropical forests	
moist forest growing on spodosols	1.5 (0.7 - 2.3)
lowland very moist forests	0.13 (0.06 - 0.33
montane moist forest	0.22 (0.11 - 0.33)
deciduous forests	0.47 (0.23 - 0.85)
(e.g., tropical dry and seasonal moist forests)	
Temperate forests	
coniferous	0.20
broadleaf	0.25
Boreal forests	
coniferous	0.25 (0.20 - 0.30)
broadleaf	0.20 (0.15 - 0.25)
forest-tundra	0.35 (0.30 - 0.50)

Sources: Brown, (1996) for tropical forests; Cooper, (1983) for temperate forests; and Bazilevich, (1993) and Isaev et al., (1993) for boreal forests:

Estimation of CO_2 emissions from belowground biomass after clearing has been identified as an area of future work.

Shifting Cultivation

Shifting cultivation, or slash-and-burn agriculture, is a common agricultural practice in the tropics in which short periods of cultivation (usually about 1 - 3 years) alternate with longer periods of fallow (about 10 to 30 years). Clearing occurs by initial cutting and felling, followed by a series of burns. When practised in the traditional manner, shifting cultivation produces some net CO_2 emissions because the forest is allowed to return part-way to its original biomass density during the fallow period.[29] However, increasing

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[29] Following the first clearing (i.e., clearing of primary forests), the forest biomass may not recover fully to its original density during the fallow period, but instead reaches a reduced level, referred to as a secondary forest.

population pressure has reduced the lengths of fallow periods so that currently much of the fallow land recovers very little and higher net CO_2 emissions are believed to result (Myers, 1989; and Houghton, 1991). Loss of soil carbon also may occur during shifting cultivation, although the loss is certainly far less than for permanent cultivation.

Calculation of net emissions due to shifting cultivation requires calculation of average annual emissions due to clearing of forests for cultivation, and calculation of average annual uptake due to abandonment of cultivated lands in the fallow period of the shifting cultivation cycle. This involves monitoring a large number of small parcels of land over time and probably requires a model to do the book keeping.

The basic concepts are not difficult. The carbon calculations would proceed almost exactly like the conversion and abandonment terms in the basic methodology; however, the difficulty is that the abandonment period may be shorter, and this may only be apparent by using a cohort-based model and a finite stock of forest. In other words the increasing rate of shifting cultivation (the likely data) will force a shorter fallow period and hence less regrowth, and this dynamic may only become apparent when one models the shifting cultivation cycle within a specific area of available forest.

One intermediate simple approach is to split the calculation into the two logical components. The initial conversion component would be treated similarly to the basic calculations; namely, convert the above ground dry biomass[30] to carbon (multiply by 0.50) and assume 90 per cent of this material is released as CO_2 less the amount taken upon by the replacing crops (default value of 10 tonnes dm per hectare). To calculate the uptake of carbon by the regrowing forest during the fallow cycle, simply estimate the amount of land in abandonment (but not yet in steady-state) and the average rate of carbon accumulation per unit area in these fallow lands. The difference would be the net flux of CO_2 associated with shifting cultivation. For the biomass burned in shifting cultivation, non-CO_2 gases (N_2O, CH_4, NO_x, CO) should be calculated as described in the Forest and Grassland Conversion section above.

Flooding and Wetland Drainage

Land Flooding

Flooding of lands due to construction of hydroelectric dams, or other activities, results in emissions of CH_4 due to anaerobic decomposition of the vegetation and soil carbon that was present when the land was flooded, as well as of organic material that grows in the floodwater, dies, and accumulates on the bottom. The CH_4 emissions from this source are highly variable and are dependent on the ecosystem "type", and the status of the ecosystem, that is flooded (i.e., above- and below-ground carbon, plant types, whether any pre-flooding clearing occurred, etc.) and on the depth and length of flooding (some regions may only be flooded for part of a year)[31]. Rates of CH_4 emissions from freshwater wetlands are also strongly dependent on temperature, and therefore vary

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[30] Generally, shifting cultivation is practised in secondary forests, since the least dense and most accessible forest areas are most susceptible to this form of clearing. Aboveground biomass density estimates for secondary forests are highly uncertain, and vary significantly both within and among countries because of varying ecosystem types as well as varying intervals between clearings.

[31] A detailed analysis of CO_2 and CH_4 emissions from hydroelectric reservoirs in the Amazon has been made and is a significant issue in this and other regions because of the vast areas of forest submerged for the construction of the reservoirs (Rosa and Schaeffer, 1994, 1995).

seasonally, as well as daily. Net emissions of N_2O and CO also may be affected by this activity, although these fluxes are not well determined.

A straightforward CH_4 flux calculation can be based on the area of land flooded, due to hydroelectric production or other human-made causes, an average daily CH_4 emission coefficient, and the number of days in the year that the area is flooded. Since measurements of CH_4 emissions from freshwater wetlands are so variable, both spatially and temporally, the area should be divided into groups based on characteristics such as length of flooding, vegetation type, and latitude. Then appropriate emission coefficients can be chosen for each group, rather than choosing one emission coefficient for the entire area of flooding. Table 5-13 presents average daily CH_4 emission rates for natural wetlands, derived from measured emission rates in field experiments, and average CH_4 production periods based on data on monthly mean temperatures and inundation lengths. These rates and production periods can be used if countries do not have more appropriate estimates.

TABLE 5-13
AVERAGE METHANE EMISSIONS AND PRODUCTION PERIODS OF NATURAL WETLANDS

Wetland Categories (mg CH_4/m^2.day)	Emission Rate (mg CH_4-C/m^2.day)	Production Period or Length of Time Flooded (days)
Bogs	11 (1-38)	178
Fens	60 (21-162)	169
Swamps	63 (43-84)	274
Marshes	189 (103-299)	249
Floodplains	75 (37-150)	122
Lakes	32 (13-67)	365

Source: A.selmann and Crutzen, 1989.

Note: Average daily emission rates are derived from measured emission rates in field experiments (the range in measured emission rates is in parentheses after the average), and average production periods are based on monthly mean temperature data and lengths of inundation.

Wetland Drainage

Freshwater wetlands are a natural source of CH_4, estimated to release 100-200 Tg CH_4/yr due to anaerobic decomposition of organic material in the wetland soils (Cicerone and Oremland, 1988). Destruction of freshwater wetlands, through drainage or filling, would result in a reduction of CH_4 emissions, and an increase in CO_2 emissions due to increased oxidation of soil organic material (Moore and Knowles, 1989). The magnitude of these effects is largely a function of soil temperature and the extent of drainage (i.e., the water content of the soil). Also, since dryland soils are a sink of CH_4, drainage and drying of a wetland could eventually result in the wetland area changing from a source to a sink of CH_4 (e.g., Harriss et al., 1982).

Loss of wetland area could also affect net N_2O and CO fluxes, although both the direction and magnitude of the effect is highly uncertain. Natural dryland soils are a source of N_2O, believed to emit 9-28 Tg N_2O/yr (3-9 Tg N_2O-N) as a result of nitrification and denitrification processes (Seiler and Conrad, 1987). This emission estimate is highly uncertain, however, as emission measurements vary both temporally and spatially by up to an order of magnitude. Moreover, the measurements are not consistently correlated with what are believed to be controlling variables such as soil temperature, moisture, and composition, and vegetation type. Dryland soils both produce and consume CO. Carbon monoxide production, estimated at 2-32 Tg CO/yr (1-14 Tg CO-C), is an abiotic process due to chemical oxidation of humus material (Seiler and Conrad, 1987). It is strongly dependent on soil temperature, moisture, and pH. Destruction of CO is a biological process believed to be due to micro-organisms present in the soil. Carbon monoxide destruction (250-530 Tg CO/yr, or 107-227 Tg CO-C/yr) increases with increasing temperature, although it is independent of soil surface temperature and requires a minimum soil moisture (Seiler and Conrad, 1987). Desert soils have always been found to be a net source of CO, as have savanna soils, at least during the hottest parts of the day. CO destruction outweighs production in humid temperate soils; humid tropical soils are believed to also be a net sink of CO because of their higher soil moisture and lower soil temperature than deserts and savannas.

To calculate the reduction of CH_4 emissions due to wetland drainage, the area drained is multiplied by the difference in the average daily CH_4 emission rate before and after draining, and is multiplied by the number of days in a year that the wetland was emitting CH_4 prior to drainage. The number of days of CH_4 emissions prior to drainage can be approximated by using the number of days in the year that the wetland was flooded.

In summary, the difference in CH_4 emissions before and after drainage will vary depending on factors such as soil temperature, extent of drainage, and wetland type.

The direction and magnitude of the effects on these gases are highly uncertain and significant advances in our understanding of the biological processes as well as determination of the area extent of the activities will be required before these calculations can be adequately accomplished. It may be possible to include CH_4 calculations associated with land flooding in early refinements of the calculations, but the N_2O and CO calculations are more difficult and as yet of uncertain importance.

Surface Waters

Some national experts have pointed out that changes in surface waters due to human activities can result in sequestration of carbon, and presumably other emissions or removals. An example is pollution of lakes due to run off, which can cause eutrophication, increasing the carbon content of waters. Pollution of coastal waters could also have similar effects. No data have been obtained thus far to indicate whether the carbon sequestration effects of such changes are large enough to be significant. However, it is possible that some countries may want to carry out preliminary calculations and report these as part of the ongoing methods development effort.

These changes in surface waters are generally a result of combined effects including land-use changes, agricultural practices, wastewater treatment, etc. in the surrounding area. Thus, they do not fit neatly into any of the broad economic sectors which form the fundamental structure of these *Guidelines*. If national experts consider the changes in surface waters to be primarily a function of land-use changes, the results of preliminary calculations could be reported in the ”Other” subcategory within the Land-Use Change and Forestry category. Alternatively, they could be reported under Waste, Agriculture, or the newly created general “Other” category.

T5 Technical Appendix: Deforestation Data

Data on rates of deforestation[32] are essential for calculating the fluxes of CO_2 and other trace gases between terrestrial systems and the atmosphere. When arranged on a country-by-country basis, these data provide the forcing function for computation of country-specific emissions from forest clearing. Recognising that such data sets are not yet available for many countries with the accuracy needed for these computations, this technical appendix provides suggestions for utilising the available global and national sources of data, while bringing new or better sources of information into the calculations when and where they are available.

T5.1 Food and Agriculture Organization (FAO) Published Data

Currently, the most comprehensive international source of data on rates of deforestation broken down to the country level is maintained by the FAO in the following forms:

1. Source data, preferably in the form of a time series, collected in co-operation with member countries, including data on: forest cover, ecofloristic zone and sub-national boundaries, biomass, plantations and conservation, collected and compiled in the form of a geographic information system.
2. Standardised estimates of forest cover, rate of deforestation, afforestation, and biomass/ha at the country level. Standardisation is done by FAO because of variations from country to country in:
   - the definitions of "forest", "deforestation" and "afforestation"
   - the reference years for forest cover and deforestation measurements

   The standardisation is intended to bring country data to common definitions of forest cover and reference data, and to make the country information useful for regional and global studies. The basis for standardisation is adjustment functions by ecological zones based on time-series data on forest cover of countries.
3. Data from a global sample survey of forest cover state and change during 1980 and 1990 based on a limited sample of high resolution satellite images using common definitions and measurement techniques. The main aim of this survey is to calibrate regional and global estimates and provide comprehensive information on various types of on-going forest cover changes, in the form of change matrices (1980 and 1990). It should be noted that the sample survey is not intended to check or replace country estimates, but only to provide reliable estimates (i.e., with standard error) of forest cover and rate of change at regional/global levels. This is being done taking into account the inherent limitations of aggregating heterogeneous country data at regional/global levels.

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[32] This appendix is limited to discussion of current and future international sources of data on rates of deforestation at the national level. It is understood, however, that other types of input data are also key sources of uncertainty in calculations and are also the subject of a great deal of ongoing activity. These include other types of land-use change and land cover data as well as more detailed information on growth rates and biomass densities for different types of forests and other ecosystems.

The survey is based on a sampling design covering all tropical countries. The World Reference System 2 (WRS2) for the LANDSAT satellites is used as the sampling frame. LANDSAT scenes covering approximately 3.4 million ha serve as sampling units.

In view of cost-benefit considerations, the sampling units were selected from all LANDSAT scenes with a minimum land area of 1 million ha and a forest cover of 10% or more, estimated on the basis of existing vegetation maps. This has restricted the area surveyed to some 62% of the total tropical land area but containing some 87% of the total tropical forest.

This first survey round is based on a 10% sample consisting of 117 sampling units randomly selected. The distribution of the selected sampling units by region is 47 in Africa, 30 in Asia and 40 in America. This sample size was chosen to estimate forest cover at global level with standard error less than ±5%. At each simple location, satellite images of the best quality and appropriate season, separated by an approximate ten-years interval, were selected for observation. The image close to 1990 provides assessment of the current state; whereas the area in common between "1990" and "1980" images provides the assessment to be made of the changes over time.

The interpretation was implemented at selected regional and national forestry and/or remote sensing institutions, which have a good knowledge of the sample locations and are traditionally involved in forest resources assessment activities. With the two-fold objective of improving national capacities for forest monitoring and the quality of image interpretation, the FAO Project organised three regional workshops and eight training sessions with national institutions, benefiting 27 countries and 81 participants.

The result and quality of the interpretation undertaken by local institutions were centrally reviewed and evaluated. The first result of the survey is its set of transition matrices, one for each Sampling Unit, that describe in detail the class-to-class changes for the *land cover classes* (see Box below).

LAND COVER CLASSES
Closed Forest
Open Forest
Long Fallow (forest affecting by shifting cultivation)
Fragmented Forest (mosaic of forest/ non-forest)
Shrubs
Short-Fallow (agricultural areas with short fallow period)
Other Land Cover
Water
Plantations (agricultural and forestry plantations)

The matrices associated with the sampling units can be aggregated at various levels following the standard statistical procedure. Mean transition matrices can be produced and subsequent change analysis has been carried out for the three regional and by three ecological zones (Wet and Very Moist, Moist, Dry).

The FAO Forest Assessment produced in the early 1980s (FAO/UNEP 1981, Lanly 1982) provides a first-order estimate of deforestation rates world-wide. These data produced on a country basis can be used as a baseline land-use rate. A 1990 assessment has been recently published (FAO 1993a), which provides estimates of deforestation rates by country for the period 1981-1990. Thus, some estimates of current and historical rates of deforestation on a country basis can be obtained from these published reports. More detailed information, at the sub-national level, can be obtained by contacting the FAO directly. Deforestation by climatic zone for each tropical country is included in the *Workbook*.

It should be noted, however, that there have been controversies and disagreements regarding FAO estimates of national deforestation rates at times. In some cases where national experts have developed substantially more detailed approaches for their own countries, results have been found to be different from the published FAO estimates. Any internationally provided data should be reviewed carefully by national experts if they are used as a basis for emissions inventory estimates.

Some countries have well-developed estimates of deforestation, based on very good measurements, which provide more detail than is available from the FAO assessments (e.g., Arbhabhirama et al., 1987; INPE, 1992). Where detailed national studies exist for the early 1990s they should be the preferred data source for experts preparing national inventories. FAO data may nonetheless be useful for comparative purposes. The choice of input data is always ultimately a decision of the national experts.

Lack of consistent time-series data at *national level* is considered by FAO staff to be the most critical problem in estimating the deforestation rate. Variation in definitions and measurement techniques from country to country is another problem in making regional and global estimates. FAO has initiated a comprehensive programme for capacity-building in forest resources assessment by mobilising technical and economic co-operation among member countries and among concerned regional and global agencies as follow-up to recommendations of UNCED Agenda 21: Programme Area D.

T5.2 Ongoing Data Efforts

The lack of a comprehensive data set on deforestation rates is a critical problem. The development of such data sets remains one of the priorities for the IPCC process in the coming years (IPCC, 1992). Methods using high resolution remote sensing in conjunction with geographic information systems appear most promising. The International Geosphere-Biosphere Programme's Data Information System (IGBP-DIS) is serving as a central focal point to collect and disseminate information about the various ongoing activities and data sets dealing with land use and changes in land cover. The IGBP-DIS is located in Paris, France (Tel: 33-1-4427-6168, Fax: 33-1-4427-6171).

Experts from around the world have begun to build the scientific, technical, and procedural underpinnings of such a system. The World Forest Watch Meeting held in Sao Jose dos Campos, Brazil (June 1992) provided a high-level international forum for the assessment of current approaches to satellite-based forest monitoring. This meeting also served as a basis for forwarding recommendations from the technical and scientific communities to the policy makers and government leaders at UNCED.

A variety of international participants were represented at the World Forest Watch Conference. The conference concluded that significant technical and methodological advancements have been made in recent years, and they are now sufficient for proceeding with an observation system which could satisfy both scientific and national-level forest management requirements. A priority action now is to establish a fully functional, permanent monitoring system. The system would support national forest management, global change science, and international policy information needs, such as those of the IPCC.

The current research and development being carried out in laboratories and research centres around the world has shown that it is now feasible to acquire repetitive satellite data sets over very large areas, and that the information derived from such data sets can form the core of a global forest monitoring programme. The International Space Year/World Forest Watch Conference has recently provided illustrations that space observation technology and the community of users are ready for regional and global applications.

Progress made on two forest monitoring projects is worth noting in this respect.

1 The National Institute for Space Research (INPE) of the Secretariat of Science and Technology of the Presidency of the Republic of Brazil has made surveys of the entire Legal Amazon (about 5 million square kilometres) using LANDSAT images. This survey was first conducted in 1978 (with 1977 and 1979 being used to cover areas covered by clouds in the 1978 imagery). The studies were repeated in 1988, 1989, 1990 and 1991. These space-based surveys mapped the extent of gross deforestation (i.e., without accounting for forest regeneration or the establishment of plantations) in the portion of the Legal Amazon covered by forest. The ecosystems ranged from dense tropical forest to thick savannas (cerradao) with a total surface area between 3.9 and 4 million square kilometres. The 1978 survey used 232 Land Sat MSS black and white images based on channels 5 and 7 at a scale of 1:250,000. The more recent studies used 229 LANDSAT TM images annually in a colour composite of channels 3,4 and 5 at a scale of 1:250,000.

2 In 1990 NASA, in conjunction with the United States Environmental Protection Agency and the US Geological Survey, began a prototype procedure for using large amounts of high resolution satellite imagery to map the rate of tropical deforestation. This activity, the LANDSAT Pathfinder Project, builds on experience gained during a proof-of-concept exercise as part of NASA's contribution to the International Space Year/World Forest Watch Project. It focused initially on the Brazilian Amazon, and has now been expanded as part of NASA's Earth Observing System activities to cover other regions of the humid tropical forests.

   This project has succeeded in demonstrating how to develop wall-to-wall maps of forest conversion and regrowth. The project is now in the process of extending its initial proof-of-concept to a large-area experiment across Central Africa, Southeast Asia and the entire Amazon Basin. The project is acquiring several thousand LANDSAT scenes at three points in time - mid 1970s, mid 1980s, and mid 1990s - to compile a comprehensive inventory of deforestation and secondary growth (regrowth of forests on land cleared and subsequently abandoned) to support global carbon cycle models. Methodology and procedures have been identified. Although this exercise is being implemented for most of the tropics, it is not an operational global programme. In principle it will provide an initial large-scale prototype of an operation programme.

   The use of geographic information system technology is crucial to the project, as it provides the overall framework upon which the raw satellite data can be synthesised with other cartographic, numerical and geographical data for scientific research and national forestry management. As its name implies, this project is exploratory, but it could readily be expanded to form the nucleus of a global scale operational programme.

These two projects demonstrate the feasibility of developing a global tropical forest information system to support an operational tropical forest monitoring programme. High resolution satellite data from LANDSAT or Spot satellites are being used to provide digital maps of deforestation.

High resolution data from the LANDSAT series of earth observation satellites can be employed to make regular measurements of deforestation. Large amounts of these data exist in national and foreign archives, dating back approximately 20 years. This satellite data system has been perfected over years of development (5 satellites have been launched) and it is expected to be an operational system into the next century (LANDSAT 7 and 8 are being designed[33]). This system is complemented by the French SPOT satellites. Thus, a continuous and consistent source of data is available upon which a high resolution, fine-scale (1:250,000 scale mapping) information system could be developed.

An operational forest monitoring using high resolution data such as that provided by LANDSAT and SPOT could provide wall-to-wall mapping for the entire humid tropical zone. The approach would be as follows:

- An initial mapping effort would define where and how much deforestation exists in the tropical forests (a baseline assessment). The stratification of forest types and critical regions could be enhanced by the use of coarse resolution information from AVHRR.
- Acquisition of LANDSAT and/or SPOT imagery can be co-ordinated regularly every 3-5 years to obtain cloud-free coverage systematically throughout the tropics. The best way to achieve this is to rely heavily on the foreign ground stations. For example, from the LANDSAT routine and complete coverage for the Amazon Basin and Southeast Asia is possible from several foreign ground receiving stations in these regions. As a rule these stations regularly collect data from every orbital pass within the line-of-sight radius of their antenna. For regions, such as central Africa where no ground station exits, programmed acquisitions from the satellite are possible.
- The imagery is analysed for deforestation using a methodology analogous to that developed by the LANDSAT Pathfinder Project, where a simple delineation of the boundary between intact forest and cleared areas is recorded into a geographic information system. Areas of secondary growth would also be delineated. Subsequent years are compared to the baseline and the increment of new deforestation and secondary growth is recorded. The resulting data set provides a 1:250,000 to 1:500,000 scale map of deforestation at a regular repeat interval, and from this a rate of deforestation is derived.
- These geographically-referenced measurements can directly support the implementation of the IPCC national inventory methodology, which requires a time series of historical forest clearing data, and would require updating at periodic intervals. The proposed accurate and precise deforestation data set would be an important asset to national experts working to implement the IPCC methodology for national emissions and removals from land-use change.
- An accuracy assessment effort will need to be put into place to define and track the measurement variance and error (e.g., ground truthing) This component will need to determine accuracy with respect to: (a) variance due to positional accuracy (i.e., the mapping precision) and (b) the variance associated with image interpretation.

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[33] Landsat 6 crashed, soon after it was launched.

- An effort focused on establishing in-country co-operation will be necessary. Such co-operation fulfils several ancillary but vital objectives: (a) it builds a process of national acceptance of the methods and results through active involvement, (b) it provides a mechanism for technology transfer and training for eventual implementation of national inventories based on remote sensing, (c) it facilitates logistical co-ordination of the field component, (d) it provides direct co-operation at various foreign ground stations, and (e) it enables co-operation with national and regional experts in the interpretation of imagery.

T5.3 Summary

Tropical deforestation and carbon emissions are important components of both science and policy. Yet, in spite of the growing need for precise estimates of deforestation to support both international policy and basic research, an operational programme of measurement, monitoring and mapping has yet to be developed. Comprehensive and systematic information on the extent of forest and forest loss is not available on a global basis. IPCC (1990), for example, considers the rate of tropical deforestation to be one of the key unknowns in global climate change assessment. Any lasting and effective implementation of a global system of national emission inventories to support the IPCC and other international processes will require a new, concerted effort to measure and map tropical deforestation, and develop the data base necessary for other important components of the calculations. These measurements of deforestation from high resolution satellite remote sensing can also support the UN/FAO Forest Assessment by providing quantitative and spatially comprehensive measures of changes in forest cover for the tropics.

This Technical Appendix summarises the most comprehensive current data sources for tropical deforestation information, and discusses ongoing efforts to improve on this data via analysis of remote sensing images. Ideally, each country would like to have data on their land-use changes and associated trace gas emissions and uptake over the past 40 to 50 years so that their estimates of current annual net emissions would include delayed and continuous emissions and uptake due to activities that occurred in prior years. Since this is not the case for many countries, the methodology described has made simplifying assumptions in order to treat the effects of past land-use activities on current emissions. This appendix provides some perspective on the available international sources for dealing with one key data gap – data on rates of forest clearing over time.

In future editions of the *Guidelines*, it may be possible to include more information on data available to assist national experts as a result of some of the ongoing efforts described in this version. It may also be possible and desirable to provide similar discussion of a range of other international data collection efforts which may assist national experts in refining other key data driven uncertainties in the national estimates of emissions and removals from land-use change and forestry.

In the meantime, it is recommended that countries continue efforts to collect historical records of land-use change and develop systems of tracking land use through time so that as the methodology is further refined, the land-use change time series needed to account better for emissions and uptake of CO_2 and other trace gases are available.

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