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Agriculture, Forestry and Other Land Use

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AGRICULTURE, FORESTRY AND OTHER LAND USE

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1 INTRODUCTION

1.1 INTRODUCTION

Volume 4 provides guidance for preparing annual greenhouse gas inventories in the Agriculture, Forestry and Other Land Use (AFOLU) Sector. This volume integrates the previously separate guidance in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* for Agriculture (Chapter 4) and Land Use, Land-Use Change and Forestry (Chapter 5). This integration recognizes that the processes underlying greenhouse gas emissions and removals, as well as the different forms of terrestrial carbon stocks, can occur across all types of land and that often the same practices influence both Agriculture and Land Use, Land Use Change and Forestry. This approach is intended to improve consistency and completeness in the estimation and reporting of greenhouse gas emissions and removals. The refinement builds on this objective by providing updates to the guidance in terms of improved emission factors, new methodologies, and examples for compilers to better understand the estimation of emissions and removals in the AFOLU sector.

The principal changes made in the *2006 IPCC Guidelines* and *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (2019 Refinment)*, as compared with the *Revised 1996 IPCC Guidelines* (for both Agriculture, and Land-Use Change and Forestry, continue to reflect the elaborations of the *Revised 1996 IPCC Guidelines* introduced in the Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (*GPG2000*) and the Good Practice Guidance for Land Use, Land-Use Change and Forestry (*GPG-LULUCF*). These include:

- Adoption of the six land-use categories used in *GPG-LULUCF* (i.e., Forest Land, Cropland, Grassland, Wetlands, Settlements, and Other Land – see Chapter 3). These land categories are further sub-divided into land remaining in the same category and land converted from one category to another. The land-use categories are designed to enable inclusion of all managed land area within a country;
- Reporting on all emissions by sources and removals by sinks from managed lands, which are considered to be anthropogenic, while emissions and removals for unmanaged lands are not reported;
- Additional reporting elements introduced in reporting all emissions and removals for managed lands, (see Table 1.2);
- Generic methods for accounting of biomass, dead organic matter and soil C stock changes in all land-use categories and generic methods for greenhouse gas emissions from biomass burning that can be applied in all land-use categories;
- Incorporating methods for non-CO_2 emissions from managed soils and biomass burning, and livestock population characterization and manure management systems from Agriculture (Chapter 5 of the *Revised 1996 IPCC Guidelines* and *GPG2000*;
- Adoption of three hierarchical tiers of methods that range from default emission factors and simple equations to the use of country-specific data and models to accommodate national circumstances;
- Description of alternative methods to estimate and report C stock changes associated with harvested wood products;
- Incorporation of key category analysis for land-use categories, C pools, and CO_2 and non-CO_2 greenhouse gas emissions;
- Adherence to principles of mass balance in computing carbon stock changes;
- Greater consistency in land area classification for selecting appropriate emission and stock change factors and activity data;
- Improvements of default emissions and stock change factors, as well as development of an Emission Factor Database (EFDB) that is a supplementary tool to the *2006 IPCC Guidelines*, providing alternative emission factors with associated documentation. The EFDB is described in Chapter 2 of Volume 1.
- Incorporation of methods to estimate CO_2 and CH_4 emissions from flooded land.

The AFOLU Sector has some unique characteristics with respect to developing inventory methods. There are many processes leading to emissions and removals of greenhouse gases, which can be widely dispersed in space and highly variable in time. The factors governing emissions and removals can be both natural and anthropogenic (direct and indirect) and it can be difficult to clearly distinguish between causal factors[1]. While recognizing this complexity, inventory methods need to be practical and operational.

The *2006 IPCC Guidelines* and this *2019 Refinement* are designed to assist in estimating and reporting national inventories of anthropogenic greenhouse gas emissions and removals. For the AFOLU Sector, anthropogenic greenhouse gas emissions and removals by sinks are defined as all those occurring on 'managed land'. Managed land is land where human interventions and practices have been applied to perform production, ecological or social functions. All land definitions and classifications should be specified at the national level, described in a transparent manner, and be applied consistently over time. Emissions/removals of greenhouse gases do not need to be reported for unmanaged land. However, it is *good practice* for countries to quantify, and track over time, the area of unmanaged land so that consistency in area accounting is maintained as land-use change occurs. The IPCC describes the Managed Land Proxy (MLP) as an approach to approximate estimates of anthropogenic emissions and removals, but this proxy estimate also contains emissions and removals resulting from natural disturbances.

This approach, i.e., the use of managed land as a proxy for anthropogenic effects, was adopted in the GPG-LULUCF and that use is maintained in the *2019 Refinement*. The key rationale for this approach is that the preponderance of anthropogenic effects occurs on managed lands. By definition, all direct human-induced effects on greenhouse gas emissions and removals occur on managed lands only. While it is recognized that no area of the Earth's surface is entirely free of human influence (e.g., CO_2 fertilization), many indirect human influences on greenhouse gases (e.g., increased N deposition, accidental fire) will be manifested predominately on managed lands, where human activities are concentrated. Finally, while local and short-term variability in emissions and removals due to natural causes can be substantial (e.g., emissions from fire, see footnote 1), the natural 'background' of greenhouse gas emissions and removals by sinks tends to average out over time and space. This leaves the greenhouse gas emissions and removals from managed lands as the dominant result of human activity.

However, some of the emissions and removals from managed land are characterised by high interannual variability. Interannual variability (IAV) refers to the variability in the annual emissions and removals estimates between years within a time series. In the AFOLU sector, the application of the MLP means that IAV can be caused by both anthropogenic and natural causes. The three main causes of IAV in GHG emissions and removals in the AFOLU sector are (1) natural disturbances (such as wildfires, insects, windthrow, and ice storms), which can cause large immediate and delayed emissions and kill trees; (2) climate variability (e.g. temperature, precipitation, and drought), which affects photosynthesis and respiration; and (3) variation in the rate of human activities, including land use (such as forest harvesting), and land-use change.

When the MLP is used and the interannual variability in emissions and removals due to natural disturbance is large, it is difficult to gain a quantitative understanding of the role of human activities compared to the impacts of natural effects. In such situations disaggregating[2] MLP emissions and removals into human and natural effects may provide increased understanding and refined estimates of the emissions and removals that are due to human activities such, land use (including harvesting) and land-use change. In this way, disaggregation can contribute to improved quantification of the trends in emissions and removals due to human activities and mitigation actions that are taken to reduce anthropogenic emissions and preserve and enhance carbon stocks.

Guidance and methods for estimating greenhouse gas emissions and removals for the AFOLU Sector now include:

- CO_2 emissions and removals resulting from C stock changes in biomass, dead organic matter and mineral soils, for all managed lands;
- CO_2 and non-CO_2 emissions from fire on all managed land;
- Optional guidance that may be used by countries that choose to disaggregate their reported MLP emissions and removals (i.e. all emissions and removals on managed land) into those that are considered to result from human activities and those that are considered to result from natural disturbances;
- N_2O emissions from all managed soils;
- CO_2 emissions associated with liming and urea application to managed soils;
- CH_4 emissions from rice cultivation;

[1] This general observation was made in the IPCC Report on *Current Scientific Understanding of the Processes Affecting Terrestrial Carbon Stocks and Human Influences upon Them* (July 2003, Geneva, Switzerland). As a specific example, emissions from wildfires on managed (and unmanaged) land can exhibit large interannual variations that may be driven by either natural causes (e.g. climate cycles, random variation in lightning ignitions), or indirect and direct human causes (e.g. historical fire suppression and past forest harvest activities) or a combination of all three causes, the effects of which cannot be readily separated.

[2] Disaggregating means that an estimate is separated into its component parts.

- CO_2 and N_2O emissions from cultivated organic soils;
- CO_2 and N_2O emissions from managed wetlands, and CH_4 emissions from flooded land;
- CH_4 emission from livestock (enteric fermentation);
- CH_4 and N_2O emissions from manure management systems; and
- C stock change associated with harvested wood products.

The scientific background and rationale for these inventory components are given in the next section.

1.2 OVERVIEW OF GREENHOUSE GAS EMISSIONS AND REMOVALS IN THE AFOLU SECTOR

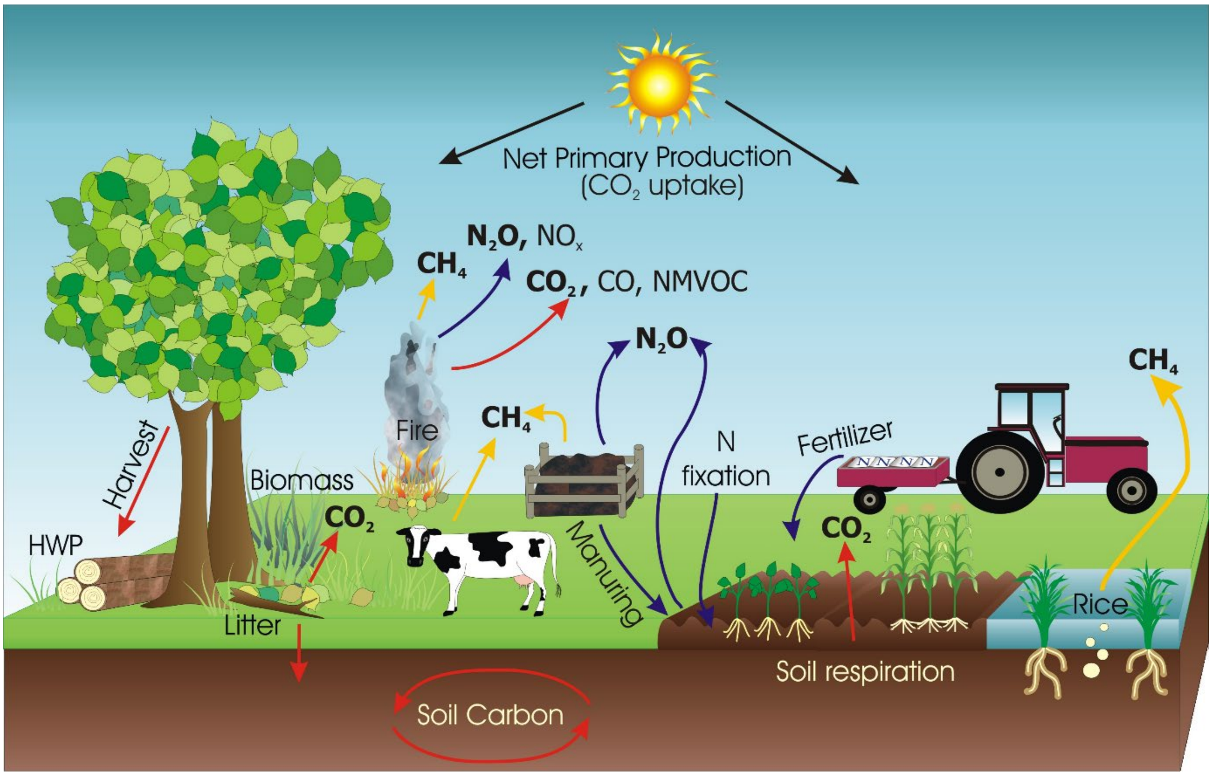
1.2.1 Science background

Land use and management influence a variety of ecosystem processes that affect greenhouse gas fluxes (Figure 1.1), such as photosynthesis, respiration, decomposition, nitrification/denitrification, enteric fermentation, and combustion. These processes involve transformations of carbon and nitrogen that are driven by the biological (activity of microorganisms, plants, and animals) and physical processes (combustion, leaching, and run-off).

Greenhouse Gases in AFOLU

The key greenhouse gases of concern are CO_2, N_2O and CH_4. CO_2 fluxes between the atmosphere and ecosystems are primarily controlled by uptake through plant photosynthesis and releases via respiration, decomposition and combustion of organic matter. N_2O is primarily emitted from ecosystems as a by-product of nitrification and denitrification, while CH_4 is emitted through methanogenesis under anaerobic conditions in soils and manure storage, through enteric fermentation, and during incomplete combustion while burning organic

Figure 1.1 The main greenhouse gas emission sources/removals and processes in managed ecosystems.



matter. Other gases of interest (from combustion and from soils) are NO_x, NH_3, NMVOC and CO, because they are precursors for the formation of greenhouse gases in the atmosphere. Formation of greenhouse gases from precursor gases is considered an indirect emission. Indirect emissions are also associated with leaching or run-off of nitrogen compounds, particularly NO_3^- losses from soils, some of which can be subsequently converted to N_2O through denitrification.

Emission and Removal Processes

Greenhouse gas fluxes in the AFOLU Sector can be estimated in two ways: 1) as net changes in C stocks over time (used for most CO_2 fluxes) and 2) directly as gas flux rates to and from the atmosphere (used for estimating non-CO_2 emissions and some CO_2 emissions and removals). The use of C stock changes to estimate CO_2 emissions and removals, is based on the fact that changes in ecosystem C stocks are predominately (but not exclusively) through CO_2 exchange between the land surface and the atmosphere (i.e. other C transfer process such as leaching are assumed to be negligible). Hence, increases in total C stocks over time are equated with a net removal of CO_2 from the atmosphere and decreases in total C stocks (less transfers to other pools such as harvested wood products) are equated with net emission of CO_2. Non-CO_2 emissions are largely a product of microbiological processes (i.e., within soils, animal digestive tracts and manure) and combustion of organic materials. Below, emission and removal processes in the AFOLU Sector are described for the major ecosystem stocks and processes, organized by ecosystem components, i.e., 1) biomass, 2) dead organic matter, 3) soils and 4) livestock.

Biomass

Plant biomass, including above-ground and below-ground parts, is the main conduit for CO_2 removal from the atmosphere. Large amounts of CO_2 are transferred between the atmosphere and terrestrial ecosystems, primarily through photosynthesis and respiration. The uptake of CO_2 through photosynthesis is referred to as gross primary production (GPP). About half of the GPP is respired by plants, and returned to the atmosphere, with the remainder constituting net primary production (NPP), which is the total production of biomass and dead organic matter in a year. NPP minus losses from heterotrophic respiration (decomposition of organic matter in litter, dead wood and soils) is equal to the net carbon stock change in an ecosystem and, in the absence of disturbance losses, is referred to as net ecosystem production (NEP).

Net Ecosystem Production (NEP) = Net Primary Production (NPP) – Heterotrophic respiration

NEP minus additional C losses from disturbance (e.g., fire), harvesting and land clearing during land-use change, is often referred to as net biome production (NBP). The carbon stock change that is reported in national greenhouse gas inventories for land-use categories is equal to NBP [3].

Net Biome Production (NBP) = NEP – Carbon Losses from Disturbance/Land-Clearing/Harvest

NPP is influenced by land use and management through a variety of anthropogenic actions such as deforestation, afforestation, fertilization, irrigation, harvest, and species choice. For example, tree harvesting reduces biomass stocks on the land. However, harvested wood requires additional consideration because some of the carbon may be stored in wood products in use and in landfills for years to centuries. Thus, some of the carbon removed from the ecosystem is rapidly emitted to the atmosphere while some carbon is transferred to other stocks in which the emissions are delayed. In non-forest ecosystems (i.e., Cropland, Grassland), biomass is predominantly non-woody perennial and annual vegetation, which makes up a much smaller part of total ecosystem carbon stocks than in Forest Land. The non-woody biomass turns over annually or within a few years and hence net biomass carbon stocks may remain roughly constant, although stocks may diminish over time if land degradation is occurring. Land managers may use fire as a management tool in grasslands and forests or wild fires may inadvertently burn through managed lands, particularly Forest Land, leading to significant losses of biomass carbon. Fires not only return CO_2 to the atmosphere through combustion of biomass, but also emit other greenhouse gases, directly or indirectly, including CH_4, N_2O, NMVOC, NO_x and CO.

Dead Organic Matter

The bulk of biomass production (NPP) contained in living plant material is eventually transferred to dead organic matter (DOM) pools (i.e., dead wood and litter – see Table 1.1 for definitions). Some DOM decomposes quickly, returning carbon to the atmosphere, but a portion is retained for months to years to decades. Land use and management influence C stocks of dead organic matter by affecting the decomposition rates and input of fresh detritus. Losses due to burning dead organic matter include emissions of CO_2, N_2O, CH_4, NO_x, NMVOC, and CO.

[3] Harvested wood or other durable products derived from biomass (e.g., clothing) products are not included in NBP; harvested wood products (HWP) are dealt with in Chapter 12.

Soils

As dead organic matter is fragmented and decomposed, it is transformed into soil organic matter (SOM). Soil organic matter includes a wide variety of materials that differ greatly in their residence time in soil. Some of this material is composed of labile compounds that are easily decomposed by microbial organisms, returning carbon to the atmosphere. Some of the soil organic carbon, however, is converted into recalcitrant compounds or bound in organic-mineral complexes that are very slowly decomposed and thus can be retained in the soil for decades to centuries or more. Following fires, small amounts of so-called 'black carbon' are produced, which constitute a nearly inert carbon fraction with turnover times that may span millennia. Biochar C[4] may be produced through pyrolysis and amended to soils with a long turnover time.

Soil organic carbon stocks are influenced by land-use and management activities that affect litter input rates and soil organic matter loss rates. Although the dominant processes governing the balance of soil organic carbon stocks are C inputs from plant residues and C emissions from decomposition, losses as particulate or dissolved carbon can be significant in some ecosystems. Inputs are primarily controlled by decisions impacting NPP and/or the retention of dead organic matter, such as how much harvested biomass is removed as products and how much is left as residues. Outputs are mostly influenced by management decisions that affect microbial and physical decomposition of soil organic matter, such as tillage intensity. Depending on interactions with previous land use, climate and soil properties, changes in management practices may induce increases or decreases in soil C stocks. Generally, management-induced C stock changes are manifested over a period of several years to a few decades, until soil C stocks approach a new equilibrium. In addition to the influence of human activities, climate variability and other environmental factors affect soil C dynamics (as well as biomass and DOM).

In flooded conditions, such as wetland environments and paddy rice production, a significant fraction of the decomposing dead organic matter and soil organic matter is returned to the atmosphere as CH_4. This can be a major source of emissions in countries with a considerable amount of land dedicated to paddy rice production or are flooded land (e.g., reservoirs created by constructing dams on rivers). Although virtually all flooded soils emit methane, net soil C stocks may either increase, decrease or remain constant over time, depending on management and environmental controls on the overall carbon balance. In well-drained soils, small amounts of CH_4 are consumed (oxidized) by methanotrophic bacteria although this impact on CH_4 removals is not addressed in the current guidance due to limited studies for quantifying the impact.[5]

Soils also contain inorganic C pools, either as primary minerals in the parent material from which the soil was formed (e.g., limestone), or as secondary minerals (i.e., pedogenic carbonates) that arise during soil formation. Inorganic soil C stocks can be affected by management, although typically not to the extent of organic C pools.

Some soil management practices impact greenhouse gas emissions beyond simply changing the C stock. For example, liming is used to reduce soil acidity and improve plant productivity, but it is also a direct source of CO_2 emissions. Specifically, liming transfers C from the earth's crust to the atmosphere by removing calcium carbonate from limestone and dolomite deposits and applying it to soils where the carbonate ion evolves into CO_2.

Nitrogen additions are a common practice for increasing NPP and crop yields, including application of synthetic N fertilizers and organic amendments (e.g., manure), particularly to cropland and grassland. This increase in soil N availability increases N_2O emissions from soils as a by-product of nitrification and denitrification. Nitrogen additions (in dung and urine) by grazing animals can also stimulate N_2O emissions. Similarly, land-use change enhances N_2O emissions if associated with heightened decomposition of soil organic matter and subsequent N mineralization, such as initiating cultivation on wetlands, forests or grasslands.

Livestock

Animal production systems, particularly those with ruminant animals, can be significant sources of greenhouse gas emissions. For example, enteric fermentation in the digestive systems of ruminants leads to production and emission of CH_4. Management decisions about manure disposal and storage affect emissions of CH_4 and N_2O,

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[4] Biochar is a solid carbonised product from thermochemical conversion through pyrolysis (heating with limited air). The term biochar is used herein only to refer to materials that have been produced under process conditions in which relatively easily mineralisable organic materials are converted to more persistent forms by heating to above 350°C with limited air through a gasification or pyrolysis process. No default methodology is provided for biochar C amendments, but guidance is provided for Tier 2 and 3 methods. However, this guidance does not deal with pyrolytic organic materials that result from wild fires or open fires, and is only applicable for biochar added to mineral soils.

[5] No default methodology exists for estimation of CH_4 removals in aerobic soils because of limited studies addressing land-use and management impacts on methane oxidation. However, there is evidence that disturbance through land-use change and addition of nitrogen (i.e., as fertilizer) may reduce rates of methane oxidation. Countries that wish to estimate and report CH_4 removals should develop, validate and document an appropriate national methodology for estimating CH_4 removals, including analysis of uncertainty. It is good practice for countries reporting CH_4 removals to also ensure symmetry by including all emissions of CH_4 on lands were CH_4 removals are reported.

which occur result from methanogenesis in decomposing manures and as a by-product nitrification/ denitrification. Furthermore, volatilization losses of NH_3 and NO_x and losses of N in leaching and runoff from manure management systems and soils leads to indirect greenhouse gas emissions.

1.2.2 Carbon pool definitions and non-CO_2 gases

Within each land-use category, C stock changes and emission/removal estimations can involve the five carbon pools that are defined in Table 1.1. For some land-use categories and estimation methods, C stock changes may be based on the three aggregate carbon pools (i.e., biomass, DOM and soils). National circumstances may require modifications of the pool definitions introduced here. Where modified definitions are used, it is *good practice* to report and document them clearly, to ensure that modified definitions are used consistently over time, and to demonstrate that pools are neither omitted nor double counted. Carbon stock changes associated with harvested wood products are normally reported at the national scale (see Chapter 12).

The non-CO_2 gases of primary concern for the AFOLU Sector are methane (CH_4) and nitrous oxide (N_2O). Emissions of other nitrogenous gases including NO_x and NH_3, which can serve as a source of subsequent N_2O emissions (and hence referred to as *indirect* emission sources), are also considered (see Chapters 10 and 11).

TABLE 1.1 (UPDATED)
DEFINITIONS FOR CARBON POOLS USED IN AFOLU FOR EACH LAND-USE CATEGORY

Pool		Description
Biomass	Above-ground biomass	All biomass of living vegetation, both woody and herbaceous, above the soil including stems, stumps, branches, bark, seeds, and foliage. Note: In cases where forest understory is a relatively small component of the above-ground biomass carbon pool, it is acceptable for the methodologies and associated data used in some tiers to exclude it, provided the tiers are used in a consistent manner throughout the inventory time series.
	Below-ground biomass	All biomass of live roots. Fine roots of less than (suggested) 2mm diameter are often excluded because these often cannot be distinguished empirically from soil organic matter or litter.
Dead organic matter	Dead wood	Includes all non-living woody biomass not contained in the litter, either standing, lying on the ground, or in the soil. Dead wood includes wood lying on the surface, dead roots, and stumps, larger than or equal to 10 cm in diameter (or the diameter specified by the country).
	Litter	Includes all non-living biomass with a size greater than the limit for soil organic matter (suggested 2 mm) and less than the minimum diameter chosen for dead wood (e.g. 10 cm), lying dead, in various states of decomposition above or within the mineral or organic soil. This includes the litter layer as usually defined in soil typologies. Live fine roots above the mineral or organic soil (of less than the minimum diameter limit chosen for below-ground biomass) are included in litter where they cannot be distinguished from it empirically.
Soils	Soil organic matter[1]	Includes organic carbon in mineral soils to a specified depth chosen by the country and applied consistently through the time series[2,3]. Live and dead fine roots and DOM within the soil that are less than the minimum diameter limit (suggested 2 mm) for roots and DOM, are included with soil organic matter where they cannot be distinguished from it empirically. The default for soil depth is 30 cm and guidance on determining country-specific depths is given in Chapter 2.3.3.1.

[1] Includes organic material (living and non-living) within the soil matrix, operationally defined as a specific size fraction (e.g., all matter passing through a 2 mm sieve). Soil C stock estimates may also include soil inorganic C if using a Tier 3 method. CO_2 emissions from liming and urea applications to soils are estimated as fluxes using Tier 1 or Tier 2 methods.

[2] Carbon stocks in organic soils are not explicitly computed using Tier 1 or Tier 2 methods, (which estimate only annual C flux from organic soils), but C stocks in organic soils can be estimated in a Tier 3 method. Definition of organic soils for classification purposes is provided in Chapter 3.

[3] Biochar C amendments are estimated separately and includes all C added to soils without regard to depth for Tier 2 methods. No default method is provided.

1.3 OVERVIEW OF INVENTORY PREPARATION FOR THE AFOLU SECTOR

To prepare inventories for the AFOLU Sector, emissions and removals of CO_2 and non-CO_2 greenhouse gases are estimated separately for each of six land-use categories. Other CO_2 emission and non-CO_2 categories, such as livestock related emissions, emissions from soil N management, soil liming emissions and harvested wood products, may be estimated at the national scale, since often only aggregate data are available. However, they can be broken out according to land-use category if data are available.

1.3.1 Land-use and management categories

A brief overview of how land area is categorized for inventory purposes is given here. Chapter 3 provides a detailed description of land representation and categorization of land area by land-use and management systems as well as stratification of land area by climate, soil and other environmental strata.

The six land-use categories (see definitions in Chapter 3) in the *2006 IPCC Guidelines* are:

- Forest Land;
- Cropland;
- Grassland;
- Wetlands;
- Settlements;
- Other Land.

Each land-use category is further subdivided into land remaining in that category (e.g., *Forest Land Remaining Forest Land*) and land converted from one category to another (e.g., Forest Land converted to Cropland). Countries may choose to further stratify land in each category by climatic or other ecological regions, depending on the choice of the method and its requirements. Greenhouse gas emissions and removals determined for each specific land use includes CO_2 (as carbon stock changes) from biomass, dead organic matter and soils, as well as non-CO_2 emissions from burning and, depending on the land-use category, emissions from other specific sources (e.g. CH_4 emissions from rice and flooded land).

CH_4 and N_2O emissions from livestock management are estimated for major animal types, e.g., dairy cows, other cattle, poultry, sheep, swine and other livestock (buffalo, goats, llamas, alpacas, camels, etc). The animal waste management systems include anaerobic lagoons, liquid systems, daily spread, solid storage, dry-lot, pasture/ range/paddock, and other miscellaneous systems.

Nitrous oxide emissions from managed soils are usually estimated from aggregate (national-level) data on N supplied to soils, including N fertilizer usage or sales, crop residue management, organic amendments and land-use conversions that enhance mineralization of N in soil organic matter. Similarly, CO_2 emissions from liming and from urea application to managed soils are typically estimated using aggregate data (e.g., national-level).

Harvested wood products constitute a component of the carbon cycle for which carbon stock changes can be estimated (guidance provided in Chapter 12), based on national-level data; however, estimation and reporting of greenhouse gas emissions for HWP is currently a matter of policy negotiations.

1.3.2 Tier definitions for methods in AFOLU

The concepts underpinning the three-tiered approach, as they relate to methods used in the AFOLU Sector, are outlined here (see Box 1.1). In general, moving to higher tiers improves reduces uncertainty in the inventory, but the complexity and resources required for conducting inventories also increases for higher tiers. If needed, a combination of tiers can be used, e.g., Tier 2 can be used for biomass and Tier 1 for soil carbon.

The methods and data presented focus on Tier 1 inventories. The methods will be generally applicable to Tier 2 inventories, but the default data presented for Tier 1 will be partly or wholly replaced with national data as part of a Tier 2 estimation. There are few exceptions with alternative methodologies to derive country-specific factors for Tier 2 (e.g., gross energy intake calculations to estimate methane emissions from enteric fermentation). Tier 3 methods are not described in detail, but *good practice* in application is outlined and some examples are provided in information boxes.

BOX 1.1
FRAMEWORK OF TIER STRUCTURE FOR AFOLU METHODS

Tier 1 methods are designed to be the simplest to use, for which equations and default parameter values (e.g., emission and stock change factors) are provided in this volume. Country-specific activity data are needed, but for Tier 1 there are often globally available sources of activity data estimates (e.g., deforestation rates, agricultural production statistics, global land cover maps, fertilizer use, livestock population data, etc.), although these data are usually spatially coarse.

Tier 2 can use the same methodological approach as Tier 1 but applies emission and stock change factors that are based on country- or region-specific data, for the most important land-use or livestock categories. Country-defined emission factors are more appropriate for the climatic regions, land-use systems and livestock categories in that country. Higher temporal and spatial resolution and more disaggregated activity data are typically used in Tier 2 to correspond with country-defined coefficients for specific regions and specialized land-use or livestock categories. For a few source categories, methodologies are provided for estimating a country-specific emission and stock change factors (e.g., CH_4 emissions from enteric fermentation).

At **Tier 3**, higher order methods are used, such as process-based models and inventory measurement systems tailored to address national circumstances, repeated over time, and driven by high-resolution activity data and disaggregated at sub-national level. These higher order methods provide estimates of greater certainty than lower tiers. Such systems may include comprehensive field sampling repeated at regular time intervals and/or GIS-based systems of age, class/production data, soils data, and land-use and management activity data, integrating several types of monitoring. Pieces of land where a land-use change occurs can usually be tracked over time, at least statistically. In most cases these systems have a climate dependency, and thus provide source estimates with interannual variability. Detailed disaggregation of livestock population according to animal type, age, body weight etc., can be used. Models should undergo quality checks, audits, and validations and be thoroughly documented.

1.3.3 Identification of *key categories*

No refinement.

1.3.4 Steps in preparing inventory estimates

The following steps describe the compilation of the greenhouse gas inventory for the AFOLU Sector:

1. Divide all land into managed and unmanaged (Chapter 3).
2. Develop a national land classification system applicable to all six land-use categories (Forest Land, Cropland, Grassland, Wetlands, Settlements and Other Land) and further subdivide by climate, soil type and/or ecological regions (i.e., strata) appropriate for the country, as described in Chapter 3.
3. Compile data on the area of land and the change in area of land in each land-use category (by category) if available. Categorize land area by specific management systems defined for each land-use category (by category), which is based on combinations of management practices (e.g., tillage and fertiliser management in Croplands). This categorization provides the basis for assigning emission factors and stock change factors, required for a particular estimation approach (see Chapter 3).
4. Compile national-level statistics for livestock, manure management systems, soil N management, crop yields, biochar C (Tier 2 and 3 only), liming and urea application (if land-use specific activity data are available for soil fertilization and liming activities, these emissions categories can be stratified as in Step 2; biochar C amendment data are stratified by Cropland and Grassland as in Step 2).
5. Estimate CO_2 emissions and removals and non-CO_2 emissions at the appropriate tier level in support of a key category analysis. A preliminary inventory is likely to utilize a Tier 1 or Tier 2 approach. However, it may be preferable to proceed with a Tier 3 approach if the methods have been previously developed and the supporting activity and input data have been compiled (see Chapter 2 for general guidance on methods).
6. Re-estimate CO_2 emissions and removals and non-CO_2 emissions if a higher Tier is recommended, based on the key category analysis (see Volume 1 Chapter 4 for methods to identify *Key Categories*).

7. Estimate uncertainties (see Volume 1 Chapter 3) and complete QA/QC procedures (which are initiated at Step 1) using the methods provided in Volume 1 Chapter 6, along with additional guidance provided in Chapters 2 to 12 of this Volume.
8. Sum CO_2 emissions and removals and non-CO_2 emissions over the inventory period for each source category by land use and stratum, as well as emissions from livestock, manure, and N management (if not analysed separately for each land-use category).
9. Transcribe summary information into reporting tables, converting C stock changes to emissions or removals of CO_2 and entering non-CO_2 greenhouse gas emissions, by land-use categories, if available. Combine with any emission estimates that are based on national aggregate data (e.g. livestock, manure management and soil management/amendment) to estimate the total emissions and removals for the AFOLU Sector (See Volume 1 Chapter 8, Reporting Guidance and Tables).
10. Document and archive all information used to produce an inventory, including activity and other input data, emission factors, sources of data and metadata documentation, methods descriptions and model software or code, QA/QC procedures and reports, in addition to the results for each source category.
11. Set priorities for future inventories in AFOLU Sector based on completeness of current inventories, uncertainties, and issues arising during QA/QC. Revise key category analysis based on the newly completed inventory to aid in decisions regarding future priorities.

1.4 ORGANISATION OF VOLUME 4 IN 2019 REFINEMENT TO THE 2006 IPCC GUIDELINES

The material in Volume 4 should be used as follows:

- Chapter 2 describes generic methods for carbon pools and biomass burning that can be applied within each of the six land-use categories, i.e., the methods are not specific to a particular land use. These consist of estimating ecosystem C stock changes and CO_2 and non-CO_2 emissions from fires and biomass burning. To avoid redundancy in the subsequent land-use specific chapters, Tier 1 equations are provided along with tables of generic emission factors and other parameters. Chapter 2 also provides guidance on choice of method and decision trees for tier selection including general guidance for Tier 2 emission factors on how to use allometric models and biomass maps; and guidance on how to parameterize and evaluate Tier 3 models, the integration of data to models, estimating uncertainties and means to increase its transparency. Some case studies demonstrating how parties have developed and worked with Tier 3 methods are presented in information boxes. In addition, Chapter 2 provides an optional approach that may be used by countries that choose to disaggregate their reported MLP emissions and removals (i.e. all emissions and removals (E/R) on managed land) into those that are considered to result from human activities and those that are considered to result from natural disturbances (ND). In particular, the approach describes a generic method to reduce interannual variability of E/R due to natural disturbances and increase the proportion of the anthropogenic contribution reported in the MLP by disaggregating from the total flux the component which is attributed to ND. The remaining E/R quantifies the anthropogenic component of E/R on managed land as the total minus that from ND. This estimate may still be somewhat affected by ND and other natural effects, but less so compared to the total E/R estimated using the MLP. Because the goal of the national GHG Inventories is to estimate and report anthropogenic E/R, the approach is proposed as a refined estimate of the anthropogenic E/R. The reason that the approach has limited the disaggregation to E/R from ND is because scientific methods to quantify all-natural effects are currently not available. Where a country choses to disaggregate E/R from ND from the remaining anthropogenic E/R estimated using the MLP, it is *good practice* to report the total MLP E/R and the two disaggregated components, and to document the methods and assumptions used.
- Chapter 3 deals with the consistent representation of land. In particular, the multiple approaches for classification of land-use categories are presented in this chapter, along with the level of disaggregation. Users will find this material helpful for understanding the general issues surrounding representation of systems, which will be needed later in order to use the estimation methods that are specific to a particular land-use and/or source category. After consulting Chapter 2 and Chapter 3, users should proceed to the appropriate chapter addressing the issues specific to a particular land-use or source category.
- Chapters 4 to 9 provide information for specific land-use categories. These chapters contain information on the application of the generic methods described in Chapter 2 and they also contain full method descriptions and application for any land-use specific methods.

- Chapter 4 deals with estimation of emissions and removals from forest lands. Separate sections cover *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*. Harvested wood products are addressed separately in Chapter 12.
- Chapter 5 deals with estimation of emissions and removals from cropland. Separate sections cover *Cropland Remaining Cropland* and *Land Converted to Cropland*. CH_4 production from rice cultivation, which is specific to cropland, is also addressed in this chapter.
- Chapter 6 deals with estimation of emissions and removals from the Grassland. Separate sections cover *Grassland Remaining Grassland* and *Land Converted to Grassland*.
- Chapter 7 deals with estimation of emissions and removals from Wetlands, including peat extraction in natural peatlands and flooded lands, including estimation of CO_2 and CH_4 emissions.
- Chapter 8 deals with estimation of emissions and removals from Settlements. Separate sections cover *Settlements Remaining Settlements* and *Land Converted to Settlements*.
- Chapter 9 deals with 'Other Land', which includes areas with bare soil, rock, and ice, in addition to all land areas that do not fall into the other five land-use categories treated in Chapters 4 to 8. Since greenhouse gas emissions and removals are not reported for unmanaged lands, methods and guidance in this chapter apply only to '*Land Converted to Other Land*', for example, from extreme degradation of forest, cropland or grassland to barren land that is no longer managed for useful purposes.
- Chapter 10 provides guidance on livestock related emissions, including CH_4 emissions from enteric fermentation and CH_4 and N_2O (direct and indirect) emissions from manure management. The guidance provides different options to adapt emission estimates to consider the productivity of the livestock systems and assures consistency among emission estimates for different sources of emissions resulting from livestock production.
- Chapter 11 provides guidance for emissions sources from managed soils, associated primarily with application of fertilizer, crop residues, manure, lime, and urea to soils. Specifically, methods and guidance are provided for estimating N_2O emissions from managed soils and CO_2 emissions from liming and urea applications. Activity data for these sources are typically not broken out by individual land use, hence Tier 1 methods are based on (national) aggregate data.
- Chapter 12 provides methodological guidance for estimation of C stock changes and emissions from harvested wood products, and is neutral with regards to the multiple alternative approaches to inventory estimation that are given.

Figure 1.4 presents the structure of AFOLU reporting with categories (including category codes) that are listed in Table 8.2 of Volume 1.

Annex 1 provides worksheets for each sub-category that can be used to estimate emissions based on Tier 1 methods and appropriate emission/stock change factors and activity data. The Reporting Tables for the greenhouse gas emissions/removals at sectoral and national levels are provided in Volume 1 Chapter 8 of the Guidelines.

Annex 2 is the summary of all equations in AFOLU that serves as quick reference for inventory compilers.

Table 1.2 provides the summary information as to what carbon pools and activities emitting non-CO_2 gases in each land-use category are treated under Tier 1 methods; in what section in AFOLU Volume the guidance is discussed, and their reference to the *Revised 1996 IPCC Guidelines*.

Figure 1.4 Structure of AFOLU Reporting

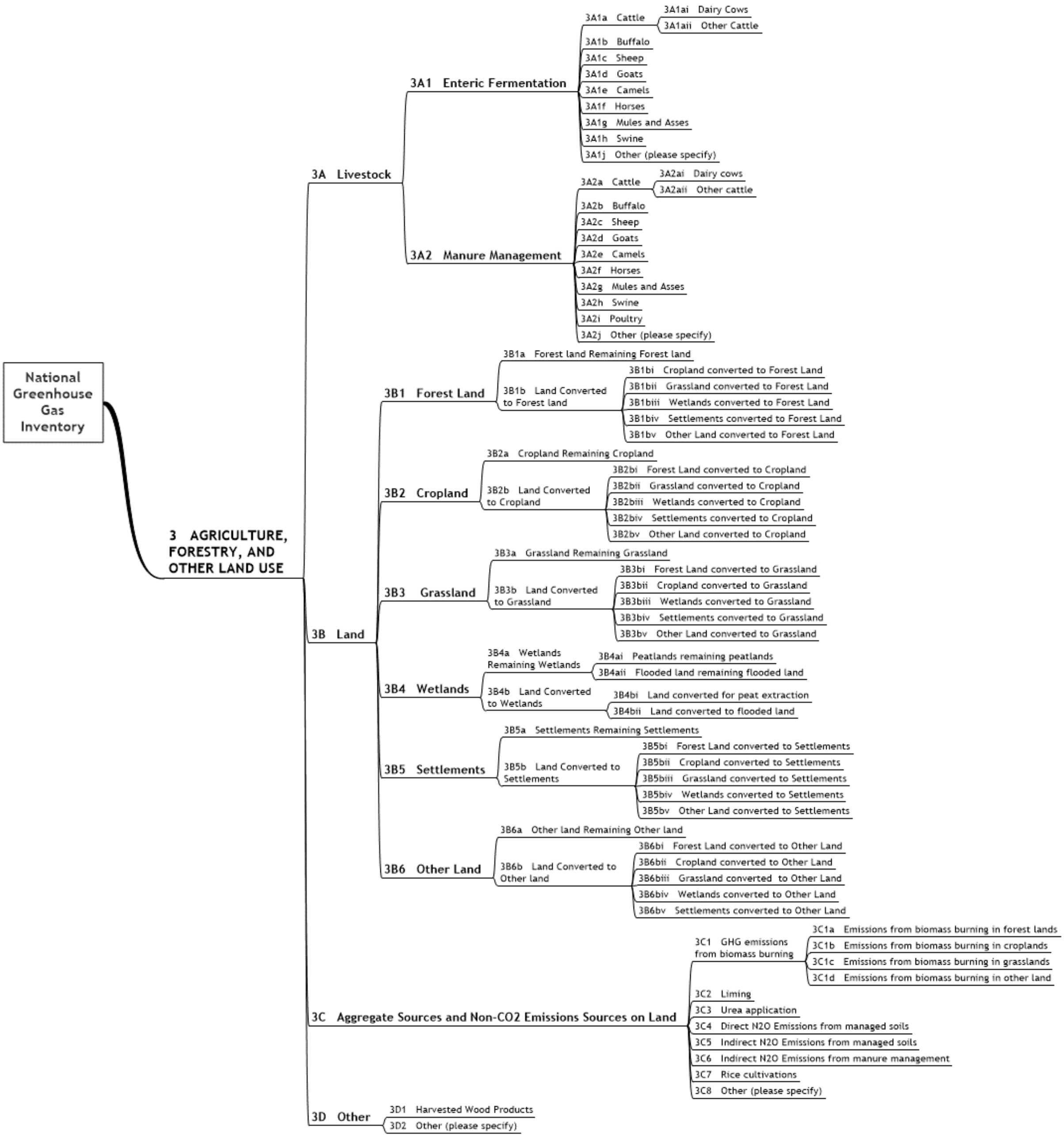

TABLE 1.2 (UPDATED)
LAND-USE CATEGORIES, CARBON POOLS AND NON-CO_2 GASES TO BE ESTIMATED UNDER TIER 1, THEIR RELEVANCE TO AFOLU SECTIONS, AND THE REFERENCE TO *REVISED 1996 IPCC GUIDELINES*

Land-use category/ Chapter	Subcategory	C pool & non-CO_2 gases	Methods Section	Chapter 2 Method	Linkage to *Revised 1996 IPCC Guidelines*	Tier 1 Method
Forest Land (Chapter 4)	Forest Land Remaining Forest Land (FF)	Above-ground biomass	4.2.1	2.3.1.1	5A	⊕
		Below-ground biomass	4.2.1	2.3.1.1	NE	⊕
		Dead organic matter	4.2.2	2.3.2.1	NE	0
		Soil carbon	4.2.3	2.3.3.1	5D	⊕ [1]
		Non-CO_2 from biomass burning	4.2.4	2.4	NE	⊕
	Land Converted to Forest Land (LF)	Above-ground biomass	4.3.1	2.3.1.2	5A, 5C	⊕
		Below-ground biomass	4.3.1	2.3.1.2	NE	⊕
		Dead organic matter	4.3.2	2.3.2.2	NE	⊕
		Soil carbon	4.3.3	2.3.3.1	5D	⊕
		Non-CO_2 from biomass burning	4.3.4	2.4	4E, 4F	⊕
Cropland (Chapter 5)	Cropland Remaining Cropland (CC)	Above-ground biomass	5.2.1	2.3.1.1	5A	⊕[3]
		Dead organic matter	5.2.2	2.3.2.1	NE	0
		Soil carbon	5.2.3	2.3.3.1	5D	⊕
		Non-CO_2 from crop residue burning	5.2.4	2.4	4F	⊕
		Methane emissions from rice	5.5	-	4C	⊕
	Land Converted to Cropland (LC)	Above-ground biomass	5.3.1	2.3.1.2	5B	⊕
		Dead organic matter	5.3.2	2.3.2.2	NE	⊕
		Soil carbon	5.3.3	2.3.3.1	5D	⊕
		Non-CO_2 from biomass (crop residue) burning	5.3.4	2.4	4E, 5B	⊕

TABLE 1.2 (UPDATED) (CONTINUED) LAND-USE CATEGORIES, CARBON POOLS AND NON-CO_2 GASES TO BE ESTIMATED UNDER TIER 1, THEIR RELEVANCE TO AFOLU SECTIONS, AND THE REFERENCE TO *REVISED 1996 IPCC GUIDELINES*						
Land-use category/ Chapter	**Subcategory**	**C pool & non-CO_2 gases**	**Methods Section**	**Chapter 2 Method**	**Linkage to *Revised 1996 IPCC Guidelines***	**Tier 1 Method**
Grassland (Chapter 6)	Grassland Remaining Grassland (GG)	Above-ground biomass	6.2.1	2.3.1.1	5A	0
		Dead organic matter	6.2.2	2.3.2.1	NE	0
		Soil carbon	6.2.3	2.3.3.1	5D	⊕
		Non-CO_2 from biomass burning	6.2.4	2.4	4E	⊕
	Land Converted to Grassland (LG)	Above-ground biomass	6.3.1	2.3.1.2	5B	⊕
		Dead organic matter	6.3.2	2.3.2.2	NE	⊕
		Soil carbon	6.3.3	2.3.3.1	5D	⊕
		Non-CO_2 from biomass burning	6.3.4	2.4	4F, 5B	⊕
Wetlands (Chapter 7)	Peatlands Remaining Peatlands	CO_2 emissions	7.2.1.1	-	NE	⊕
		Non-CO_2 emissions	7.2.1.2	-	NE	⊕
	Land Being Converted for Peat Extraction	CO_2 emissions	7.2.2.1	-	NE	NA
		Non-CO_2 emissions	7.2.2.2	-	NE	⊕
	Flooded Land Remaining Flooded Land	CO_2 emissions	7.3.1.1	-	NE	0
		Non-CO_2 emissions	7.3.1.2	-	NE	⊕
	Land Converted to Flooded Land	CO_2 emissions	7.3.2.1	-	NE	⊕
		Non-CO_2 emissions	7.3.2.2	-	NE	⊕
Settlements (Chapter 8)	Settlements Remaining Settlements (SS)	Above-ground biomass	8.2.1	2.3.1.1	5A	0
		Dead organic matter	8.2.2	2.3.2.1	NE	0
		Soil carbon	8.2.3	2.3.3.1	NE	⊕ [1]
	Land Converted to Settlements (LS)	Above-ground biomass	8.3.1	2.3.1.2	5B	⊕
		Dead Organic Matter	8.3.2	2.3.2.2	NE	⊕
		Soil carbon	8.3.3	2.3.3.1	NE	⊕
Other Land (Chapter 9)	Land Converted to Other Land (LO)	Above-ground biomass	9.3.1	2.3.1.2	5B	⊕
		Dead Organic Matter	9.3.2	2.3.2.2	NE	NA
		Soil carbon	9.3.3	2.3.3.1	NE	⊕

TABLE 1.2 (UPDATED) (CONTINUED)
LAND-USE CATEGORIES, CARBON POOLS AND NON-CO_2 GASES TO BE ESTIMATED UNDER TIER 1, THEIR RELEVANCE TO AFOLU SECTIONS, AND THE REFERENCE TO *REVISED 1996 IPCC GUIDELINES*

Land-use category/ Chapter	**Subcategory**	**C pool & non-CO_2 gases**	**Methods Section**	**Chapter 2 Method**	**Linkage to *Revised 1996 IPCC Guidelines***	**Tier 1 Method**
Livestock (Chapter 10)	Enteric Fermentation	CH_4 emissions	10.3	-	4A	⊕
	Manure Management	CH_4 emissions	10.4	-	4B	⊕
		N_2O emissions	10.5	-	4B	⊕
Managed soils (Chapter 11)	Soil Management	N_2O emissions	11.2	-	4D	⊕
	Liming	CO_2 emissions	11.3	-	_	⊕
	Urea Fertilization	CO_2 emissions	11.4	-	NE	⊕
Harvested wood products (Chapter 12)	Wood Products	C stock changes	Chapter 12	-	NE	⊕ [2]

The *Revised 1996 IPCC Guidelines* cover the following categories: 5A Changes in Forest and Other Woody Biomass Stocks; 5B Forest and Grassland Conversion; 5C Abandonment of Managed Lands; 5D Emissions and Removals from Soils, and 5E Other (Reporting Instructions p. 1.14 - 1.16)

NE: not estimated under default method in the *1996 IPCC Guidelines*

NG – no guidance provided in the Guidelines

Notes for column "Tier 1 Method":

⊕ - Tier 1 methods and default parameters are available in the Guidelines.

0 = Tier 1 (default) assumption is that emissions are zero or in equilibrium; no methods and parameters are provided in the Guidelines.

1 = Tier 1 and default factors available only for organic soils.

2 = Tier 1 method available to estimate HWP variables which may be used to compute HWP Contribution to AFOLU.

3 = Tier 1 and default factors only available for perennial woody vegetation

NA – not applicable

Annex 1A Historical background on IPCC greenhouse gas inventory guidance for AFOLU Sector

No refinement.

References

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IPCC (2003). *Good Practice Guidance for Land Use, Land-Use Change and Forestry*. Penman J., Gytarsky M., Hiraishi T., Krug, T., Kruger D., Pipatti R., Buendia L., Miwa K., Ngara T., Tanabe K., Wagner F. (Eds).Intergovernmental Panel on Climate Change (IPCC), IPCC/IGES, Hayama, Japan.

Appendix 4 Method for Estimating the Change in Mineral Soil Organic Carbon Stocks from Biochar Amendments: Basis for Future Methodological Development

This appendix provides a basis for future methodological development of a Tier 1 method for estimating the change in mineral soil organic C stocks from biochar amendments to soils, rather than complete guidance.

For the purpose of this methodology, biochar is defined as a solid material generated by heating biomass to a temperature in excess of 350°C under conditions of controlled and limited oxidant concentrations to prevent combustion. These processes can be classified as either pyrolysis (in which oxidants are excluded), or gasification (in which oxidant concentrations are low enough to generate syngas). The change in soil organic C stocks from biochar amendments is estimated separately from other organic amendments over a 100-year time frame. This method does not deal with pyrolytic organic materials that result from wild fires or open fires, and is only applicable for biochar added to mineral soils in grasslands and croplands. Biochar is more persistent with only a small portion mineralised each year at a decreasing rate over many centuries, and therefore the stock change method cannot be used to track changes in biochar C stocks over time as is done for other management practices in mineral soils.

The methodology used to estimate biochar C additions to minerals soils is based on a top-down approach in which the total amount of biochar generated and added to mineral soil in cropland and grassland[1] is required to estimate the contribution of biochar to annual changes in mineral soil C stocks. Information is not needed on the application rate. Interactions between biochar C fate and soil type or land management are not considered with this method. However, the method does require compilers to track the source of feedstock and temperature of the pyrolysis. The total change in carbon stocks of mineral soils receiving biochar amendments is estimated with Equation 4Ap.1.

EQUATION 4AP.1

ANNUAL CHANGE IN BIOCHAR CARBON STOCK IN MINERAL SOILS RECEIVING BIOCHAR ADDITIONS

$$\Delta BC_{Mineral} = \sum_{p=1}^{n} \left(BC_{TOT_p} \bullet F_{C_p} \bullet F_{perm_p} \right)$$

Where

$\Delta BC_{Mineral}$ = the total change in carbon stocks of mineral soils associated with biochar amendment, tonnes sequestered C yr^{-1}

BC_{TOT_p} = the mass of biochar incorporated into mineral soil during the inventory year for each biochar production type p, tonnes biochar dry matter yr^{-1}

F_{C_p} = the organic carbon content of biochar for each production type p, tonnes C tonne^{-1} biochar dry matter, Table 4Ap.1

F_{perm_p} = fraction of biochar carbon for each production type p remaining (unmineralised) after 100 years, tonnes sequestered C tonne^{-1} biochar C, Table 4Ap.2

n = the number of different production types of biochar

[1] This method is not applicable for application of biochar to soils in forest land, settlements, other lands or wetlands. The studies used in the derivation of F_{perm} values included only cropland and grassland mineral soils. Thus, the F_{perm} values provided in Table 4Ap.2 are only applicable to mineral soils under those land uses.

Global estimates of the organic C content of biochar (F_{C_p}) as a function of feedstock and heating temperature are provided in Table 4Ap.1, as well as estimates of the proportion of biochar C that would persist for 100 years (F_{perm_p}) years in Table 4Ap.2[2].

The biochar-C addition is estimated for cropland and grassland, or in total without disaggregation to the amounts applied in cropland and grassland. If biochar-C is entered without disaggregation, then the C stock change should be associated with the land use receiving the majority of the biochar.

TABLE 4AP.1
VALUES FOR ORGANIC C CONTENT FACTOR OF BIOCHAR BY PRODUCTION TYPE (F_{C_p}).

Feedstock	Pyrolysis Production Process	Values for F_{C_p} [2]
Animal manure	Pyrolysis [1]	0.38 ± 49%
	Gasification [1]	0.09 ± 53%
Wood	Pyrolysis	0.77 ± 42%
	Gasification	0.52 ± 52%
Herbaceous (grasses, forbs, leaves; excluding rice husks and rice straw)	Pyrolysis	0.65 ± 45%
	Gasification	0.28 ± 50%
Rice husks and rice straw	Pyrolysis	0.49 ± 41%
	Gasification	0.13 ± 50%
Nut shells, pits and stones	Pyrolysis	0.74 ± 39%
	Gasification	0.40 ± 52%
Biosolids (paper sludge, sewage sludge)	Pyrolysis	0.35 ± 40%
	Gasification	0.07 ± 50%

Notes:

[1]An explanation of the conversion technologies is provided in Annex 2A.2.

[2] All values are presented in the format of the mean value ± the 95% confidence limit expressed as a percentage of the mean (that is ± 1.96 * standard error /mean *100).

Source:

F_{Cp} was calculated from the organic carbon content of biochar from regressions by Neves et al. (2011), corrected for ash content using biochar yield from Woolf et al. (2014). Data on ash, lignin, and carbon content of biomass feedstocks, which are parameters in these regression equations, were taken from ECN (2018).[3]

[2] Estimating biochar C remaining for durations of <100 years, such as 20 years, would require additional detailed information on the chemical nature of the biochar, how it is applied, as well as climatic and edaphic properties of the location it was applied.

[3] https://phyllis.nl/Home/Colophon (24/10/2018).

TABLE 4AP.2
VALUES FOR F_{perm_p} (FRACTION OF BIOCHAR C REMAINING AFTER 100 YEARS)

Production	Value for F_{perm_p} [1, 2]
High temperature pyrolysis and gasification (> 600 °C)	0.89 ± 13%
Medium temperature pyrolysis (450-600 °C)	0.80 ± 11%
Low (350-450 °C)	0.65 ± 15%

Notes:

[1] All values are presented in the format of the mean value ± the 95% bootstrap confidence limit expressed as a percentage of the mean (note that the bootstrap confidence intervals are symmetric about the mean to within 2 significant digits and are therefore given as ± a percentage of the mean value).

[2] The studies used in the derivation of F_{perm_p} values included only cropland and grassland mineral soils. Thus the f F_{perm_p} values provided are only applicable to mineral soils under those land uses, and not for forest land, settlements, other land or wetlands.

Sources:

Major *et al.* 2010; Zimmerman 2010; Singh *et al.* 2012; Zimmerman & Gao 2013; Fang *et al.* 2014; Herath *et al.* 2015; Kuzyakov *et al.* 2014; Dharmakeerthi *et al.* 2015; Wu *et al.* 2016

Background Information on Derivation of F_{C_p} and F_{perm_p} Values

F_{C_p} was calculated using the organic carbon content of biochar on a dry ash-free (daf) basis according to equation 14 from Neves et al. (2011), which was based on a regression (n=128) of data from 26 papers. This daf organic carbon content was corrected for ash content of the biochar to provide F_{C_p} as the carbon content per unit mass of biochar using the regression equation (n=146 from 18 articles) of biochar yield from Woolf *et al*. (2014). Data on ash (n=1276), lignin (n=516), and carbon (n=1276) content of biomass feedstocks, which are parameters in these regression equations, were taken from ECN (2018).

The values for F_{permp} were calculated from field and laboratory studies for biochars that were made under different conversion conditions based on a comprehensive survey of the literature. The amount of biochar C remaining after 100 years was estimated by fitting a two-pool double-exponential model to only those datasets within the list of references that exceeded one year and allowed a two-pool model to be fitted following the rationale outlined by Lehmann *et al.* (2015). The data included all available studies that met these stringent quality criteria (Major *et al*. 2010; Zimmerman 2010; Singh *et al.* 2012; Zimmerman & Gao 2013; Fang *et al.* 2014; Herath *et al.* 2015; Kuzyakov *et al.* 2014; Dharmakeerthi *et al.* 2015; Wu *et al.* 2016). F_{permp} values were adjusted to an ambient temperature of 20°C, which is higher than current estimates of approximately 10°C average land surface temperature (Rohde *et al*. 2013) and therefore conservative since decomposition increases with increasing temperature. F_{permp} values were then calculated for the three categories shown in Table 4Ap.2 as means for each of the three temperature categories (Figure 4Ap.1). Categories were preferred to using a linear regression due to the non-linear relationship between pyrolysis temperature and biochar C persistence (Whitman *et al*. 2013; Bird *et al*. 2015). Long-term field data of naturally accumulated char and anthropogenically added biochar with unknown production temperatures were assessed separately as a cross-check on the results (Figure 4Ap.1) and include all available studies with periods exceeding 10 years of observation (Cheng *et al*. 2008; Hammes *et al*. 2008; Lehmann *et al*. 2008; Liang *et al*. 2008; Nguyen *et al*. 2008; Vasilyeva *et al*. 2011; Lutfalla *et al*. 2017). These data do not utilize isotopes or determine physical losses by leaching and erosion, and therefore do not allow actual mineralization rates to be quantified. Rather, the biochar and char C remaining can be understood as a minimum value below which persistence will not fall over decadal to millennial time scales.

Pyrolysis temperature is used for this methodology, as it is more easily available than biochar property measurements for country-wide estimation. Methods could employ biochar property measurements, e.g., H/Corg (Lehmann *et al.* 2015) or O/Corg (Spokas 2010) ratios, together with country-specific soil properties, temperatures and moisture regimes, but these properties are not considered in this method.

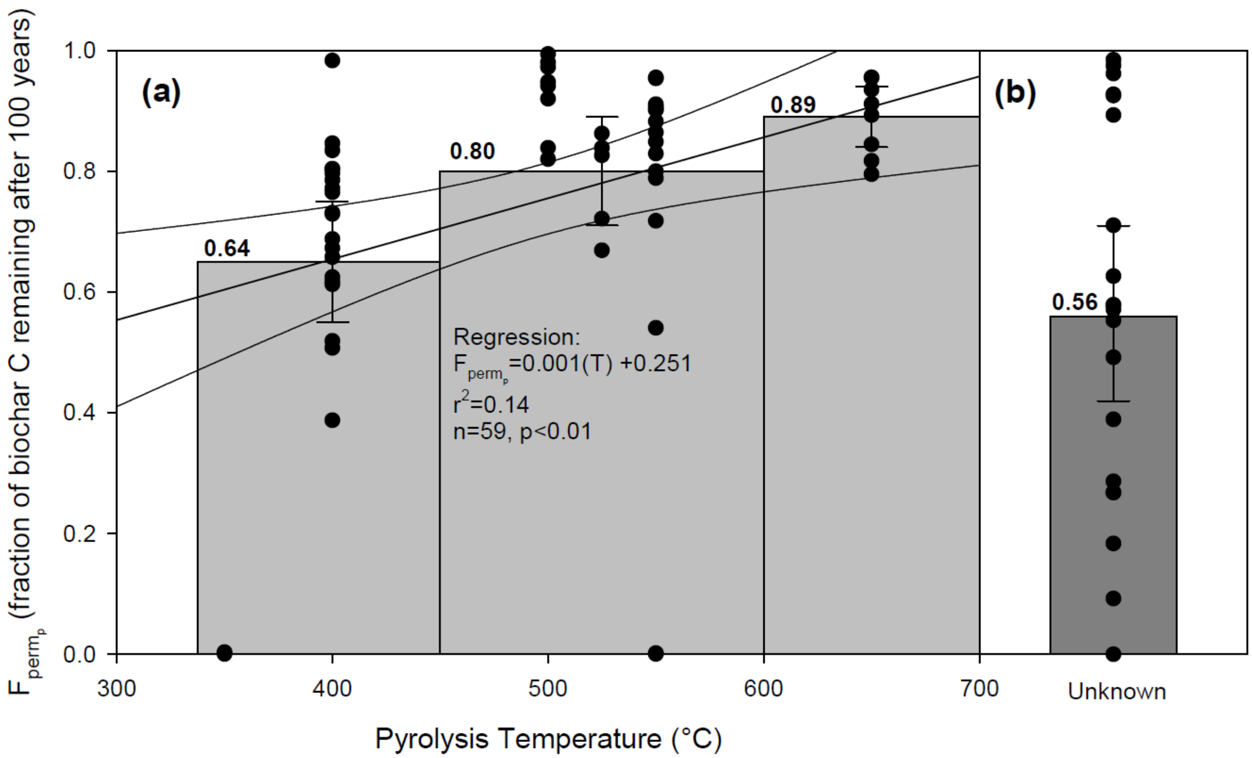

Figure 4Ap.1 F_{perm_p} calculated from field and laboratory studies for biochars that were made under different conversion conditions: (a) F_{perm_p} estimated for biochars with known production temperatures by fitting a two-pool double-exponential model to 59 datasets from eight mineralization experiments that exceeded one year and allowed a two-pool model to be fitted and adjusted to a decomposition temperature of 20°C recalculated as shown in Lehmann *et al*. (2015) (Sources of data include: Major *et al*. 2010; Zimmerman 2010; Singh *et al.* 2012; Zimmerman & Gao 2013; Fang *et al.* 2014; Herath *et al.* 2015; Kuzyakov *et al.* 2014; Dharmakeerthi *et al.* 2015; Wu *et al.* 2016); (b) F_{perm_p} estimated for naturally occurring chars and added biochars with unknown production temperatures using 20 observations from eight long-term field assessments (decadal to millennial time scales) where physical export is not determined (Cheng *et al*. 2008; Hammes *et al*. 2008; Lehmann *et al*. 2008; Liang *et al*. 2008; Nguyen *et al*. 2008; Vasilyeva *et al*. 2011; Lutfalla *et al*. 2017; mean residence times taken directly from the sources without recalculation).

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CHAPTER 3

CONSISTENT REPRESENTATION OF LANDS

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3 CONSISTENT REPRESENTATION OF LANDS

3.1 INTRODUCTION

This chapter provides guidance on using different types of data to represent land-use categories, and conversions between land-use categories, so that they are applied as appropriately and consistently as possible in inventory calculations.

Countries use various methods to obtain data, including annual census, periodic surveys and remote sensing. Each of these methods of data collection will yield different types of information (e.g., maps or tabulations), at different reporting frequencies, and with different attributes. Guidance is provided on the use of three generic approaches.

Approach 1 identifies the total area for each individual land-use category within a country, but does not provide detailed information on the nature of conversions between land uses. Approach 2 introduces tracking of conversions between land-use categories. Approach 3 extends Approach 2 by allowing land-use conversions to be tracked through time on a spatially explicit basis. Countries may use a mix of Approaches for different regions over time.

The guidance presented here is intended to assist countries in making the best use of available data and reducing, as far as practicable, possible overlaps and omissions in reporting. The guidance allows informed decisions on the appropriate use of data of different types by those preparing greenhouse gas inventories, but is not intended to be prescriptive on how data may be collected. Generally, all data should be:

- adequate, i.e., capable of representing land-use categories, and conversions between land-use categories, as needed to estimate carbon stock changes and greenhouse gas emissions and removals;
- consistent, i.e., capable of representing land-use categories consistently over time, without being unduly affected by artificial discontinuities in time-series data;
- complete, which means that all land within a country should be included, with increases in some areas balanced by decreases in others, recognizing the bio-physical stratification of land if needed (and as can be supported by data) for estimating and reporting emissions and removals of greenhouse gases; and
- transparent, i.e., data sources, definitions, methodologies and assumptions should be clearly described.
- The descriptions of land use follow the framework of:
- land-use category - is the broad land use (one of the six land-use categories described below) reported as either land remaining in a land-use category (i.e., remaining in the same use throughout the inventory time-series) or land converted to a new land-use category (representing a change in land use).
- sub-category - refers to special circumstances (e.g., areas of grazing within Forest Land) that are estimated and reported separately but do not duplicate land in the broad land-use category.
- Land-use categories and sub-categories may be further stratified on the basis of land-use practices and bio-physical characteristics in order to create more homogeneous spatial units as may be used for emissions estimation (see Table 3.1 for examples).

Using the above approaches and framework, consistent representation of lands at the national level for inventory purposes is achieved by following the main steps outlined below:

1. provide country-specific definitions of land-use categories (see Section 3.2);
2. decide which Approaches and methods to use to develop activity data (see Sections 3.3.1 and 3.3.3), considering the methods to be used for estimating greenhouse gas emissions and removals (see Section 3.4) and for estimating uncertainties (see Section 3.5).;
3. stratify the entire land area of the country as appropriate (see Section 3.3.6);
4. obtain data for these categories ensuring that the data cover the total land area of the country (see Section 3.2 and 3.3);
5. where needed, develop rules to translate land cover information into IPCC land-use and land-use change categories, using auxiliary information as appropriate (see Section 3.3.5);
6. collect additional information if required (e.g., in situ or ground reference data, sampling, land use statistics etc.);

7. develop area estimates for land-use and land-use change categories according to good practice ensuring that all IPCC requirements for completeness, avoidance of double-counting, accuracy and time-series consistency (Chapter 5, Volume 1), are met;
8. develop uncertainty estimates for the area estimates (see section 3.5).

3.2 LAND-USE CATEGORIES

While the terms "land-use" and "land cover" are sometimes used interchangeably, they are not the same. Land cover refers to the bio-physical coverage of land (e.g., bare soil, rocks, forests, buildings and roads or lakes). Land-use refers to the socioeconomic use that is made of the land (e.g. agriculture, commerce, residential use or recreation) (UNEP/FAO 1993). The definitions of land-use categories may incorporate management options and predominance over other land-uses when a land is subject to multiple uses.

Attribution is the process of associating observed land cover and cover changes with land-use and land use change. Because different management and disturbance types have different impacts on carbon stocks and GHG emissions, knowledge of the cause of disturbance is needed not only to estimate areas of land-use and land-use change but also to estimate the associated GHG emissions and removals.

The six broad land-use categories described below form the basis for estimating and reporting greenhouse gas emissions and removals from land-use and land-use conversions. The land-uses may be considered as top-level categories for representing all land-use areas, with sub-divisions describing specific circumstances significant to emissions estimation. The categories are broad enough to classify all land areas in most countries and to accommodate differences in national land-use classification systems, and may be readily stratified (e.g., by climate or ecological zones). The categories (and sub-categories) are intended to be identified through the use of Approaches for representing land-use area data described in subsequent sections.

The land-use categories for greenhouse gas inventory reporting are listed below. These definitions are provided for the IPCC land-use categories because they are:

- robust as a basis for emissions and removals estimation;
- implementable; and
- complete, in that all land areas in a country may be classified by these categories without duplication.

(i) Forest Land

This category includes all land with woody vegetation consistent with thresholds used to define Forest Land in the national greenhouse gas inventory. It also includes systems with a vegetation structure that currently fall below, but in situ could potentially reach the threshold values used by a country to define the Forest Land category.

(ii) Cropland

This category includes cropped land, including rice fields, and agro-forestry systems where the vegetation structure falls below the thresholds used for the Forest Land category.

(iii) Grassland

This category includes rangelands and pasture land that are not considered Cropland. It also includes systems with woody vegetation and other non-grass vegetation such as herbs and bushes that fall below the threshold values used in the Forest Land category. The category also includes all grassland from wild lands to recreational areas as well as agricultural and silvi-pastural systems, consistent with national definitions.

(iv) Wetlands

This category includes areas of peat extraction and land that is covered or saturated by water for all or part of the year (peatlands and other wetland types) and that does not fall into the Forest Land, Cropland, Grassland or Settlements categories. It includes reservoirs as a managed sub-division and natural rivers and lakes as unmanaged sub-divisions. Further definitions of wetlands sub-divisions are provided in the IPCC Wetland Supplement (IPCC 2014).

(v) Settlements

This category includes all developed land, including transportation infrastructure and human settlements of any size, unless they are already included under other categories. This should be consistent with national definitions.

(vi) Other Land

This category includes bare soil, rock, ice, and all land areas that do not fall into any of the other five categories. It allows the total of identified land areas to match the national area, where data are available.

If data are available, countries are encouraged to classify unmanaged lands by the above land-use categories (e.g., into Unmanaged Forest Land, Unmanaged Grassland, and Unmanaged Wetlands). This will improve transparency and enhance the ability to track land-use conversions from specific types of unmanaged lands into the categories above.

Countries can apply other definitions within the IPCC categories, which may or may not refer to internationally accepted definitions, such as those proposed by FAO, Ramsar[1], SEEA[2], WCA[3] and others. However, where there are inconsistencies between these other definitions and the IPCC land-use categories definitions, the data should be adjusted to fit within the IPCC categories. To ensure and show consistency and completeness of the land representation reported, it is *good practice* to map the relationship between IPCC land-use categories and any other land-use and land cover classification systems[4] from which data for the land representation are derived. All definitions and classifications of land-use categories (and sub-categories) should be specified at the national level, described in a transparent manner, and be applied consistently over time. To avoid double-counting of land areas or misallocation of lands, each land unit is only reported in one category (or sub-division) in each year.

When moving unmanaged land to managed land, it is *good practice* to describe the processes that lead to the re-categorization. Managed land generally cannot become unmanaged as the legacy effects of past management can continue for extended periods, and such moves could result in anthropogenic emissions and removals being unreported.

Where countries choose to develop country-specific methods for addressing issues of interannual variability (IAV), it is *good practice* to describe the methods used to identify lands subject to natural disturbances (see Section 2.6, Chapter 2, Volume 4) and to transparently report the area of these lands together with the rest of the lands in the same land use category.

LAND-USE CONVERSIONS

Full application of the guidance requires estimation of land-use conversions that take place between data collection intervals, particularly when different carbon stock estimates and different emission and removal factors are associated with lands before and after a transition. Applicable land-uses and land-use conversions are shown below:

FF	=	Forest land Remaining Forest land	LF	=	Land Converted to Forest land
CC	=	Cropland Remaining Cropland	LC	=	Land Converted to Cropland
GG	=	Grassland Remaining Grassland	LG	=	Land Converted to Grassland
WW	=	Wetlands Remaining Wetlands	LW	=	Land Converted to Wetlands
SS	=	Settlements Remaining Settlements	LS	=	Land Converted to Settlements
OO	=	Other Land Remaining Other Land	LO	=	Land Converted to Other Land

Where detailed data about the origin of land converted to a category are available (which will depend on the Approach available to a country to represent land-use areas), countries can specify the land-use conversion. For example, LC can be sub-divided into Forest Land Converted to Cropland (FC) and Grassland Converted to Cropland (GC). While both land areas end up in the Cropland category, the differences in their emissions and removals of greenhouse gases due to their origin should be represented and reported wherever possible. When applying these land-use category conversions, countries should classify land under only one (end land-use) category to prevent double counting. The reporting category is therefore the end-use category, not the category of origin prior to the land-use conversion.

If a country's national land-use classification system does not match categories (i) to (vi) as described above, the land-use classifications should be combined or disaggregated in order to represent the categories presented here. (See Section 3.3.5 "Derivation of IPCC Land-Use Categories from Land Cover Information" in this Chapter). Countries should report on the procedure adopted for the reallocation. The national definitions for all categories used in the inventory and any threshold or parameter values used in the definitions should be specified. Where

[1] Refers to Ramsar Convention on Wetlands. The Convention on Wetlands, signed in Ramsar, Iran, in 1971, is an intergovernmental treaty which provides the framework for national action and international cooperation for the conservation and wise use of wetlands and their resources.

[2] System of Environmental Economic Accounting (SEEA) - https://seea.un.org/

[3] World Programme for the Census of Agriculture (WCA) - http://www.fao.org/world-census-agriculture/en/

[4] The relationship between IPCC, SEEA, WCA and FAO land cover and land-use classifications can be found at: http://www.fao.org/economic/ess/ess-standards

national land classification systems are being changed or developed for the first time, compatibility with land-use classes (i) to (vi) above should be sought.

The broad land-use categories listed above may be further stratified (as described in Section 3.3.6) by climate or ecological zone, soil and vegetation type, etc., as necessary, to match land areas with the methods for assessing carbon stock changes and greenhouse gas emissions and removals described in Chapters 2 and 4 to 9 of this Volume. Default climate and soil classification schemes are provided in Annex 3A.5. Examples of stratifications that are used for Tier 1 emissions and removals estimation are summarized in Table 3.1. Specific stratification systems vary by land use and carbon pools and are used in the estimation methods later in this Volume. Guidance on stratifying land-use areas to match data needs for estimating emissions and removals is provided in Section 3.3.6 of this chapter.

The method of determining areas of land-use and land-use change should be capable of representing lands according to the definitions applied by the country, and ensure that losses or gains smaller than the minimum mapping unit do not lead to bias in emission and removal estimates.

In some cases, the spatial resolution of existing maps or sample units may be coarser than the definitions used to describe some of the land-use categories (e.g., if the Forest Land definition applied by a country includes a minimum area of, say, one hectare, yet the available land-use data has a minimum mapping unit of five hectares). This may lead to a situation where:

- small areas of one or more land-use categories are reported under another category; and,
- areas of land-use change are either under or overestimated.

Where this occurs, it is *good practice* to assess the extent of under or over reporting and, where necessary, supplement the results with further samples or auxiliary information (e.g., concession boundaries, subsidies for land use changes or land management) that reflect the chosen definitions to validate the results and/or correct for these errors. Where data are not available, techniques provided in Chapter 5 of Volume 1: Time Series Consistency can be used to address the data gaps.

When land cover change information is used, auxiliary data is commonly required to allocate land cover change to the underlying cause of disturbance and to assign lands to the IPCC land-use categories through time. This process of attribution typically requires a combination of information including, but not limited to, past and current land cover, management practices and country-specific decisions on a series of reporting rules (see Box 3.1a). Moreover, reporting rules can also be applied to help countries determine how land-use change is categorized (Box 3.1a).

BOX 3.1A (NEW)
EXAMPLES OF ASSIGNING IPCC LAND-USE AND LAND-USE CHANGE CATEGORIES

IPCC land-use categories	Key elements that may need to be considered	Examples
Forest Land	Definition of Forest Land to be applied to determine areas of Forest Land.	While countries can set their own definitions, Forest Land should include all land with woody vegetation that meets country specific thresholds (e.g., a combination of minimum canopy cover, minimum height and minimum area) used to define Forest Lands.
	Reporting lands converted to Forest Land but where the vegetation structure currently does not necessarily meet the national definition of Forest Land.	When establishing new forests (e.g., reforestation, forest restoration) it is often the case that the vegetation will not meet the national definition of Forest Land for some years. However, this land can be classed as Forest Land at the point of conversion. Determining if the land has the 'potential' to reach the national definitions can consider criteria such as 1) that a woody vegetation type exists on the land (e.g., newly planted or regrowing trees), and 2) it will be able to reach the Forest Land definition thresholds (e.g., the forest type will be able meet the Forest Land definition on that land). Countries typically document the assumptions used to assess if land meets these criteria. Countries also often include the time period within which the land should reach the Forest Land definition thresholds following the conversion.
	Reporting Forest Land areas that in a specific inventory year or years fall below the country definition of Forest Land.	There are typically two reasons that Forest Land temporarily falls below the country definition: 1) forest harvesting 2) other disturbances (e.g., fire, pest attack). When cover loss is only temporary countries generally continue to report these areas under Forest Land. Countries may use tenure or forest type maps to determine if a loss of cover is due to harvest or clearing. For other disturbances data on the type of disturbance can be obtained from maps or statistical information. It is possible that some areas of temporarily destocked Forest Land will not recover to meet the definition of Forest Land. Countries can decide how long an area of Forest Land can remain temporarily destocked before it should be moved to a conversion category. The time chosen typically depends on expected recovery rates and may vary by, for example, forest type, land conditions and management practices and tenure.
Cropland	Reporting lands that are under opportunistic or rotational cropping/grazing/fallow practices.	Management of agricultural lands often moves opportunistically between cropping-pasture/grazing systems or fallow depending on climate, soils and market conditions. Where this occurs countries may choose to either 1) keep reporting these lands under the predominant Land use, if any, or 2) transfer the lands between land use categories each reporting year. Countries using option 1 still apply the methods and emissions factors relevant for the actual land use and management system for estimating emissions and removals. Countries using option 1 typically document the land management practices and how they are grouped into a land use. They also may define the number of years after which if the land has not been cropped the land is moved to Grassland.
	Reporting of orchards, agroforestry or other woody crops.	Depending on the definition of Forest Land used, some areas of orchards, agroforestry and woody crops can meet the definition of Forest Land. Countries typically document which woody crops meet the Forest Land definition and may also create sub-divisions under Cropland or Forest Land to separate these lands.
Grassland	Reporting of wooded areas and other non-grass vegetation such as herbs and brushes that fall below the threshold values used in the Forest Land category.	Where areas of wooded grasslands meet the national definition of Forest Land, they are reported under Forest Land. There may also be some areas of wooded grassland that are considered woody crops, such as naturally occurring areas of fruit or nut trees.

BOX 3.2A. (NEW) (CONTINUED)
EXAMPLES OF ASSIGNING IPCC LAND-USE AND LAND-USE CHANGE CATEGORIES

IPCC land-use categories	Key elements that may need to be considered	Examples
Wetlands	Separating different types of Wetlands and water bodies.	Wetlands include a range of different lands and waterways that occur within a national boundary. Countries typically adopt national definitions of Wetlands. Some also use globally available products such as maps of wetlands reported under the Ramsar [1] convention to assist with sub-categorisation.
	Determining the boundary between land and marine systems.	In many areas there is an indistinct boundary between land and marine ecosystems (e.g., mangroves). To remain consistent with other areas of the inventory, countries typically use the agreed national border to separate land from marine systems. Emissions occurring in the marine ecosystem outside of the national borders are not captured under the AFOLU sector.
Settlements	Reporting of areas that could also be classified as other land-uses.	Settlements may also contain lands with a cover that could be included in other land uses, such as urban parks, lawns and small semi-urban farms. Where an area of land meets the national definition of Forest Land then the land is reported as Forest Land. Other areas, such as lawns, may be included under Settlements unless they meet the definition applied for the other land uses, such as Grassland or Cropland. For example, urban areas with a land cover of scattered trees and grass are often classed as Settlements as they do not meet the definition of Forest Land and are not managed in line with the national definitions for other land use categories.

[1] https://www.ramsar.org/

TABLE 3.1
EXAMPLE STRATIFICATIONS WITH SUPPORTING DATA FOR TIER 1 EMISSIONS ESTIMATION METHODS

Factor	Strata
CLIMATE (see Annex 3A.5)	Boreal Cold temperate dry Cold temperate wet Warm temperate dry Warm temperate moist Tropical dry Tropical moist Tropical wet
SOIL (see Annex 3A.5)	High activity clay Low activity clay Sandy Spodic Volcanic Wetland Organic
BIOMASS (ECOLOGICAL ZONE) (see Figure 4.1, in Chapter 4 Forest Land)	Tropical rainforest Tropical moist deciduous forest Tropical dry forest Tropical shrubland Tropical desert Tropical mountain systems Subtropical humid forest Subtropical dry forest Subtropical steppe Subtropical desert Subtropical mountain systems Temperate oceanic forest Temperate continental forest Temperate steppe Temperate desert Temperate mountain systems Boreal coniferous forest Boreal tundra woodland Boreal mountain systems Polar
MANAGEMENT PRACTICES (more than one may be applied to any land area)	Intensive tillage/Reduced till/No-till Long term cultivated Perennial tree crop Liming High/Low/Medium Input Cropping Systems Improved Grassland Unimproved Grassland

3.3 REPRESENTING LAND-USE AREAS

This section describes three Approaches that may be used to represent areas of land-use using the categories defined in the previous section. The Approaches are presented below in order of increasing information content. Approach 1 identifies the total change in area for each individual land-use category within a country but does not provide information on the nature and area of conversions between land-uses. Approach 2 introduces tracking of land-use conversions between categories, but it does not allow land-use conversions to be tracked through time. Approach 3 extends Approach 2 by allowing land-use conversions to be tracked through time on a spatially explicit basis.

The Approaches are not presented as a hierarchical system. When considering which Approach to adopt countries should consider their national circumstances, including data availability and quality, patterns of land use and land-use change, land management, ecosystem characteristics and the emissions estimation methods to be used. Using activity data that are not consistent with the emissions estimation methods can decrease accuracy of carbon stock changes and the associated emissions and removals estimates.

The Approaches are not mutually exclusive, and a country can use a mix of Approaches for different regions of the country and/or land uses based on national circumstances. In all cases, it is good practice to describe how the approaches are used together and demonstrate how approaches applied cover all the land uses and land use changes, provide consistent time-series and prevent misallocation of lands within and between land use categories.

All data should reflect the historical trends in land-use area, as needed for the inventory methods described in Chapters 2 and 4 to 9 of this Volume. The commencement time for the historical data required is based on the amount of time needed for dead organic matter and soil carbon stocks to reach equilibrium following land-use conversion (20 years is recommended as a default, but can e.g. be longer, e.g., for temperate and boreal systems). After the period to reach equilibrium has passed, land that was added to a land-use conversion category needs to be transferred to "land remaining in a land-use category". The time-series data on land-use conversion is therefore also used to determine the annual transfer of area from the category "land converted to category" to "land remaining in a land-use category".

TIME-SERIES

Inventories require data on land-use area for at least two points in time relevant to the inventory year. For Approach 1 (identifying only the net national change in area of each land-use category, but not the transfers between them), the historical land-use may still not be known. In such circumstances countries should either infer the previous land-use (see Section 3.3.7 below) or assume that the land has remained in the land-use category for all time prior to the land-use conversion. This assumption may underestimate removals where conversions to land-uses with higher carbon contents predominate, or underestimate emissions in the opposite case.

It is important that there is a consistent time-series in the preparation of land-use category and conversion data so that artefact from method change is not included as an actual land-use conversion. Care should also be taken to ensure that the areas of managed and unmanaged land are both defined and estimated consistently. The following section details how to deal with changes in managed land areas (and consequent changes in carbon stock) when using stock change methods for emissions estimation.

CONSISTENT USE OF LAND AREA IN CARBON STOCK ESTIMATES

Over the time-series of a national inventory, it is likely that the total area of managed lands will increase as unmanaged lands are converted to managed land. In this case, where the land area is used to estimate the carbon stock (when using a stock-difference method of emissions estimation), it is possible that the entry of additional land into the inventory (by changing from an unmanaged to managed status) will incorrectly appear as a carbon stock increase. This could wrongly be inferred as a removal from the atmosphere, whereas in reality it is only an increase due to the expanded land-use area over the inventory time-series. To separate carbon stock increases arising from changes in area from true carbon stock changes, carbon stock estimates should be recalculated for the complete inventory time-series area whenever the total area of managed land changes in an annual inventory.

The maximum area of land (and associated carbon stock) at any point in the time-series should be used as the basis for emissions and removals estimation throughout the inventory time-series. Carbon stocks on unmanaged lands can be assumed to remain constant (thus, carbon stock changes would be zero) until the year in which land is classified as a managed use. The recalculation will therefore change the initial carbon stock estimate in the year the land entered the inventory but will not affect the estimation of carbon stock change over the inventory time-series until the relevant land becomes managed.

DATA AVAILABILITY

For many countries, implementing these inventory guidelines may require new data collection. Annex 3A.2.4 provides guidance on remote sensing techniques, Annex 3A.3 provides general guidance on sampling techniques and Annex 3A.4 on spatially explicit (Approach 3) datasets. Where the data needed to apply these inventory guidelines on land-use are not available nationally, data on land categories may be derived from global datasets. For instance, FAO has such datasets, however, care should be taken as these are compiled with national data, (primary data), or secondary data gathered by a third party. More examples are provided in Annex 3A.1, but generally report on the basis of land cover only, and not land-use (See Section 3.3.5). It is preferable that data used should be capable of producing input to uncertainty calculations (See Section 3.5).

When using land-use data, inventory compilers should:

- Harmonize definitions between the existing independent databases as well as with the land-use categories to minimize gaps and overlaps. For example, overlaps might occur if woodland on farms were included both in forestry and agricultural datasets. In order to harmonize data, the woodland should be counted only once for greenhouse gas inventory purposes, taking into account the forest definition adopted nationally (See Section "Multiple land-uses in a single unit of land"). Information on possible overlaps for the purposes of harmonization should be available from agencies responsible for surveys. Harmonization of definitions does not mean that agencies should abandon definitions that are of use to them but should establish the relationship between definitions in use with the aim of eliminating double counting and omissions. This should be done throughout the dataset to maintain time-series consistency.

- Ensure that the land-use categories used can identify all relevant activities. For example, if a country needs to track a managed land-use category such as Forest Land, then the classification system must distinguish managed from unmanaged Forest Land.
- Ensure that data acquisition methods are reliable, well documented methodologically, timely, at an appropriate scale, and from reliable sources.
- Ensure the consistent application of category definitions between time periods. For example, countries should check whether the definition of forest has changed over time in terms of tree crown cover and other parameters. If changes are identified, use the corrected data for recalculation consistently throughout the time-series, and report on actions taken. Guidance on recalculation can be found in Volume 1 Chapter 5.
- Prepare uncertainty estimates for those land-use areas and conversions in area that will be used in the estimation of carbon stock changes, greenhouse gas emissions and removals.
- Ensure that the national land area is consistent across the inventory time-series; otherwise stock changes will reflect false C increases or decreases due to a change in total land area accounted for when using a stock change emissions estimation method.
- Assess whether the sum of the areas in the land classification databases is consistent with the total national area, given the level of data uncertainty. If coverage is complete, then the net sum of all the changes in land area between two time periods should be zero to within the uncertainties involved. In cases where coverage is incomplete, the difference between the area covered and the national area should, in general, be stable or vary slowly with time, again to within the uncertainties expected in the data. If the balancing term varies rapidly, or (in the case of complete coverage) sums are not equal, inventory compilers should investigate, explain, and make any corrections necessary. These checks on the total area should take into account the uncertainties in the annual or periodic surveys or censuses involved. Information on uncertainties should be obtained from the agencies responsible for the surveys. Remaining differences between the sum of areas accounted for by the available data and the national area should be within the expected uncertainty for area estimation.

For some activities reported, such as the application of nitrogen fertilizer, liming and harvested wood products, only national aggregate data may be available. Where emissions and removals estimation methods are applied at a national level, it is appropriate to use such data without categorization by land-use

3.3.1 Three Approaches

APPROACH 1: TOTAL LAND-USE AREA, NO DATA ON CONVERSIONS BETWEEN LAND-USES

Approach 1 represents land-use area totals within a defined spatial unit, which is often defined by political boundaries, such as a country, province or municipality. Another characteristic of Approach 1 data is that only the net changes in land-use area can be tracked through time. Consequently, the exact location or pattern of the land-uses is not known within the spatial unit, and moreover the exact changes in land-use categories cannot be ascertained. Datasets are likely to have been prepared for other purposes, such as forestry or agricultural statistics. Frequently, several datasets will be combined to cover all national land classifications and regions of a country. In this case the absence of a unified data system can potentially lead to double counting or omission, since the agencies involved may use different definitions of specific land-use for assembling their databases. Ways to deal with this are suggested below.

Tables 3.2 and 3.3 show summary land-use area data for a hypothetical country (with a national land area of 140 million ha) using locally relevant land classifications. Table 3.2. is prepared at the level of the broad land-use categories. Table 3.3 depicts the same information with example stratifications to estimate the effect of various activities using the emissions estimation methods described elsewhere in this Volume.

Determination of the area of land-use conversion in each category is based on the difference in area at two points in time, either with partial or full land area coverage. No specification of inter-category conversions (i.e., 'land remaining in a land-use category' and 'land converted to a new land-use category') is possible under Approach 1 unless supplementary data are available (which would then introduce a mix with Approach 2).

The land-use area data may come originally from periodic sample survey data, maps or censuses (such as landowner surveys), but will probably not be spatially explicit. The sum of all land-use category areas may or may not equal the total area of the country or region under consideration, and the net result of land-use conversions may or may not equal zero, depending on the consistency in data collection and application in the inventories for each land-use category. The final result of this Approach is a table of land-use at given points in time. Because the total land base that is reported each year for all land-use categories should remain constant, a table similar to Table 3.3 should be generated as a QA/QC measure. If inconsistencies are found, it is *good practice* to identify and correct the problem(s) for future inventories. This may require closer coordination among inventory teams for separate land-use categories (if analysed separately) or possibly new surveys or other types of data collection.

Other parts of this Volume require information on land area in each land-use category presented in Table 3.3 to be broken down into the categories “land remaining in the same land-use category” and “land converted to a new land-use category”. This is dependent on methodological requirements in other chapters of this Volume. If land-use data are not sufficient to support Approach 2 (see below), where the total (gross) land conversion areas can be quantified, the emissions and removals may be reported in the “land remaining in the same land-use category” (as specified in Table 3.2). This is because the data may only be sufficient to identify the net change in area of each land-use category, and not the total effect of all land conversions. However, in general the methods for both soils and biomass related emissions estimation require land area data categorized by “lands remaining” and “converted to” categories and thus it is desirable to do this if possible, even if this is done using expert judgment.

Note that by reporting only in the “land remaining” category, emissions and removals will include, but not explicitly reflect a changing land base within a land-use category (different areas, e.g., by the net transition in areas to and from the Forest Land category) over time. This may overestimate or underestimate emissions for that particular “land remaining” category. However, a complete inventory will tend to counter-balance this with emissions and removals from another “land remaining” category in the inventory.

It is acceptable to report non-CO_2 emission by source category without attribution to land-uses if emissions are estimated based on national statistics, without reference to individual land-uses (e.g., N_2O emissions from soils). Methods outlined in this Volume frequently estimate emissions using national statistics in this manner.

TABLE 3.2
EXAMPLE OF APPROACH 1: AVAILABLE LAND USE DATA WITH COMPLETE NATIONAL COVERAGE

Time 1			Time 2			Net land-use conversion between Time 1 and Time 2		
F	=	18	F	=	19	Forest Land	=	+1
G	=	84	G	=	82	Grassland	=	-2
C	=	31	C	=	29	Cropland	=	-2
W	=	0	W	=	0	Wetlands	=	0
S	=	5	S	=	8	Settlements	=	+3
O	=	2	O	=	2	Other Land	=	0
Sum	=	140	Sum	=	140	Sum	=	0

Note: F = Forest Land, G = Grassland, C = Cropland, W = Wetlands, S = Settlements, O = Other Land. Numbers represent area units (Mha in this example).

TABLE 3.3
ILLUSTRATIVE EXAMPLE OF STRATIFICATION OF DATA FOR APPROACH 1

Land-use category/ strata	Initial land area (million ha)	Final land area (million ha)	Net Change in area (million ha)	Status
Forest Land total	**18**	**19**	**1**	
Forest Land (Unmanaged)	5	5	0	Not included in the inventory estimates
Forest Land (temperate continental forest; converted to another land-use	7	8	1	Estimates should be prepared on the 8 million ha
Forest Land (boreal coniferous)	6	6	0	No land-use conversion. Could require stratification for different management regimes etc.
Grassland total	**84**	**82**	**-2**	
Grassland (Unimproved)	65	63	-2	Fall in area indicates land-use conversion. Could require stratification for different management regimes etc.
Grassland (Improved)	19	19	0	No land-use conversion. Could require stratification for different management regimes etc.
Cropland total	31	29	-2	Fall in area indicates land-use conversion. Could require stratification for different management regimes etc.
Wetlands total	**0**	**0**	**0**	
Settlements total	**5**	**8**	**3**	
Other Land total	**2**	**2**	**0**	Unmanaged - not in inventory estimates
TOTAL	**140**	**140**	**0**	Note: areas should reconcile

Note: "Initial" is the category at a time previous to the date for which the assessment is made and "Final" is the category at the date of assessment. Activities for which location data are not available should be identified by further sub-categorisation of an appropriate land category.

APPROACH 2: TOTAL LAND-USE AREA, INCLUDING CHANGES BETWEEN CATEGORIES

The essential feature of Approach 2 is that it provides an assessment of both total losses and gains in the area of specific land-use categories and what these conversions represent (i.e., changes both from and to a category). Thus, Approach 2 differs from Approach 1 in that it includes information on conversions between categories, but is still only tracking those changes across two points in time. Tracking land-use conversions in this manner will normally require estimation of initial and final land-use categories for all conversion types, as well as of total area of unchanged land by category. The final result of this Approach can be presented as a non-spatially-explicit land-use conversion matrix. The matrix form is a compact format for representing the areas that have come under different conversions between all possible land-use categories. Existing land-use databases may have sufficient detail for this Approach, or it may be necessary to obtain data through sampling or other methods. The input data may or may not have originally been spatially-explicit (i.e., mapped or otherwise geographically referenced).

For Approach 2, emission and removal factors can be chosen to reflect differences in the rate of changes in carbon according to the conversions between any two categories, and differences in initial carbon stocks associated with different land-uses can be taken into account. For example, the rate of soil organic carbon loss will commonly be much higher from cropping than from pasture.

Approach 2 is illustrated in Table 3.4 using the data from the Approach 1 example (Table 3.3) by adding information on all the conversions taking place. Such data can be written in the more compact form of a matrix and this is presented in Table 3.5. To illustrate the added value of Approach 2 and this land-use conversion matrix format, the data of Table 3.5 is given in Table 3.6 without the stratification of the land-use categories. This can be compared with the more limited information from Approach 1 in Table 3.2. In Table 3.6, the conversions into and out of land categories can be tracked, whereas in Table 3.2 only the net changes in a broad land-use category are detectable.

In Tables 3.5 and 3.6, the area in the diagonal cells represents the area in each land-use category that was not affected by land-use conversion in this inventory year. In preparation for the greenhouse gas emission and removal estimations described elsewhere in this Volume, this area should be further sub-divided into the area that has remained in the land-use category and area that has been affected by a land-use conversion (i.e., the land converted to a different land-use category) in the previous Y years (where Y is the time period during which C pools are expected to reach equilibrium (the IPCC default is 20 years, based on soil C pools typical time to equilibrium after land-use conversion).

Therefore, under the default assumption in every inventory year, the area converted to a land-use category should be added to the category "land converted to" and the same area removed from the land remaining in the land-use category. The area of land that entered that "land converted to" category, 21 years ago (if using the default 20 year period), should be removed and added to the category "land remaining land". For example, in Table 3.5 if data indicated that four of the 56 Mha in the Grassland category had been converted from Forest Land 21 years ago, then four Mha of land should be moved from the *category Land Converted to Grassland* to the *category Grassland Remaining Grassland* in this annual inventory.

TABLE 3.4
ILLUSTRATIVE EXAMPLE OF TABULATING ALL LAND-USE CONVERSION FOR APPROACH 2 INCLUDING NATIONALLY DEFINED STRATA

Initial land-use	Final land-use	Land area, Mha	Inclusions/Exclusions
Forest Land (Unmanaged)	Forest Land (Unmanaged)	5	Excluded from GHG inventory
Forest Land (Managed, temperate continental)	Forest Land (Managed, temperate continental)	4	Included in GHG inventory
Forest Land (Managed, temperate continental)	Grassland (Unimproved)	2	Included in GHG inventory
Forest Land (Managed, temperate continental)	Settlements	1	Included in GHG inventory
Forest Land (Managed, boreal coniferous)	Forest Land (Managed, boreal coniferous)	6	Included in GHG inventory
Grassland (Unimproved)	Grassland (Unimproved)	61	Included in GHG inventory
Grassland (Unimproved)	Grassland (Improved)	2	Included in GHG inventory
Grassland (Unimproved)	Forest Land (Managed, temperate continental)	1	Included in GHG inventory
Grassland (Unimproved)	Settlements	1	Included in GHG inventory
Grassland (Improved)	Grassland (Improved)	17	Included in GHG inventory
Grassland (Improved)	Forest Land (Managed, temperate continental)	2	Included in GHG inventory
Cropland	Cropland	29	Included in GHG inventory
Cropland	Forest Land (Managed, temperate continental)	1	Included in GHG inventory
Cropland	Settlements	1	Included in GHG inventory
Wetlands	Wetlands	0	Included in GHG inventory
Settlements	Settlements	5	Included in GHG inventory
Other Land	Other Land	2	Excluded from GHG inventory
TOTAL		**140**	

Note: Data are a stratified version of those in Table 3.3. Sub-categories are nationally defined and are illustrative only. “Initial” indicates the category at a time previous to the date for which the assessment is made and “Final” the category at the date of assessment.

TABLE 3.5
ILLUSTRATIVE EXAMPLE OF APPROACH 2 DATA IN A LAND-USE CONVERSION MATRIX WITH CATEGORY STRATIFICATION

Initial / Final	Forest Land (unmanaged)	Forest Land (managed, temperate continental)	Forest Land (managed, boreal coniferous)	Grassland (unimproved)	Grassland (improved)	Cropland	Wetlands	Settlements	Other Land	Final area
Forest Land (unmanaged)	5									**5**
Forest Land (managed, temperate continental)		4		1	2	1				**8**
Forest Land (managed, boreal coniferous)			6							**6**
Grassland (unimproved)		2		61						**63**
Grassland (improved)				2	17					**19**
Cropland						29				**29**
Wetlands							0			**0**
Settlements		1		1		1		5		**8**
Other Land									2	**2**
Initial area	**5**	**7**	**6**	**65**	**19**	**31**	**0**	**5**	**2**	**140**
Net change	0	1	0	-2	0	-2	0	+3	0	**0**

Note: Column and row totals show net conversion of land-use as presented in Table 3.3. "Initial" indicates the category at a time previous to the date for which the assessment is made and "Final" the category at the date of assessment. Net changes (bottom row) are the final area minus the initial area for each of the (conversion) categories shown at the head of the corresponding column. Blank entry indicates no land-use conversion for this transition.

TABLE 3.6
SIMPLIFIED LAND-USE CONVERSION MATRIX FOR APPROACH 2 EXAMPLE

Gross and Net land-use conversion matrix

Initial / Final	F	G	C	W	S	O	Final sum
F	**15**	3	1				**19**
G	2	**80**					**82**
C			**29**				**29**
W				**0**			**0**
S	1	1	1		**5**		**8**
O						**2**	**2**
Initial sum	**18**	**84**	**31**	**0**	**5**	**2**	**140**

Note:
F = Forest Land, G = Grassland, C = Cropland, W = Wetlands,
S = Settlements, O = Other Land
Numbers represent area units (Mha in this example).

APPROACH 3: SPATIALLY-EXPLICIT LAND-USE CONVERSION DATA

The key defining characteristic of Approach 3 is that it is both spatially and temporally consistent and explicit. Sample-based, survey-based and wall-to-wall methods can be considered Approach 3 depending on the design of the sampling/mapping program and the way the data is processed and analysed (Table 3.6A). The decision to use sample based, survey based or wall-to-wall methods, and how to process them, depends on national circumstances and the method applied to estimate carbon stock changes and the associated emissions and removals.

Approach 3 data can be summarized in tables similar to Tables 3.5 and 3.6. The main advantage of spatially-explicit data is that analysis tools such as Geographic Information Systems can be used to link multiple spatially-explicit data sets (such as those used for stratification) and describe in detail the conditions on a particular piece of land prior to and after a land-use conversion. This analytical capacity can improve emissions estimates by better aligning land-use categories (and conversions) with strata mapped for classification of carbon stocks and emission factors by soil type, vegetation type. This may be particularly applicable for Tier 3 emission estimation methodologies. However, issues of compatible and comparable spatial resolutions need to be taken into account. An overview of potential methods for developing Approach 3 datasets is provided in Annex 3A.4.

3.3.2 Data of Land Representation

Figure 3.1 is a decision tree to assist in describing and/or obtaining the data on land-use areas. It provides guidance on which Approach and method a country can use for representing lands depending on the availability of primary and secondary datasets. Approach 3 method, for example, can be applied if spatially explicit land-use data is available for the whole country including complete time series coverage. Geographically mixed Approach (1, 2 & 3) can be used where limited spatial data is available. As shown in this figure, where data is missing new data can be collected or international datasets can be used to minimise gaps in geographical coverage. Similarly, interpolation or extrapolation techniques can be used where complete time series is not available and new data cannot be collected. This will ensure all lands are represented consistently using one of the three generic approaches. Lastly, it is important to document the choice of methods applied for land representation.

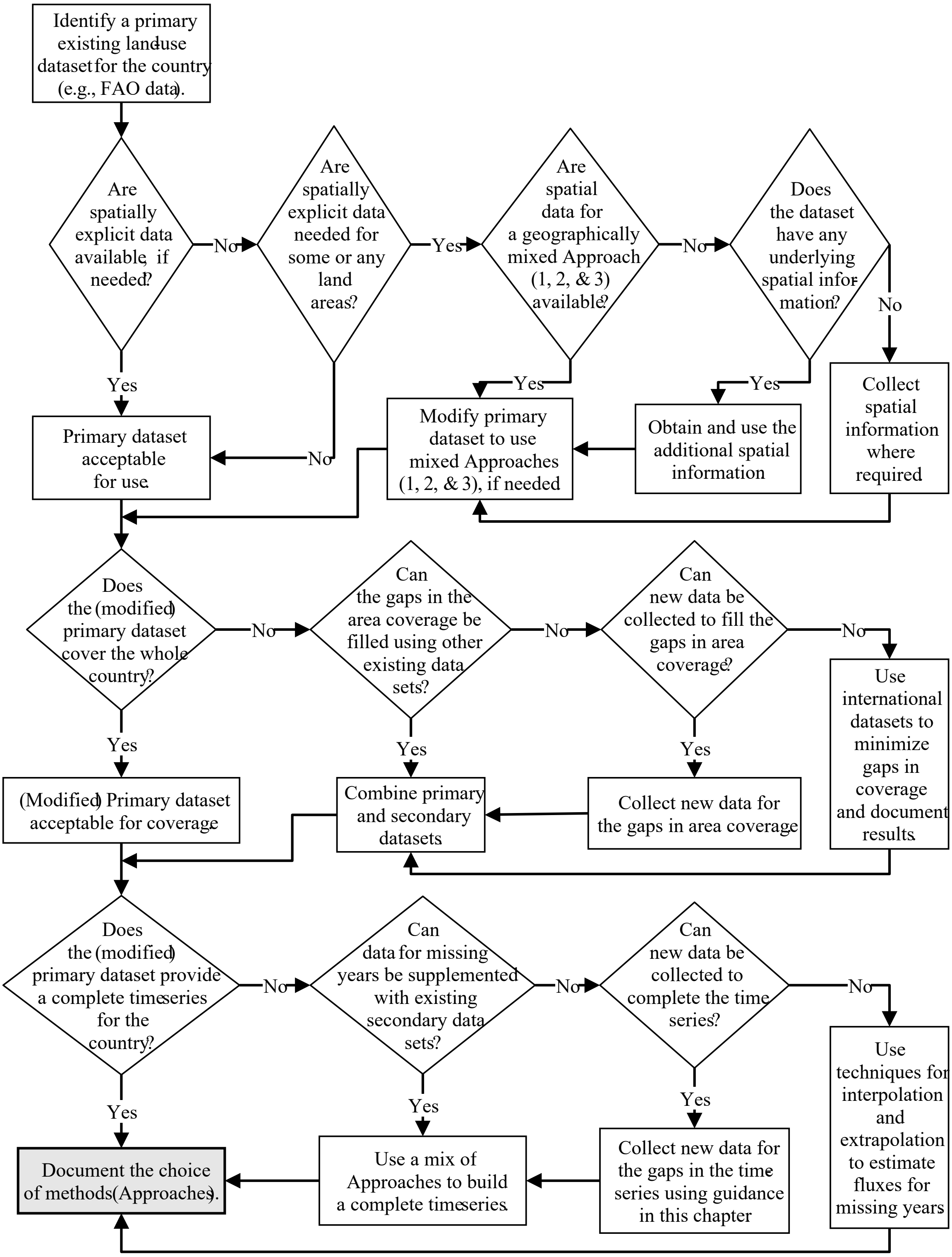
All three Approaches can, if implemented appropriately and consistently, be used to produce robust greenhouse gas emission and removal estimates. However, it should be noted that Approach 1 will probably not detect changes in biomass, such as those due to the full extent of deforestation and reforestation on separate areas of land, but only those due to the net conversion of land-use area from a forest to a non-forest use. In general, only Approach 3 will allow for the spatial representation required as an input to spatially-based carbon models.

Different Approaches may be more effective over different time periods or may be required for different reporting purposes. Methods to carry out matching of the time-series between the different periods or uses should be applied.

There are numerous sources of data and methods to process data that can be used to derive activity data. It is not necessarily the data itself that determines of the approach. For example, depending on how the data is used, a time-series of data could be used to generate information at Approaches 1, 2 or 3. Other data, such as single surveys or sample processes used in isolation can only generate activity data at Approach 1. Where the data available allow for the application of approach higher than approach 1 it is *good practice* to do so to ensure that uncertainties are minimized as far as practicable. Table 3.6A provides some examples of different data and methods and the resulting Approach.

TABLE 3.6A (NEW) EXAMPLES OF DIFFERENT DATA INPUTS AND METHODS TO DERIVE IPCC LAND-USE CLASSES AND THE RESULTING APPROACHES (1, 2 OR 3)[1]			
Method	**Approach 1**	**Approach 2**	**Approach 3**
Sample-based methods	• Single sample • Temporary sample units	• Samples collected from permanent units but changes only tracked across two consecutive sample periods.	• Permanent and consistent georeferenced ground plots. • Continuous and consistent samples using remote sensing data.
Survey-based methods	• Single census at one point in time. • Repeat census but without reference to previous censuses.	• General surveys between two periods. • National census data that can refer a past period.	• Specific survey designs that identify activities through time for each land unit within a known region.
Wall-to-Wall methods	• Single map • Inconsistent maps developed at different times.	• Inconsistent maps through time combined with Approach 2-type samples (e.g. using maps as stratifications). • Maps developed using consistent methods changes tracked across two consecutive maps only not tracked through a time-series of maps.	• Tracking pixels / land units using time-series consistent data.
[1] These examples assume that only one type of data and process is used. In many cases the data inputs and processes can be combined resulting in a higher quality of the land representation than can be achieved with any one single data source.			

Figure 3.1 Decision tree for preparation of land-use area data



3.3.3 Methods for Land-Use and Land-Use Change Estimation

The three main methods for estimating areas of land-use and land-use change are sample-based, survey-based and wall-to-wall. These methods are not mutually exclusive; for example, wall-to-wall methods typically require samples for calibration, validation and uncertainty analysis, and some sample methods require wall-to-wall maps for scaling as well as for dimensioning the sample size and designing the sample grid. The method itself does not determine the Approach and all these methods can be used to develop land-use information at Approaches 1, 2 or 3 (see Table 3.6A).

Wall-to-wall methods

The continually increasing volume and improving quality of data available from remote sensing allows countries to develop wall-to-wall maps of land cover and land cover change that, when combined with other data, can be used to generate land-use and land-use change information. There are numerous potential applications for remote sensing products to derive consistent land use and land use change estimates:

- identifying land cover and land cover change (e.g., forest cover change and multiple land cover change types);
- attribution of land cover change to specific disturbances (e.g., harvesting, clearing, fire) and processes (e.g., biomass growth) to determine land use; and,
- stratification of land-use categories into logical units that facilitate the estimation of emissions and removals, such as forest condition, growth stage, time since disturbance and forest type.

Although there is an ever-increasing focus on and availability of remote sensing data for wall-to-wall mapping, it is also possible to generate wall-to-wall methods using traditional mapping processes. For example, some countries have access to detailed maps of forest stands or agricultural areas with associated records of human interventions (such as harvesting) and other disturbances, such as fire. Combining these maps and records can produce time-series consistent activity data. Where maps are not available, the record data can still be used in a survey type approach.

There are two broad wall-to-wall methods:

1. a consistent time-series of data using the same or similar sensors, common analysis methods and time-series processing methods; and,
2. one or more maps developed using different sensors and methods, and not applying time-series consistent processes.

When using Approach 3, wall-to-wall methods it is *good practice* to:

- minimize the influence of misalignment of images or artefacts in data (e.g., cloud cover);
- ensure the data will be consistent with the methods for estimating emissions and removals
- ensure the time-series is dense enough to identify activities that drive emissions and removals (e.g., if the period between two points in time (i.e. the change detection period) is 5 years, but forest cover following clearing or harvesting recovers in 2 years, then management events affecting emissions and removals may be missed, depending on the method applied);
- demonstrate that, in cases where the time between maps differ (e.g., a 5-year gap, followed by a 2-year gap), this does not bias results by changing detection rates;
- use that the sensor data used in the maps does not cross over the mapping time period. For example, when creating composite products (e.g., to remove cloud or sensor errors) ensure that the images selected for one year are not the same or cross over image dates in the previous or following years (cross over occurs when e.g., a 2005 map uses data from 2002-2008 and a 2010 map uses data from 2007-2013);
- demonstrate that the changes tracked through time are consistent and to report on any corrected biases and known uncertainties of the analysis.
- ensure that any improvements made to any single map in the time-series are consistently applied to the other maps in the time-series and the results are recalculated, in particular when new maps are added to the time-series; and
- evaluate the final products to ensure consistent representation of land-use with no double counting or omission of lands.

An example of an Approach 3 wall-to-wall approach can be found in Australia's national inventory report (Department of the Environment and Energy 2018).

It is challenging to maintain a spatially consistent time series where different land cover maps have been developed using different data (e.g., different sensors) or methods (different algorithms or operators using visual interpretation). In such cases it may not be possible to use this data in an Approach 3 context, since it is difficult to ensure that the land-uses will be spatially consistent through time in the time series. However such data may be used to stratify samples used in the application of Approach 2 (GFOI 2016).

When using wall-to-wall Approach 2 methods it is *good practice* to:

- describe the difference between the land cover data in the time series;
- apply sample-based methods to determine uncertainties and correct for bias; and
- describe how areas with potential multiple changes in land-use through time are addressed in estimating emissions and removals using the data.

Sample based methods

Sample based methods directly estimate land-use and land-use change from repeated samples. Samples may be obtained from ground surveys (such as a national forest inventory or national land survey) or remote sensing (e.g., satellite imagery, aerial photography or lidar or a combination of both). Well-designed sample-based methods provide an accurate statistical representation of land-use and land-use change but do not provide information on every specific area of the land territory (i.e. is not wall-to-wall spatially explicit).

The two most common sampling methods applied are:

- permanent sampling methods, where the same sample area is measured or analysed through time using consistent methods and processes; and,
- temporary sampling methods, where data is collected for only one point in time or, if repeated measurements are taken through time, these are not taken for the same locations.

Within these two broad methods there are a range of options countries can apply, including combining permanent and temporary sampling methods.

Where permanent sample methods have been applied it is possible to use these data in an Approach 3 system by tracking each sample unit through time and determining the history and scaling appropriately. These units could also be used in an Approach 2 method by only determining land use and land use change between two consecutive periods. An example of Approach 3 sample based method for estimating land-use and land-use change can be found in Sweden's national inventory report (Swedish Environmental Protection Agency 2016).

Where only temporary sample units are used without repeat measurements, it is not possible to apply Approach 2 or 3 methods unless temporary sample data is combined with other data (auxiliary data or permanent plots).

A key issue when selecting a sampling design is that the sampling methods must be able to be applied over the whole area of interest and the sample size must be large enough to produce sufficiently accurate estimates of land-use and land-use change categories and sub-divisions, given the policy requirement and the costs involved. No matter what type of sample method applied (ground or remote sensing), it is *good practice* to ensure:

- a sufficient number of samples are used with repeat measurements over time to identify both land-use and land-use changes with a desired level of uncertainty;
- where samples are used to determine land cover, that these data are used with other information, if necessary, to identify the land-use category;
- samples are collected or re-measured with sufficient temporal frequency to ensure land-use changes and management events affecting emissions and removals are identified;
- samples are collected with sufficient temporal consistency that detection rates of change do not alter due to differences in sampling frequency;
- where sampling methods have changed through time, these changes do not lead to inconsistencies in the reporting of areas of land-use and land-use change; and
- the sample assessment protocols are well documented.

Survey based methods

Statistical survey methods involve obtaining information on land-use and land-use change and land management practices either through national programs or through targeted requests to land holders, land management agencies and companies.

There are two broad methods for statistical surveys:

- surveys that collect information on land management practices through time for a specific area or land use; and,
- surveys that aim to collect information on land use and management practices in a specific period only, or only on land use without information on land management.

Surveys can provide inventory compilers with access to lists of stands or land areas subject to different land-use and activities. These lists can provide detailed information on land areas and their management but may or may not include information on the exact location of the land unit. For example, within a region, information on the area, species, type and management of all forest areas (stands) may be available to the inventory compiler as a table, but the exact location of the stand is unavailable (e.g., due to privacy, commercial or political reasons). This data can be particularly accurate for land-uses with high-commercial value as detailed data is collected on these. However, these types of survey data do have temporal consistency and known geographic boundaries and can be considered Approach 2 or 3 depending on whether the land use changes are tracked across time or not. When using this method, it is *good practice* to:

- ensure that the area of the land units surveyed is consistent with the area of the entire land use category and other land uses, in particular where the land units do not cover all the land-use categories (i.e., where a mix of Approaches are applied); and
- where possible, compare the area estimates obtained from other methods, such as sample-based methods.

Surveys that provide an estimate of the area of land use for a single point in time or where land use and activities cannot be assigned to any land unit only can be used to develop Approach 1 land representation. This data is often used in combination with other data to develop a complete land use estimate. An example of an Approach 3 survey based approach for estimating land-use and land-use change can be found in Canada's national inventory report (Environment and Climate Change Canada 2018).

3.3.4 Combining Multiple Data Sources

Remote sensing products are increasingly being used by countries as a source of information to estimate land-use and land-use change (GFOI 2016). The most common use of these products is to detect land cover and cover change. There are few cases where one single data source or method are used to develop area estimates for land-use and land-use change for all strata, sub-strata and reporting categories. For instance, while remote sensing data is useful for identifying land cover and where a change in cover has occurred, the resulting products often do not provide information on the drivers that occurred to cause the change, the actual land uses and the likely associated emissions and removals. Combining remote sensing data products with other data sources is often required to obtain all the required information for estimating emissions and removals and to correctly allocate lands to the IPCC land-use categories over time.

Typically, countries will combine a variety of different data sources and approaches to estimate areas of land-use. This could include multiple remote sensing products (including wall-to-wall and sampling approaches), census, survey, farmer interviews, field observations, expert knowledge, or some combination of these sources (Ogle *et al.* 2013; GFOI 2016). Combinations of data sources may also occur within a type of data. (e.g., national and regional or local statistics may be combined when national data is incomplete). These may occur for several reasons, including that the time-series is incomplete (i.e. some years are missing and are supplemented with other statistics), a land-use class or stratum is missing (e.g. sugarcane area is missing in the national cropland area statistics), more accurate statistics are available (e.g. from a different data provider).

When combining different data types and sources it is *good practice* to:

- report the spatial and temporal scales of the data sources;
- ensure consistency between different temporal or spatial scales in the data sources;
- verify spatial datasets conform to national mapping standards (e.g., appropriate equal area projections) to ensure accurate area calculations, and that raster and/or vector layers align and are within official national boundaries;
- ensure that land conversion areas are consistent with each other across the entire time-series. For example, losses in the area of Forest Land categories are consistent with gains in the areas of Forest Land converted to Cropland, Grassland, Settlements, Wetlands, and Other Land;
- ensure that the land conversion period is applied consistently across all land-use categories (i.e., that the same number of years is used before lands in a 'converted to' sub-category move to the 'remaining' sub-category);
- establish a hierarchy among various data sources and proceed to their integration accordingly (i.e., higher quality data prevail to other data when an inconsistency appears among them);
- fill data gaps to derive consistent time-series of land-use and land-use change (See Section 5.3, Chapter 5 Volume 1); and,
- report uncertainties of land-use and land-use change estimates.

Spatially explicit approaches are commonly combined with other spatial data (e.g., forest and/or soil types, climate data) to produce emissions estimates. When using multiple spatial data layers, especially when combining vector and raster data sources of different spatial and temporal resolutions (Merchant & Narumalani 2009) it is *good practice* to ensure that:

- all data layers are registered to a common projection, and that the layers align as far as possible, to prevent errors due to misalignment such as slivers or areas of false change along the edges of boundaries between different land-use categories;
- reprojection of spatial data do not cause errors if applied correctly using appropriate type of projection for a given location (Seong 2003);
- when combining data of different pixel sizes (e.g., climate data at 1km, with satellite land cover data at 25m) that the pixels align with ground coordinates; and,
- if pixels are resampled (e.g., resampling of Landsat pixels from nominal 30 m to 25 m) this is done prior to classification.

3.3.5 Derivation of IPCC Land-Use Categories from Land Cover Information

Inferring land use from land cover at a specific point in time can lead to misclassification of the predominant land-use. It is *good practice* to clearly document the country-specific rules applied in the inventory to consistently derive land-use from land cover, both spatially and temporally, including predominance among land use categories. When deriving IPCC land-use and land-use change categories from land cover data, the following generic steps should be considered:

- translate remote sensing data to land cover types using decision rules and image classification;
- develop rules to translate land cover and cover change types to land-use and land-use change categories (i.e., attributing land cover information to land-use) using well-defined specific supplementary information
- collect any required supplementary information and apply the developed rules.

Existing national data

Existing national data can be used for estimating land areas, alone or in combination with other data to derive IPCC land-use categories. Defining the equivalence between national land-use categories and IPCC land-use categories may not be straightforward, as national datasets are often developed for other purposes and do not necessarily match the IPCC definitions. For example, the definition of forest cover in some existing remote sensing products may differ from the nationally adopted definition for Forest Land. Even where the definitions are the same, existing forest type maps generally cannot compare to new remote sensing products due to differences in spectral and geometrical resolutions and the methods applied for land-use classification. This is particularly the case for older forest type maps derived from visual interpretation compared to semi-automated and automated methods.

In developing IPCC land-use information, it is *good practice* to:

- define the national land-use categories and develop rules to track them in the inventory, where needed;
- describe how multiple data sources are combined to classify land-use and how the methods ensure consistent representation of lands;
- demonstrate that the land-use categories definitions cover the entire variability of land-uses of the country territory, and do not overlap;
- report an equivalence table between the categories used in the national land-use classification scheme and the IPCC land-use categories defined in Section 3.2, and
- report which land cover elements and classification rules are used to identify land-use categories and attributions, including predominance among land uses. The applied classification rules need to be explained by reporting additional information used and any assumptions made to match land-use categories for the national classification system and the IPCC Guidelines discussed in this Chapter.

Global datasets for land-use classification

Accuracy of global products (Table 3.A.1.1) varies regionally due to factors including differential sensitivity of detection at biome and eco-regional scales, limited availability of regional data to calibrate algorithms and limited validation of outputs. Furthermore, many global products only produce estimates of land cover not land-use, with definitions that may not match national country definitions. Because of these issues, using global maps for inventory reporting can lead to inconsistencies in data and tend to produce activity data estimates with lower accuracy and higher uncertainty than are attainable by national mapping (GFOI 2016). Conversely, national products can be tuned to national circumstances and land-use definitions using knowledge and auxiliary data available at the national/international level. Therefore, when using global data sets, it is *good practice* to:

- assess the consistency of the global dataset with national definitions of land-use and suitability for reporting (e.g., time-series consistency, spatial scales, update processes);
- assess the accuracy of the products for the mapped land-use categories and correct for bias by using ground or other reference data; and,
- ensure that the accuracy assessment processes represent not just the IPCC land-use categories, but also the strata (e.g., by forest types, areas impacted by disturbances, soil classes) used to estimate emissions and removals.

National assessment of the relative advantages of global and national maps to generate national level estimates of land-use and change are also related to: 1) preferences for national ownership of the process; 2) whether national mapping capacity already exists and 3) national needs for a land cover map (e.g. related to forest definition and land cover classifications, for integration with domestic planning).

The relationship between global data and the national land-use definitions is important and in comparing national estimates and global products, it is *good practice* to:

- ensure that products are applied to the same geographic extent and time period;
- ensure that the land-use area and changes derived from the global data correspond as nearly as possible to the national definitions and legend;
- use reference observations consistent with the national definition. If the reference data are stratified, e.g. by accessibility or biomass quantity, strata should be applied consistently over time irrespective of whether national or global map products are being used; and,
- reduce common inconsistencies between global data and national definitions which are related to e.g. the minimum canopy cover thresholds, detailed consideration of land-use, the minimum size of land-use areas, and the minimum tree height.

Addressing gaps in remote sensing data

National inventories require annual estimates of emissions and removals and ideally, annual data would enable the generation of annual estimates of change for all land-uses. In practice, such data is not always available for all land-uses for every year and the cost of obtaining and processing the data may be too high. Consequently, inventory compilers will likely need to decide which data to collect, how frequently and to apply methods, such as splicing techniques, to cover these gaps.

When covering data gaps from unavailable land-use and land cover data, it is *good practice* to:

- define, document and report the years where remote sensing data are missing. When the number of years between data availability varies, demonstrate that the land-use change detected across the time series is consistent and not influenced by the change in frequency of observations;
- justify the choice of the methods used to fill the data gap, and describe the method used for interpolation or extrapolation consistent with the guidance provided in Chapter 5, Volume 1. When using interpolation methods, if the land-use category on a sample unit or on a land use changes between consecutive inventories the year of conversion should be identified. If this is not possible a random year for the conversion should be selected. When extrapolating missing data based on trends and proxies, justify the length of the time-series used to develop the trend. Whenever possible use functional proxies (i.e. driver of changes) for extrapolation or interpolation; and
- report the limitations and consequences of filling land cover data gaps with the chosen method. Whenever possible, estimate, document and report the uncertainty linked to the remote sensing annual data available and the uncertainty linked to the periods where this data is not available.

Further, in the case of remote sensing data, some areas of land may not be covered with data in every period. This often occurs due to persistent cloud or haze, errors in the satellite or due to limited acquisitions in some areas. These areas are often removed from the analysis and classed as ‘no data’. Where wall-to-wall approaches are used, these gaps may lead to errors in the estimates of land-use and land-use change. This problem increases with increasing temporal density of the data. As such it is *good practice* to apply methods that can accurately fill these data gaps in a time-series consistent manner (See Annex 3A.2.4 for examples).

3.3.6 Stratification of land-use data

Once land-use and land-use conversion areas have been established, it is necessary to consider the capacity and need for further stratification.

Stratification is the process of disaggregating a land-use category (e.g. Forest Land, Cropland, Grassland) into logical, typically homogenous, sub-divisions (e.g. tropical/dry forest, crop types, improved or unimproved pastures). This process is commonly applied to reduce the uncertainty of emissions and removals estimates as it is useful to:

- estimate emissions and removals for key land-use sub-categories;
- enable tailoring of specific methods or data collection processes in different strata. For example, due to weather conditions and cloud effects, it is much more difficult to measure Forest Land converted to other land uses using multispectral remote sensing data in fragmented dryland forests than contiguous moist tropical forests;
- track areas under conversion across time-series, especially to deal with subsequent changes;
- assist in the management of uncertainties and plan continuous improvement of the inventory;
- increase the flexibility in reporting of monitored data, such as the effectiveness of policies tailored to specific strata (e.g. forest types, risk types).

Stratification may be needed to locate relevant data from subsequent chapters for emissions factors, carbon stocks, etc. Table 3.1 shows the typical stratifications for which data are available for the application of Tier 1 emissions and removals estimation. Throughout the default tables used to populate equations to calculate a Tier 1 inventory, specific data cells are highlighted that represented the pre-defined stratifications applied to Tier 1 inventories. That is, Tier 1 default data (tables) conform to a consistent stratification so that there is no further calculation or ambiguity in the appropriate selection of default data to populate equations. Where countries are preparing Tiers 2 and 3 inventories, it is likely that stratification schemes may differ based on country-specific information and selection, manipulation or supplementation of default data may be required.

Common strata include layers such as soils, site class, topography, aspect, dominant tree species or species clusters are commonly used for stratification. However, unless all land-use area and stratification data are spatially-explicit (Approach 3), the development of rules for allocations to strata may be required. Table 3.6B provides some examples of possible data types and assumptions to stratify land-use and land cover.

TABLE 3.6B (NEW)
EXAMPLES OF AUXILIARY DATA AND POSSIBLE ASSUMPTIONS THAT CAN HELP TO DETERMINE AND STRATIFY LAND-USE.

Issue	Data	Possible assumptions[1]
Separate forest cover change due to management activities from land use changes	Maps of forest management areas Data on forest management practices and harvesting plans	Areas of cover change in Forest Land are due to harvesting (i.e., not land use change)
Separate cover changes between those associated with natural disturbances (these are only cover changes)l and those due to human intervention (e.g. land use changes or harvesting)	Maps of disturbances, such as fire or pest extent maps Maps of National parks and protected areas	Changes in cover that occur at the same time as fire or pest attack may be considered due to these causes unless otherwise noted. In certain circumstances, cover changes under certain tenures (such as national parks) may be due to natural processes, but these still need to be assessed.
Determine if the forest type is natural or plantation	Maps of plantation management areas, private plantation areas. Knowledge of new planting areas and policies Soils and climate	Forest areas within the plantation areas can be considered plantations. Areas of newly established forest classes depending on known planting types Commercial plantations only occur on specific soils or in climatic ranges
Separate crop types and management practices	Climate (rainfall, temperature etc), soil characteristics or soils types Known crop products by region (agricultural stats)	Certain crops and management practices can occur in certain regions (e.g. no crops in a desert, no-tillage cultivation in low organic matter soils) Use product offtake to determine the types of crops being grown
Separate pasture from rangelands	Livestock statistics Agricultural census data	Land with a certain concentration of animals are pastures Producers in a certain region use pastures (e.g. in cropland rotation).

Source: based on (GFOI 2016).

[1] the validity of these assumptions will vary by country, so all assumptions should be clearly justified

To establish and report consistent land-use stratification scheme it is *good practice* to:

- assess the availability of reliable data to classify land-use categories into sub-divisions that are available over time;
- ensure that strata can be sufficiently distinct to be identifiable and establish clear definitions for land-use strata;
- ensure that strata area cover the total land area of the category being stratified; as the boundaries of strata can change over time e.g. if the frontier of disturbance moves into areas of previously undisturbed forest.
- ensure that the strata have the attributes required to develop estimates of emissions and removals (e.g., emissions factors or model parameters); and,
- review the effect of the stratification to determine if further stratification would improve the estimates of emissions and removals.

For example, Approach 1 land-use data are stratified by climate and soil type to estimate soil C stock changes. Optimally, the land-use data can be down-scaled to capture the proportion of land-uses in each climate or soil type, with auxiliary information and expert knowledge. If re-scaling is not possible, inventory estimation can still proceed, but the emissions and removals estimates should reflect uncertainties in the assignment of emission/stock change factors (and associated parameters) that vary by climate and/or soil.

Management data may only be available in an Approach 1 format (e.g., expert knowledge or periodic surveys of different sets of land owners) even if Approach 2 or 3 data are available for land-use categories. In this case, management can be summarized as a proportion of the management practice (e.g., % no till, intensive tillage and reduced tillage) in each "lands remaining" and "lands converted" land-use category. This will be a limiting assumption if the management classes are not evenly distributed as the impact of management on the emission or removal depends on land-use category.

Tiers 2 and 3 methods may also evaluate interactions between management practices that affect emission/stock change factors. Determining the appropriate combinations of management is another issue that needs careful consideration. Tier 1 methods typically do not address the temporal trends in emissions/stock change factors (assuming a linear change) or capture interactions among management practices on a specific land-use, but rather represent an average effect. Consequently, assignment of emission/stock change factors may become more complicated with higher Tier methods and require careful explanation of the scaling processes that were used to delineate the appropriate combinations of the climate, soil, ecological zones, and/or management systems.

In some cases, management data may not cover the entire territory, being available only for specific regions, and so up-scaling of the data may be required to obtain national average coverage. A typical example is using project and activities data (e.g. mitigation actions/activities at the sub-national/corporate/project: see Box 2.0A, Chapter 2, Volume 4) to derive extrapolation methods to transform local data into consistent national level data and report description of these methods. In other cases, statistical/auxiliary information may be available at the aggregated national level, so down-scaling of attributes may occur to assign management practices to particular land units.

3.3.7 Preparing area data for emissions and removals estimation

Preparing a greenhouse gas inventory for AFOLU requires the integration of land-use area with data of land management and biomass, dead organic matter and soil carbon stock pools, in order to estimate carbon stock changes and CO_2 and non-CO_2 emissions and removals associated with land-use. Depending on the type of data available (Approach 1, 2 or 3), there are implications for the subsequent use of the data in the preparation of estimates of emissions and removals according to the land-use conversion framework represented in the reporting tables.

Countries that only have access to Approach 1 data have two options for reporting land-use category conversions. Total areas for categories of “land remaining in a land-use” may include some portion of land that was converted to that land-use since the last inventory. Countries should wherever possible apportion change in land-use areas over time to inferred land-use conversion categories for the purposes of determining appropriate carbon stock and emission factor estimates. For example, a country with 1 Mha of forest, 1,000 ha deforestation and 1,000 ha afforestation has a zero net change in Forest Land area (presuming these changes occurred on managed land), but will have a reduction in forest biomass C stocks, at least until sufficient regrowth occurs. Subsequent decisions will be needed to relate these inferred area conversions between land-use categories to appropriate land management, biomass and soil C stocks and emission factors. Where this is done, countries should report the basis for these decisions, and any methods of verification or cross-checking of estimates that have been applied, and the effects on inventory uncertainty. If this apportioning is not done, then countries should state this, and report the effect on uncertainties associated with doing so.

For countries with Approach 2 data, where information on the areas of each land-use conversion is known but is not spatially-explicit, these area estimates still need to be linked to appropriate initial carbon stocks, emissions factors, etc. In some cases, this may require the assignment of the land-use conversion data to climate, and/or vegetation type, soil and management strata. Again, this can be done by some form of sampling, scaling or expert judgement. Countries should report the basis for these decisions, and any methods of verification or cross-checking of estimates that have been applied.

For countries using Approach 3 data, it is possible to apportion areas of land-use conversion by spatially intersecting the data with other spatial datasets, such as those on climate, and/or vegetation type, soil and management strata. However, it is likely that inference, for example, based on survey data and expert judgement, will be needed to apportion the land-use conversion and biophysical data by management practices as data on management practices are rarely available in spatially explicit formats.

3.4 MATCHING LAND AREAS WITH FACTORS FOR ESTIMATING GREENHOUSE GAS EMISSIONS AND REMOVALS

This section provides brief guidance on matching the land-use area data with carbon stocks, emissions factors and other relevant data (e.g., forest biomass stocks, average annual net increment) to estimate greenhouse gas emissions and removals. An initial step in preparing national inventory estimates is to assemble the required activity data (i.e., land-use areas) and match them with appropriate carbon stock, emissions and removal factors, Tier 3 models and other relevant data.

This Volume provides default data (specifically marked) needed to make Tier 1 estimates for all AFOLU categories according to specified climate and ecological zone stratifications. In addition, countries may develop country-specific carbon stock, emission and removal factors and other relevant data (Tiers 2 and 3 inventory methods). The following summarizes the principles to be followed when matching activity data with carbon stock, emission and removal factors and other relevant data:

- match national land-use area classifications to as many land-use categories as possible;
- when national land-use classifications do not conform to the land-use categories of these guidelines, document the relationship between classification systems;
- use classifications consistently through time and, when necessary, document any modifications made to classification system;
- document definitions of land categories, land-use area estimates, and how they correspond to emission and removal factors; and,
- match each land-use category or sub-category to the most suitable carbon stock estimates, emission and removal factors and other relevant data.

Following are the recommended steps for matching land areas with emission and removal factors:

1. Start with the most disaggregated land-use area stratification as well as the most detailed available emission and removal factors needed to make an estimate. For example, the Forest Land methodologies, described in Chapter 4 of this Volume, provide a default factor for above-ground biomass stocks in forest plantations that is disaggregated at the most detailed stratification, relative to other factors (i.e., forest type, region, species group, age class, and climate). These strata would be used as an initial base stratification.
2. Include only those strata applicable in your country and use this as a base stratification.
3. Match land-use area estimates to the base stratification at the most disaggregated level possible. Countries may need to use expert judgment to align the best available land-use area estimates with the base stratification.
4. Map emission and removal factors onto the base stratification by matching them as closely as possible to the stratification categories. Note that many of the default stock change and emissions factors and other parameters in Tier 1 (default) equations were statistically derived for specifically defined strata (e.g., climate type, soil type) so that countries wishing to use Tier 1 methods for these emissions and removals should stratify land-use categories using the definitions as specified for Tier 1 change factors and parameters.

If a national land-use classification is fitted to the land-use categories (and sub-categories) this facilitates matching of emission and removal factors that follow the same classification. For example, default soil carbon factors for Forest Land, Cropland, and Grassland are disaggregated by the same climate regions (see Annex 3A.5). Therefore, the same land area classification can be used to estimate soil carbon changes in each of the land-use categories, enabling consistent tracking of lands and carbon fluxes on lands resulting from land-use category conversions.

Countries may find that national land classifications change over time as national circumstances change and more detailed activity data and emission/removal factors become available. In some cases, the stratification will be elaborated with the addition of more detailed emission and removal factors. In other cases, new stratifications systems will be established when countries implement new forest inventories or remote sensing sampling designs. When changes to the stratification system occur, countries should recalculate the entire time-series of estimates using the new stratification if possible.

3.4.1 Use of different approaches and methodological Tiers when estimating emissions and removals due to land-use change

Emissions and removals of CO_2 for the AFOLU sector are calculated from estimates of the total changes in carbon stocks for each land-use category. The overarching calculation process is described in Chapter 2, Volume 4.

The change in carbon stocks can be estimated using emissions factors (Tier 1 and 2), models (Tier 3 gain-loss methods) or direct measurements (Tier 3 stock difference) or any logical and consistent combination of all three. As the different Approaches provide different levels of detail, the methods for estimating emissions and removals need to be tailored to the available land-use data. When considering how to apply methods for estimating GHG emissions and removals using activity data from different Approaches, it is important to differentiate between:

- emissions and removals that occur in the year of the activity, such as fire or biomass loss from harvesting or clearing of land and emissions from drainage of organic soils and removals from forest growth; and,
- lagged emissions/removals that may occur for years after an activity or change in land-use occurs, such as forest regrowth, decay/accumulation of soil organic matter or decay of carbon stock in forest products.

As Approach 1 does not produce estimates for changes in land use, estimates for lagged emissions from carbon pools following transitions might produce emission and removals estimates that are different from those that can be calculated using Approach 2 or 3 (see Boxes 2.1 and 2.2). This limitation needs to be considered where Approach 1 data are being used in countries where land use change is occurring.

Approach 2 data allow for the use of estimation methods that account for emissions and removals both in the year of the activity and also lagged emissions and removals from past activities. Approach 2 data can be used with any combination of Tier 1 and 2 emissions factors or Tier 3 models. Approach 2 does not allow for the tracking of multiple changes (>2) in land use on a single land unit through time. As such, when using Approach 2 methods it is *good practice t*o stratify land into appropriate age or condition classes that can address these issues. For example, when using Tier 1 methods in forest land, stratifying into young forest land (less than 20 years) and mature forests (older than 20 years) can enhance the estimate of a land use change occurring in forest land. Similarly, a stratification into forest types or condition classes can enhance the accuracy of GHG estimates since the conversion of a mature forest typically results in higher C stock losses and associated GHG emissions than the conversion of a young, heavily disturbed or plantation forest. The same considerations apply to Approach 1 land representation.

Approach 3 uses the time-series of data for land units to capture multiple changes in land-use increases the complexity of Tier 3 modelling systems for estimating emissions and removals. While it is possible to use different emissions estimation methods in spatially explicit approaches, it is important to ensure that all the estimation methods are applied consistently. For some carbon pools, such as biomass, using different methods and models for different land uses or sub-divisions of land use (e.g., forest type) will not create any inconsistencies even when land-use changes. However, other pools, in particular soil carbon, require that the estimation methods be consistent. For example, if two or more methods are used for estimating soil carbon changes for different land-uses, then the stocks and estimated stock changes need to be handled consistently when the land-use changes. Where multiple methods are applied for estimating changes in carbon stocks within and between land-uses it is *good practice* to describe how these models work consistently across land-uses. These issues are addressed in more depth in Chapter 2.5, Volume 4.

For Approach 3 gain-loss methods, the quantity of information on land-use and change through time often makes it difficult to use spreadsheets to calculate emissions and removals. Advanced methods using integrating tools (Brack *et al*. 2006; Kurz & Apps 2006) are typically used is such circumstances. These tools estimate emissions and removals for each uniquely identified land unit, assign the land unit to an IPCC land-use category then sum the results for reporting.

Use of biomass maps with approach 3 data

There is active research ongoing on methods to estimate biomass in tropical forests using remote sensing techniques, including analysis of spectral indices and use of SAR and lidar data. Information on the current state of biomass maps is provided in Chapter 2 Volume 4.

The use of biomass maps needs to be considered in the context of the national inventory system to ensure that reporting of carbon stock changes for all pools and across land-uses is consistent. If biomass maps are used then it is *good practice* to demonstrate how the maps are consistent with national land-use classification system, in particular how they are integrated with the land-use data chosen by the country.

3.5 UNCERTAINTIES ASSOCIATED WITH THE APPROACHES

Uncertainties should be quantified and reduced as far as practicable. Land-use area uncertainty estimates are required as an input to overall uncertainty analysis. Although the uncertainty associated with the Approaches (1 to 3) obviously depends on how well they are implemented, it is possible to give an indication of what can be achieved in practice. Table 3.7 sets out the sources of uncertainty (not the significance) for different Approaches. This provides a guide to sources of uncertainties, indicative levels of uncertainty under certain conditions that might be encountered, and a basis for reducing uncertainties.

The number of potential sources of uncertainty in area estimates will tend to increase from Approach 1 to Approach 3, because successively more data are brought into the assessment. This does not imply that uncertainty increases, however, because of the additional cross-checks that are made possible by the new data, and because of the general reduction in uncertainties due to cancellation of errors. The main difference between Approach 1 and Approaches

2 and 3 is that percentage uncertainties on conversion between land-uses are likely to be greater in Approach 1 (if known at all). This is because in Approach 1 land-use conversions are derived from differences (net change) in total areas. The effect of this Approach 1 uncertainty on emissions and removals from conversions will depend on the relative amount of land conversion in the country as a fraction of total land area. Approach 3 produces detailed spatially-explicit information; which may be required e.g., for some spatial modelling approaches to emissions estimation.

TABLE 3.7
SUMMARY OF UNCERTAINTIES UNDER APPROACHES 1 TO 3

	Sources of uncertainty	Ways to reduce uncertainty	Indicative uncertainty following checks
Approach 1	Sources of uncertainty may include some or all of the following, depending on the nature of the source of data: Error in census returns Differences in definition between agencies Sampling design Sampling error variability Interpretation of samples Only net change in area is known In addition: Cross-checks on area changes between categories cannot be conducted under Approach 1 and this will tend to increase uncertainties.	Check for consistent relationship with national area Correct for differences in definitions Consult statistical agencies on likely uncertainties involved Compare with international datasets	Order of a few % to order of 10% for total land area in each category. Greater % uncertainty for changes in area derived from successive surveys. Systematic errors may be significant when data prepared for other purposes is used.
Approach 2	As Approach 1, but gross changes in area are known, and with ability to carry out cross-checks	As above, plus consistency checks between inter-category changes within the matrix	Order of a few % to order of 10% for total land area in each category, and greater for changes in area, since these are derived directly
Approach 3	As Approach 2 plus uncertainties linked to interpretation of remote sensing data where used, and minus any sampling uncertainty	As Approach 2 plus formal analysis of uncertainties using principles set out in Volume 1 Chapter 3	As Approach 2, but areas involved can be identified geographically. However, for Approach 3, the amount of uncertainty can be estimated more accurately than for Approach 2 because errors are mapped and can be tested against independent data/field checked.

Evaluation of land-use and land-use change information generated from remote sensing techniques and estimation of uncertainties

Accuracy assessments on the land cover inputs can be useful in understanding the influence these inputs have on overall uncertainty, but alone such assessments are unlikely to be representative of the total uncertainty of the data used in estimating emissions and removals.

When using remote sensing data to generate estimates of land use and land use change, it is *good practice* to ensure that:

- uncertainty estimates are specific for the relevant land-use and land-use change categories, not for interim products;
- uncertainty estimates include consideration of all sources of potential error
- uncertainty assessment methods can be applied through the entire time-series, either as a single value or for set periods;

- evaluation and uncertainty estimation methods are relevant to the Approach;
- when using remote sensing data to assess accuracy, validation data of higher quality (e.g., greater spatial resolution or spectral range) are used;
- analysis should be consistent with the discussion in Chapter 3 of Volume 1: Uncertainties.

Collection of validation data

Validation data (also called reference or accuracy assessment data) used in accuracy assessments can be collected using direct observations of ground conditions by field crews or from other remote sensing sources, such as high-resolution satellite data or aerial imagery including drone surveys.

Many biophysical features of interest can be collected on the ground to support the development and evaluation of land area estimates. However, ground measurements can be time consuming and expensive. Additionally, certain features are difficult to measure accurately from the ground but can be achieved relatively easily using high-resolution satellite data or aerial imagery. Also, it is important to consider spatial variability and plot size when ground information is used for validating pixel level data.

Remote sensing data are typically available at lower cost, allowing for more samples to be collected rapidly and often are available for the entire time series to create a suitable validation dataset. Use of high-resolution remote sensing data can be cost effective to validate medium resolution remote sensing outputs. As such, many countries will use a combination of ground and remotely sensed reference data to make best use and advantage of each data source (GFOI 2016).

It is *good practice* to ensure that validation data is:

- of at least the same quality as the calibration data;
- collected close to the time of the images used in the maps; and
- of sufficient size and positional accuracy compared to the spatial resolution of the maps.

When designing the validation sampling strategy countries may also consider assessing other spatial input data used to estimate emissions (e.g., underlying strata used in emissions estimation, such as soil type maps).

Evaluation of sample-based method

Remote sensing data can be used in a sample-based method. In these cases, the remote sensing data can often be treated in a similar manner to point based ground samples and uncertainties estimated using standard methods outlined in Chapter 3 of Volume 1: Uncertainties. However, unlike ground measurements, additional steps are often required to create land-use data as the remote sensing samples will represent land cover. As such, some of the methods used to develop wall-to-wall methods will be applicable for sample approaches as well.

When using sample-based methods where the sample units are large (e.g., greater than 1km2) but the spatial assessment unit is small (e.g., a 30 m pixel), it may be appropriate to apply the same methods used to evaluate wall-to-wall methods to the sample unit to assess accuracy of the sample units themselves.

Evaluation of wall-to-wall methods

Wall-to-wall maps of land-use and land-use change data can be derived from remote sensing and other data. Multiple steps are required to develop time-series consistent maps of land-use and land-use change data; including but not limited to developing time-series consistent maps of land cover, attributing cover and cover changes to specific activities then applying country specific policy rules of assigning lands to an IPCC land-use category through time.

Wall-to-wall mapping products are a form of census. Census approaches are subject to two types of error within each IPCC category: errors of inclusion (commission errors) and errors of exclusion (omission errors). Wall-to-wall methods typically do not apply a sample-based estimator and therefore there is no estimate of bias. However, it cannot be assumed that wall-to-wall methods are free of bias, as errors will occur through all the processes of developing the land-use maps.

Classification accuracy refers to the percentage of sample units correctly classified and can be calculated as commission and omission errors for each mapped category as well as an overall accuracy for all categories. Confusion or error matrices and map accuracy indices, can inform issues of systematic errors and precision in the maps, but do not produce the information necessary to construct confidence intervals (GFOI 2016).

A statistical estimator corresponding to the sampling design (see Chapter 3 of Volume 1: Uncertainties) can be used to assess (and adjust for) bias and construct confidence intervals.

To assess map accuracy and create information that can be used for estimating the uncertainty of emissions and removals estimates it is *good practice* to collect and use validation data relevant to the estimation of emissions and removals, noting that:

- the method and Tier adopted for generating emissions and removals estimates may influence how and when bias in activity data is addressed; and,
- activity data accuracy needs to be assessed at the scale and for the strata used to develop the emissions and removals estimates otherwise the resulting emissions and removals estimates may still be biased.

For transparency purposes it is *good practice* to clearly document the sampling methods (including sample sizes), how the samples relate to the classification system, and the QA/QC processes applied in sampling.

Annex 3A.1 Examples of international land cover datasets

In recent decades, satellite remote sensing has become the primary source of data for developing for global estimates of land cover. Several global products are currently available (Table 3A.1.1.) and more are under development. Countries considering the use global products should refer to the issues raised in Annex 3A.2.1.

TABLE 3A.1.1 (UPDATED)
EXAMPLES OF GLOBAL LAND COVER DATASETS IN 2017

	(A)	(B)	(C)	(D)
Dataset name	ESA Climate Change Initiative – Global Land Cover Products (CCI – LC)	Global Forest Change Global Forest Watch	MODIS Land Cover Type Product (MCD12Q1)	Global PALSAR-2/PALSAR/JERS-1 Forest/Non-Forest Map
Author	European Space Agency (ESA)	University of Maryland (UMD) World Resources Institute (WRI)	NASA / US Geological Survey	Japan Aerospace Exploration Agency (JAXA)
Brief description of contents	Consistent global land cover maps at 300 m spatial resolution on an annual basis from 1992 to 2015.	Global forest extent, forest cover loss and gain based on land cover information from 2000 to 2017 using Landsat.	Time-series analysis of MODIS data at 500 m spatial resolution to characterize global land cover from 2001-2013.	The global forest/non-forest map (FNF) generated by classifying the backscattering intensity values at 25 m spatial resolution using PALSAR-2/PALSAR mosaic
Classification scheme	The system uses a hierarchical classification, which allows adjusting the thematic detail of the legend to the amount of information available to describe each land cover class, whilst following a standardized classification approach.	This dataset captures vegetation taller than 5 m in height and tree canopy cover (0 to 100%) for year 2000, global forest cover gain (2000-2012), year of gross forest cover loss event defined as stand replacement disturbance, data mask and cloud free Landsat mosaics for 2000 and 2017.	Contains five classification schemes derived from yearly Terra and Aqua MODIS data. The primary land cover scheme identifies 17 land cover classes defined by the IGBP. This includes 11 natural vegetation classes, 3 developed and mosaicked land classes and 3 non-vegetated classes.	Forest is defined with an area larger than 0.5 ha and forest canopy cover over 10% (FAO definition).
Remote sensing data type	Optical	Optical	Optical	Radar

TABLE 3A.1.1 (CONTINUED) EXAMPLES OF GLOBAL LAND COVER DATASETS IN 2017				
	(A)	**(B)**	**(C)**	**(D)**
Data acquisition year	Annual from 1992 to 2015	Annual from 2000 to 2017	Annual from 2001 to 2013	2007, 2008, 2009, 2010, 2015, 2016
Spatial resolution or grid size	300 m (1100m for 1992-1999 years using AVHRR)	30 m	500 m	25 m, 100 m, 1000 m and 0.25 degree
Revision interval (for time-series datasets)	Annual (1992-2015) – baseline 10-year global land cover map	Annual time-series from 2000 to 2017	Annual time-series from 2001 to 2013	PALSAR - 2007, 2008, 2009, 2010, 2015 and 2016 JERS-1 1993, 1994, 1995, 1996, 1997 & 1998 (for tropics only); Global-1996
Quality description	The land cover maps are delivered along with four quality flags which document the reliability of the classification and change detection.	Data mask shows areas of no data, mapped land surface and permanent water bodies.	Contains quality control flags for each pixel. Use latest collection of MODIS data processing.	The overall agreement with forest/non-forest assessments from PALSAR data using the Degree Confluence Project, the Forest Resource Assessment and Google Earth images was 85%, 91% and 95% respectively.
Contact address and reference URL	http://maps.elie.ucl.ac.be/CCI/viewer/download.php	http://earthenginepartners.appspot.com/science-2013-global-forest https://www.globalforestwatch.org/	http://glcf.umd.edu/data/lc/	http://www.eorc.jaxa.jp/ALOS/en/palsar_fnf/fnf_index.htm

Annex 3A.2 Development of land-use databases

There are three broad sources of data for the land-use databases needed for greenhouse gas inventories:

- databases prepared for other purposes;
- collection by sampling; and
- complete land inventory.

The following subsections provide general advice on the use of these types of data. Greenhouse gas inventory preparers might not be involved in the detailed collection of remote sensing data or ground survey data but can use the guidance provided here to help plan inventory improvements and communicate with experts in these areas.

3A.2.1 Use of data prepared for other purposes

Two types of available databases may be used to classify land. In many countries, national datasets of the type discussed below will be available. Otherwise, inventory compilers may use international datasets. Both types of databases are described below.

NATIONAL DATABASES

These will usually be based on existing data, updated annually or periodically. Typical sources of data include forest inventories, agricultural census and other surveys, censuses for urban and natural land, land registry data and maps.

INTERNATIONAL DATABASES

Several projects have been undertaken to develop international land-use and land cover datasets at regional to global scales (Annex 3A.1 lists some of these datasets). Almost all of these datasets are stored as raster data generated using different kinds of satellite remote sensing imagery, complemented by ground reference data obtained by field survey or comparison with existing statistics/maps. These datasets can be used for:

- Estimating spatial distribution of land-use categories. Conventional inventories usually provide only the total sum of land-use area by classes. Spatial distribution can be reconstructed using international land-use and land cover data as auxiliary data where national data are not available.
- Reliability assessment of the existing land-use datasets. Comparison between independent national and international datasets can indicate apparent discrepancies and understanding these may increase confidence in national data and/or improve the usability of the international data, if required for purposes such as extrapolation.
- When using an international dataset, inventory compilers should consider the following:
    - (i) The classification scheme (e.g., definition of land-use classes and their relations) may differ from that in the national system. The equivalence between the classification systems used by the country and the systems described in Section 3.2 (Land-use categories) therefore needs to be established by contacting the international agency and comparing their definitions with those used nationally.
    - (ii) Spatial resolution (typically 1km nominally but sometimes an order of magnitude more in practice) may be coarse, so national data may need aggregating to improve comparability.
    - (iii) Classification accuracy and errors in geo-referencing may exist, though several accuracy tests are usually conducted at sample sites. The agencies responsible should have details on classification issues and tests undertaken.
    - (iv) As with national data, interpolation or extrapolation will probably be needed to develop estimates for the time periods to match the dates required for reporting.

3A.2.2 Collection of new data by sampling methods

Sampling techniques for estimating areas and area changes are applied in situations where total tallies by direct measurements in the field or assessments by remote sensing techniques are not feasible or would provide inaccurate results. Sampling concepts that allow for estimation procedures that are consistent and unbiased, and result in estimates that are precise, should be used.

Sampling usually involves a set of sampling units that are located on a regular grid within the inventory area. A land-use class is then assigned to each sampling unit. Sampling units can be used to derive the proportions of land-use categories within the inventory area. Multiplying the proportions by the total area provides estimates of the area of each land-use category. Where the total area is not known it is assumed that each sampling unit represents a specific area. The area of the land-use category can then be estimated via the number of sampling units that fall into this category.

Where sampling for areas is repeated at successive occasions, area changes over time can be derived to construct land-use conversion matrices.

Applying a sample-based type for area assessment enables the calculation of sampling errors and confidence intervals that quantify the reliability of the area estimates in each category. Confidence intervals can be used to verify if observed category area changes are statistically significant and reflect meaningful changes.

Annex 3A.3 provides more information on sampling.

3A.2.3 Collection of new data in complete inventories

A complete inventory of land-use of all areas in a country will entail obtaining maps of land-use throughout the country at regular intervals. This can be achieved by using remote sensing techniques. As outlined under Approach 3, the data will be most easily used in a GIS based on a set of grid cells or polygons supported by ground truth data needed to achieve unbiased interpretation. Coarser scale data can be used to build data for the whole country or appropriate regions.

A complete inventory can also be achieved by surveying all landowners and each would need to provide suitable data where they own many different blocks of land. Inherent problems in the method include obtaining data at scales smaller than the size of the owner's land as well as difficulties with ensuring complete coverage with no overlaps.

3A.2.4 Tools for data collection

REMOTE SENSING (RS) TECHNIQUES

An increasingly remarkable array of remote sensing and other geospatial data, methods, and tools have become available in the last decade for consistent country-specific representation of land-use and land-use change. Advances in a) spatial and temporal higher coverage leading to increased availability of remotely sensed data routinely collected through earth observation satellites, b) time-series classification algorithms and related geodata processing workflows, and c) geographic information system (GIS)-based integration of in situ, collateral, and remote sensing data can be leveraged by inventory compilers for this purpose. Increased coordination and collaboration between the international space agencies such as NASA, JAXA, ESA, etc., have led to improved global remote sensing data collection and free availability and open access of high and moderate resolution datasets.

Determination of fitness for use of remote sensing and other geospatial data, products, and tools is the responsibility of the user; the producer of remote sensing data on the other hand should provide the user with sufficient metadata to help make such a determination. The current geospatial metadata standard is based on ISO 19115 which includes workflow provenance or lineage information. Provenance is vital to understand the exact sources, nature, and order of processing steps taken to generate a remote sensing product, and is required to understand how errors are expressed and propagated during the product's creation (Tullis *et al.* 2015). Expertise in remote sensing systems and data processing (Jensen 2016) is necessary to interpret fitness for use in this context, and collaboration with a national or regional geospatial laboratory in the development of seamless remote sensing derived products is strongly encouraged. It should be noted that relevant remote sensing theory and applications have developed over more than a century (e.g., Thenkabail (2015); Jensen (2016)), and a detailed treatment cannot be replicated here. Instead, key aspects will be highlighted relative to the point of view of an inventory compiler. Determination of fitness for use may change over time as new sensors, methods, and workflows are developed and become available. This process is punctuated as earth observation satellites are decommissioned at their end of life and international investments are made in new launches with superior observation capacity.

There is no a priori restriction on which remote sensing products may contribute to a consistent representation of lands, and no methodological requirement to maintain historical tradition. On the contrary, increased transparency, replicability, and accuracy in representation of land-use activity data benefits from the development of new and innovative geospatial workflows. Ensuring that land-use (of interest due to human activity) is consistently and accurately represented over time is more important than the specific methods that are ultimately selected. To aid compilers or reviewers in fitness for use determinations associated with remote sensing data and products, it is suggested that remote sensing resolutions, time-series consistency, compatibility with forest and other land-use definitions, and attribution of land-use change all be considered.

Remotely sensed data, as discussed here, are those acquired using sensors (e.g., optical, radar or lidar) on board satellites, or airborne. Before these data can be effectively used to generate land-use activity data, various forms of calibration and harmonization may be required. Classification can be accomplished either through expert visual interpretation of the remotely sensed imagery, or by digital methods, or by some combination of the two. Some remote sensing approaches produce reliable sample datasets while others generate wall-to-wall maps for each epoch in the time-series of interest. Reliable reference data samples including (where possible) in situ or ground survey data is utilized to both improve land-use products (e.g., to refine area estimates) as well as to estimate accuracy of products incorporated in subsequent stages of the inventory process.

The strengths of remote sensing come from its ability to provide spatially explicit information for land representation and repeated coverage, including the possibility of covering large and/or remote areas that are difficult to access in situ. Archives of remote sensing data also span several decades and can therefore be used to reconstruct historical time-series of land-use information. Remote sensing is particularly useful for obtaining area estimates of land-use categories and for assisting in the identification of relatively homogeneous strata that can guide the selection of sampling schemes and the number of samples to be collected. The challenges of remote sensing are related to interpretation: the images need to be consistently and reliably translated into meaningful information on land-use. Depending on the satellite sensor(s) involved, the data acquisition may be impaired by the presence of atmospheric clouds, smoke and haze. Another concern, particularly when comparing data over long time periods, is that remote sensing quality and resolutions may change over time. Further guidance is provided to address these challenges in the context of common remote sensing definitions, state of the art methods and approaches, and future possibilities particularly relevant to inventory compilers.

Remote sensing resolutions

Spatial

Spatial resolution refers to the approximate ground-projected dimensions of remotely sensed image pixels. Landsat 8 Operational Land Imager (OLI), for example, has a spatial resolution of 30 m, while the Sentinel 2 multispectral instrument has higher spatial resolutions of 10 m and 20 m, depending on the band. In choosing appropriate spatial resolution for land representation, it is critical to consider the minimum mapping unit (MMU), the smallest size which determines whether a feature is captured from a remotely sensed image. Pixel area and detectability are two important factors in assessing MMU suitability. A commonly accepted criterion is that the pixel area should not exceed 1/4 MMU. For example, if MMU is 0.5 ha (5,000 m^2) then Landsat data at 30 m spatial resolution (900 m^2 pixel area) would meet the MMU criteria as there will be at least 5 Landsat pixels within the MMU. In contrast, using MODIS sensor data at 250m pixel (62,500 m^2 pixel area) would fail the MMU criteria as the area covered by a single pixel is greater than the MMU. Spatial resolution is generally inversely related to spatial coverage; higher spatial resolution sensors cover smaller areas and vice versa. This relationship has direct implications for required processing time and expertise required and thus influences the total cost of the inventory.

Spectral

Spectral resolution describes the ability of a sensor to define wavelength intervals. As spectral resolution increases, there is a greater number of possible channels or bands, and corresponding wavelength ranges for those bands are narrower. Often a specific sensor’s spectral resolution is fixed and thus its potential applications are limited. In general, the higher the spectral resolution, the greater the ability of the sensor to separate different variables and to detect change. However, narrow wavelength ranges mean that less electromagnetic energy is available to impinge upon the detectors, which can decrease signal to noise ratio (SNR). Given this principle, many of the higher spatial resolution commercial satellites have relatively lower spectral resolutions. In general, there should be a good balance between the amount of spectral bands and the spatial resolution depending on the application.

Temporal

Temporal resolution refers to the length of time required for a satellite to revisit a land area of interest. Temporal resolution is related to image coverage and spatial resolution; i.e., sensors that cover the Earth more frequently, on the order of a day (e.g., MODIS) or 16 days (e.g., Landsat 8), have higher coverage and lower spatial resolution. However, this is changing with recent and planned satellite constellations (e.g., small satellites from Planet; RADARSAT Constellation Mission, etc.). Due to some degree of overlap in the imaging swaths of adjacent orbits and an increase in this overlap with latitude, some areas of the Earth tend to be re-imaged more frequently. Also, some satellite systems can point off-nadir to image the same area between different satellite passes separated by periods from one to five days. Adequate temporal resolution is critical for the development of image time-series that contain information relevant to human activity.

Radiometric

Radiometric resolution is related to the sensitivity of the detector elements in a sensor. In general, higher radiometric sensitivity leads to better discrimination of land cover and ultimately land use. Due to introduction of noise from a variety of sources, consistent sensor radiometric resolution may be somewhat less than the bit-depth reported in sensor specifications and may vary between bands due in part to the limitations of wavelength-dependent irradiance and atmospheric transmittance. Noticeable improvements in radiometric resolution and in its reliability, has been observed in recent years as a function of sensor technology, such as the increase from the 8-bit specification in Landsat 5 TM, 12-bits in Landsat 8 OLI, and 14-bits in Landsat 9 OLI-2 (planned for launch in 2020).

Types of remote sensing data

Commonly used types of remote sensing data are: 1) aerial imagery, 2) satellite imagery using visible and/or infrared bands, 3) satellite or airborne radar imagery and, 4) satellite or airborne lidar data. Combinations of different types of remote sensing data (e.g., visible/infrared and radar; different spatial or spectral resolutions) might very well be used for assessing different land-use categories or regions. A complete remote sensing system for tracking land-use conversions can include multiple sensor and data type combinations at a variety of resolutions, with appropriate processing methods to ensure sensor system-related variables do not introduce classification errors.

Important criteria for selecting remote sensing data and products are:

- Adequate land-use categorisation scheme;
- Appropriate spatial resolution and image extent;
- Appropriate temporal resolution for estimating of land-use conversion;
- Capability to perform accuracy assessment;
- Transparent methods applied in data acquisition and processing; and
- Consistency and availability over time.

1. Aerial photographs

Analysis of aerial photographs and most recently very high-resolution digital air photos can reveal forest tree species and forest structure from which relative age distribution and tree health (e.g., needle loss in coniferous forests, leaf loss and stress in deciduous forests) may be inferred. In agriculture, analysis can show crop species, crop stress, and tree cover in agro-forestry systems. The smallest spatial unit possible to assess depends on the type of aerial photos used, but for standard products it is often as small as 1 square meter.

2. Satellite images in visible and near infrared wavelengths

Complete land-use or land cover of large areas (national or regional) may be facilitated by the use of satellite images. The possibility exists of obtaining long time-series of data from the desired area since the satellite continuously and regularly passes over it. The images usually generate a detailed mosaic of distinct categories, but the labelling into proper land cover and land-use categories commonly requires ground reference data from maps or field surveys. The smallest unit to be identified depends on the spatial resolution of the sensor and the scale of work. The most common multispectral sensor systems used for regional to national land cover and land-use mapping have a spatial resolution of 10 – 30 meters. At a spatial resolution of 30 meters, for example, units as small as 1 ha can be identified. Data from higher spatial resolution satellites are now also widely available (e.g., ESA Sentinel-2).

3. Radar imagery

The most common type of radar data is from the so-called Synthetic Aperture Radar (SAR) systems that operate at microwave frequencies. A major advantage of such systems is that they can penetrate clouds and haze and acquire data during night-time. They may therefore be the only reliable source of remote sensing data in many areas of the world with quasi-permanent cloud cover. By using different wavelengths and different polarisations, SAR systems may be able to distinguish land cover categories (e.g., forest/non-forest), or the biomass content of vegetation, although there are at present some limitations at high biomass due to signal saturation. Reports from Japan Aerospace Exploration Agency (2010; 2011; 2014) provide detailed examples of orbital SAR data analysis in support of forest and wetland monitoring.

4. Lidar

Like SAR, light detection and ranging (lidar) is an active sensor technology (transmits and later detects its own energy). Laser light at a specific wavelength (e.g., 532 nm, 1,064 nm) is transmitted to the surface and some portion is reflected/scattered back to the instrument. However, in contrast to SAR, lidar is used mostly to determine the distance to and position of the reflective surface from the precise time and angles the pulse takes to return to the sensor. By using stream of pulses transmitted across the surface, the relative elevation of each reflecting target can be derived, producing a 3-dimensional (3D) point cloud that can be analysed for surface elevation and vegetation structure as well as composition. In addition, although currently less commonly implemented, the intensity of reflected energy can be used to evaluate properties of the reflected surface. Lidar generally has a narrow swath width, particularly with airborne systems which generate the most precise and detailed data. It therefore requires significant time and expense to acquire full coverage of large areas. In dynamic landscapes where, higher temporal resolution is needed, such data are best suited for high spatial resolution sample-based analysis.

Remote sensing data pre-processing

Imagery captured by airborne or spaceborne sensors must be corrected for radiometric, geometric and topographic distortions prior to using this data for land cover and land-use classification. The type of pre-processing depends on type of sensor system such as optical or radar. A detailed description of pre-processing methods can be found in Jensen (2016) and Richards (2013). Availability of seamless radiometrically corrected data in recent years has made it much easier to use this data for land cover and land-use change detection (Roy *et al.* 2010; Hansen & Loveland 2012; Hansen *et al.* 2013; Teillet 2015). Optical imagery might be affected by cloud cover, which can be removed by combining data from multiple images acquired in the same season. Ubiquitous cloud cover can benefit from recent advances (e.g., Fmask; see Zhu *et al.* 2015). GFOI (2016) provides detailed guidance on cloud removal including the effects of shadows.

Development of country-specific remote sensing pre-processing capabilities may not always be practical. Fortunately, major remote sensing data suppliers such as US Geological Survey (USGS), European Space Agency (ESA), Japan Aerospace Exploration Agency (JAXA), and others are increasingly offering analysis ready data (ARD), which is most suitable for extraction of land-use categories required for national GHG inventories. For example, USGS (2017) is beginning to offer Landsat ARD using harmonized collections from Landsat 4, 5, 7, and 8 between 1982 and the present. When using global or country-specific georeferenced datasets, it is *good practice* to ensure they meet national geodetic mapping standards.

Time-series consistency

Methodological changes and improvements in satellite data processing and calibration over time is a normal practice and often result in improved products for change detection. It is also common to source data from multiple sources and sensors, which, if not accounted properly, may result in inconsistent products that are unsuitable for detecting land use change. It is therefore *good practice* to reprocess time-series data when new data or methods become available such as those identified below:

- Availability of improved ground control points (GCPs). For example, when using Landsat data from the USGS, it is important to use data from the same collection and tier for the entire time series. Combining data from different tiers may result in misregistration;
- Availability of improved calibration or recalibration of sensors in response to degradation of sensor performance over time;
- Availability of new data and processing methods such as Data Cube (CEOS 2016; Lewis *et al.* 2017); and cloud-based data processing platforms (FAO 2018);
- Correction of errors.

There are many new sensors and types of remote sensing data available in recent years to assess land cover and land-use changes. Using data from multiple sensors and sources, which is increasingly common, requires consistent processing of time-series remote sensing data following the principles discussed in Chapter 5 of Volume 1: Time-Series Consistency. Summary of splicing techniques applicable to remote sensing data processing are:

- Overlap techniques can be used when a new higher resolution sensor data becomes available in recent years, but such data are not available in the past. In such cases, data from old and new sensors can be compared for at least one year (preferably more) to establish a consistent relationship between the two products. This technique can be used, for example, to construct a consistent time-series using historic Landsat sensors and the more recent Sentinel-2 sensors (Zhang *et al.* 2018).
- Interpolation techniques can be used where availability of remote sensing data from historic archives is limited. In such cases best available data for intermittent years in the time-series can be interpolated to fill gaps in the missing data.

Other techniques such as merging of different spatial resolution data can be used to fill the data gaps. Pixel compositing is also another proven technique to construct best quality cloud free composites for classification. It is important to collect remote sensing data obtained in the same season throughout the time-series to minimise errors due to seasonal changes.

Ground reference data

To make use of remote sensing data for inventories, and in particular to relate land cover to land-use it is *good practice* to complement remote sensing data with in situ or ground reference data (often mistakenly called ground "truth" data even though it may also contain sources of error). Ground reference data can either be collected independently or obtained from forest or agricultural inventories. Land-uses that are rapidly changing over the estimation period or that have vegetation cover known to be easily misclassified should be more intensively ground sampled than other areas. This can typically only be done by using ground reference data, preferably from field surveys collected independently. High spatial resolution imagery obtained from aerial/drone or orbiting satellites may also be useful for reference and verification purposes.

Integration of remote sensing and geographical information systems

Visual interpretation of images is often used for identifying sampling sites for forestry inventories. The method is simple, and reliable. However, it is labour intensive and therefore restricted to limited areas and may be affected by subjective interpretations by different operators.

Effective use of remote sensing data generally requires integration of the extensive coverage that remote sensing can provide with ground-based measurements or map data to represent areas associated with particular land uses in space and time. This is generally achieved most cost effectively using a geographic information system (GIS). Use of a GIS is the most common approach to combine multiple data sources including field measurements, survey and census data. This information is essential to train image classification or machine learning algorithms used for extracting land cover and land-use change. A number of important factors should be considered when combining multiple data sources as discussed in Section 3.3.4.

Land-Use classification using remote sensing data

Classification of land cover using remotely sensed data may be done by visual or digital (computer based) analysis. Each approach presents advantages and disadvantages. Visual analysis of imagery allows for human inference through the evaluation of overall characteristics of the scene (analysis of the contextual aspects in the image). Digital classification, on the other hand, allows several manipulations to be performed with the data, such as merging of different spectral data, which can help to improve modelling of the biophysical ground data (such as tree diameter, height, basal area, biomass) using the remotely sensed data. In addition, digital analysis allows for the immediate computation of areas associated with the different land categories. It has developed rapidly in recent decades, along with the associated technical computer development, making hardware, software and satellite data readily available at low cost in most countries. Capacity to use these data and facilities may have to be outsourced (e.g., using cloud-based computing platforms), particularly in mapping at the national level.

There has also been extensive research on the best methods for image classification and as a result a wide variety of choices are available. Common image classification and machine learning algorithms include maximum likelihood, decision trees (e.g., random forest), support vector machines and neural networks. Many of these are available in standard image processing and statistical software packages (Jensen 2016).

Image classification begins with the definition of the categories or classes to be included in the map. In supervised classification, it is necessary to provide training samples of each of the classes to be included. These samples could come from a variety of sources, including sample sites from a national forest inventory, or could be obtained from high spatial resolution images (GFOI 2016). Often images from a single date are used for image classification. However, multiple images from different seasons can also be used in image classification to try to capture classes with seasonal dynamics. Multi-season satellite data is particularly useful for mapping croplands, grasslands and fallow lands. As the level of stratification increases, alternative sources of reference data to train classifiers will be needed, such as prior vegetation maps or field plots.

Extraction of information from satellite images can also be done by visual interpretation. This is best done by a subject matter expert familiar with the area being interpreted. However, this method can be very human resource intensive (GOFC-GOLD 2016) because the number of pixels may be very large, and the interpretations can largely vary due to human judgement, since it is hard to maintain consistency and repeatability between interpreters. Moreover, the minimum mapping unit for land classification is often less than 5 ha, which can be tedious to implement using visual interpretation. Further, differencing visually interpreted maps to develop change estimates by polygon overlay analysis typically results in gaps between polygons. It is also very difficult to make improvements to the resulting maps, especially once the time-series includes more than 3 or 4 epochs.

This may be overcome by applying image classification algorithms to give consistent results in allocating a pixel to a category or another, or to segment the data. Unsupervised approaches use classification algorithms to assign image pixels into one of many unlabelled class groupings. Expert image interpreters then assign each of the groupings of pixels a value corresponding to the desired land class. Supervised approaches use ground reference data or expert knowledge of the region to train the classification algorithms which then identify and label areas similar to the input training data. The approaches have different challenges which are best addressed by iterative trials: supervised classification may wish to use more classes than are statistically separable; unsupervised methods may generate fewer classes than are desired and a given cover type may be split between several groupings. In both cases data analysts can check the accuracy of classification outputs.

Rarely does the first attempt at image classification result in the final product. Close examination of the classification results often reveals issues and problems that can be resolved by changing or refining training data in the classification process. There are many ways to try to improve the results of a classification with noticeable problems, including the addition of more or improved training data. It may also be helpful to include additional kinds of data in the classification, such as topographic or climatic data (GFOI 2016). Any improvements in data processing methods should be reflected in the entire time-series to improve the accuracy and consistency of output data.

While two dates of satellite imagery may be useful for quickly depicting land cover change, identification of permanent land-use changes may require more data and analysis. It is therefore *good practice* to ensure that all land cover changes identified by satellite data are verified using sufficient spatial and temporal resolution imagery, ground reference and other auxiliary datasets to isolate permanent land-use change from that of temporary loss of forest cover. This process, referred as attribution of satellite derived land cover change, helps to identify human induced land-use change. Typical data sets used in attribution include those with information relating to fires, forest management areas, agricultural areas, road coverage and urban areas (Mascorro *et al.* 2015). As data processing algorithms detect increasingly diverse change processes, the need to distinguish among the agents causing the change becomes critical. Not only do different change types have different impacts on natural and anthropogenic systems, they also provide insight into the overall processes controlling landscape condition. Reaching this goal requires overcoming two central challenges. The first is related to scale mismatch: change detection in digital images occurs at the level of individual pixels but change processes in the real world operate on areas larger or smaller than pixels, depending on the process. The second is related to separability: change agents are defined by natural and anthropogenic factors that have no connection with the spectral space on which the change is initially detected. Different change agents may have nearly identical spectral signatures of change at the pixel and even the patch level, and must be distinguished by factors completely outside the realm of remote sensing (Kennedy *et al.* 2007).

Detection of land-use conversion using remote sensing

Remote sensing can be used to detect locations of change. Methods for change detection can be divided into two categories (Singh, 1989):

Post-classification change detection: This refers to techniques where two or more predefined land cover/use classifications exist from different points in time, and where the changes are detected, usually by subtraction of the datasets. The techniques are straightforward but are also sensitive to inconsistencies in interpretation and classification of the land-use categories.

Pre-classification change detection: This refers to more sophisticated and biophysical approaches to change detection. Differences between spectral response data from two or more points in time are compared by statistical methods and these differences are used to provide information on land cover/use changes. This type is less sensitive to interpretation inconsistencies and can detect much more subtle changes than the post-classification approaches but is less straightforward and requires access to the original remotely sensed data.

There are also other viable methods. For example, one can use change enhancements and visual interpretation. Areas of change are highlighted through display of different band combinations, band differences or derived indices (e.g., vegetation indices). This focuses attention on potential land-use conversions sites that can then be delineated and attributed through manual or automated techniques. These methods are subject to human interpreter inconsistencies but are capable of detecting subtle changes and better detecting and mapping land-use conversion where land cover, context and auxiliary information is needed to determine land-use conversion.

Change detection is one of the most common uses of remote sensing data, and many methods have been used, tested and proposed in the literature. GOFC-GOLD (2016) includes descriptions and examples of several change detection methods and is a useful resource when considering options for combinations of methods and remote sensing data to be used for mapping change. In general, at least two dates of images (end-points) are necessary to map change. Image classification methods are commonly used, in which case multiple images are used to make the assignment to stable classes (places that have not changed) as well as change classes, such as Forest Land to Grassland (Woodcock *et al.* 2001). Such methods use the change in a spectral bands or indices as the basis for detecting change land cover (Lambin & Strahlers 1994; Coppin *et al.* 2004).

Time-series classification

Data processing methods that use many images, or a time-series of images, have been developed and tested (Chen *et al.* 2004; Kennedy *et al.* 2007; Furby *et al.* 2008; Zhuravleva *et al.* 2013). These approaches have many advantages, as they are not so dependent on the conditions at the time the individual images were collected. Use of a time-series of images can help avoid some kinds of errors in the monitoring of forest change (GFOI 2016). For example, classification of time-series data can help make the distinction between permanent land-use change and temporary loss of forest due to harvesting.

Change detection using two images has some advantages but also has some limitations (Jensen 2016). Direct mapping of change categories has important benefits. The Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO) National Inventory System – Land Cover Change Project (NIS-LCCP) provides an example of how change can be confirmed from time-series information (Shimabukuro *et al.* 1998; Caccetta *et al.* 2007; Potapov *et al.* 2012; Hansen *et al.* 2013).

Emerging remote sensing-derived land surface phenology (Morisette *et al.* 2009) represents a future opportunity for innovation in national inventories. Land surface phenology not only supports the extraction of land cover classes (e.g., Zhong *et al.* 2012), but offers valuable information on homogeneous landscape units (e.g., Bunker *et al.* 2016). Areas with unique forest and agricultural cycles characterized by both natural and anthropogenic influence may be difficult to ascertain with only a few representative images from a time-series. For example, even relatively coarse spatial resolution homogenous landscape units extracted from a relatively dense time-series (e.g., from bi-monthly MODIS-derived vegetation index) may support adaptive land-use extraction methodologies (e.g., based on finer spatial resolution Landsat-derived time-series) within entire countries or regions.

Analysis of dense time-series remote sensing data can help in identifying forest disturbance events such as extent, type and year of disturbance, status of pre and post-disturbance land cover, disturbance intensity and rates of recovery (White *et al.* 2017).

Evaluation of mapping accuracy

Whenever a map of land cover or land-use is being used, inventory compilers should acquire information about the reliability of the map. When such maps are generated from classification of remote sensing data, it should be recognised that the reliability of the map is likely to vary between the different land categories. Some categories may be uniquely distinguished while others may be confounded with others. For example, coniferous forest is often more accurately classified than deciduous forest because its reflectance characteristics are more distinct, while deciduous forest may easily be confounded with, for example, Grassland or Cropland. Similarly, it is often difficult to ascertain changes in land management practices through remote sensing. For example, it may be difficult to detect a change from intensive to reduced tillage on a specific land area.

Inventory compilers should estimate the accuracy of land-use/land cover maps on a category-by-category basis. A number of sample points on the map and their corresponding real-world categories are used to create a confusion matrix (see footnote 5 in Annex 3A.4) with the diagonal showing the proportion of correct identification and the off-diagonal elements showing the relative proportion of misclassification of a land category into one of the other possible categories. The confusion matrix expresses not only the accuracy of the map but it is also possible to assess which categories are easily confounded with each other. Based on the confusion matrix, a number of accuracy indices can be derived (Congalton, 1991). Multi-temporal analysis (analysis of images taken at different times to determine the stability of land-use classification) can also be used to improve classification accuracy, particularly in cases where ground truth data are limited.

GROUND-BASED SURVEYS

Ground-based surveys may be used to gather and record information on land-use, and for use as independent ground-truth data for remote sensing classification. Prior to the advent of remote sensing techniques such as aerial photography and satellite imagery, ground-based surveys were the only means of generating maps. The process is essentially one of visiting the area under study and recording visible and/or other physical attributes of the landscape for mapping purposes. Digitisation of boundaries and symbolising attributes are used to make hard copy field notes and historical maps useful in Geographical Information Systems (GIS). This is done via protocols on minimum land area delineation and attribute categorization that are linked to the scale of the resultant map and its intended use.

Very precise measurements of area and location can be made using a combination of survey equipment such as theodolites, tape measures, distance wheels and electronic distance measuring devices. Development of satellite navigation systems means that location information can be recorded in the field directly into electronic format using portable computer devices. Data are downloaded to an office computer for registration and coordination with other layers of information for spatial analysis.

Landowner interviews and questionnaires are used to collect socio-economic and land management information but may also provide data on land-use and land-use conversion. With this census type, the data collection agency depends on the knowledge and records of landowners (or users) to provide reliable data. Typically, the resident is visited and interviewed by a representative of the collection agency and data are recorded in a predetermined format, or a questionnaire is issued to the land-user for completion. The respondent is usually encouraged to use any relevant records or maps they may have, but questions may also be used to elicit information directly (Swanson *et al*. 1997).

Census surveys are probably the oldest form of data collection methods (Darby, 1970). Land-user surveys can be conducted on the entire population or a sample of suitable size. Modern applications employ a full range of validation and accuracy assessment techniques. The survey may be undertaken through personal visits, telephone interviews (often with computer-assisted prompts) or mail-out questionnaires. Land-user surveys start with the formulation of data and information needs into a series of simple and clear questions soliciting concise and unequivocal responses. The questions are tested on a sample of the population in order to ensure that they are understandable and to identify any local technical terminology variations. For sample applications, the entire study area is spatially stratified by appropriate ecological and/or administrative land units, and by significant categorical differences within the population (e.g., private versus corporate, large versus small, pulp versus lumber, etc.). For responses dealing with land areas and management practices, some geographic location, whether precise coordinates, cadastral description or at least ecological or administrative units should be required of the respondent. Post-survey validation of results is conducted by searching for statistical anomalies, comparing with independent data sources, conducting a sample of follow-up verification questionnaires or conducting a sample of on-site verification surveys. Finally, presentation of results must follow the initial stratification parameters.

Annex 3A.3 Sampling

No refinement.

Annex 3A.4 Overview of potential methods for developing Approach 3 datasets

No refinement.

Annex 3A.5 Default climate and soil classifications

Climate regions are classified in order to apply emission and stock change factors for estimating biomass, dead organic matter and soil C stock changes. The default climate classification, provided in Figure 3A.5.1 (updated), has been derived using the classification scheme shown in Figure 3A.5.2 based on the gridded Climate Research Unit (CRU) Time Series (TS) monthly climate data for the period from 1985 to 2015 following the methodology described by Harris *et al.* 2014. This classification should be used for Tier 1 methods because the default emission and stock change factors were derived using this scheme. Note that climate regions are further subdivided into ecological zones to apply the Tier 1 method for estimating biomass C stock changes (see Table 4.1, Chapter 4). Inventory compilers have the option of developing a country-specific climate classification based on local climate data, updated annually, if using Tier 2 and 3 methods, along with country-specific emission and stock change factors. It is *good practice* to apply the same classification, either default or country-specific, across all land-use types. Thus, stock change and emission factors are assigned to each pool in a national inventory using a uniform classification of climate.

Soils are classified in order to apply reference C stocks and stock change factors for estimation of soil C stock changes, as well as the soil N_2O emissions (i.e., organic soils must be classified to estimate N2O emissions following drainage). Organic soils are found in wetlands or have been drained and converted to other land-use types (e.g., Forest Land, Cropland, Grassland, Settlements). Soils having organic material (Histosols) are defined as (WRB, 2015):

1. Starting at the soil surface and having a thickness of ≥ 10 cm and directly overlying:
    a. Ice, or
    b. Continuous rock or technic hard material, or
    c. Coarse fragments, the interstices of which are filled with organic material; or
2. Starting ≤ 40 cm from the soil surface and having within ≤ 100 cm of the soil surface a combined thickness of either:
    a. ≥ 60 cm, if ≥ 75% (by volume) of the material consists of moss fibres; or
    b. ≥ 40 cm in other materials

All other types of soils are classified as mineral. A default mineral soil classification is provided in Figure 3A.5.3 for categorizing soil types based on the USDA taxonomy (USDA, 1999) and Figure 3A.5.4 for the World Reference Base for Soil Resources Classification (FAO, 1998) (Note: Both classifications produce the same default IPCC soil types). The default mineral soil classification should be used with Tier 1 methods because default reference C stock and stock change factors were derived according to these soil types. Inventory compilers have the option of developing a country-specific classification for mineral and/or organic if applying Tiers 2 and 3 methods, in combination with developing country-specific reference C stocks and stock change factors (or emission factors in the case of organic soils). It is *good practice* to use the same classification of soils across all land-use types.

Figure 3A.5.1 (Updated) **Delineation of major climate zones, updated from the 2006 IPCC Guidelines.**

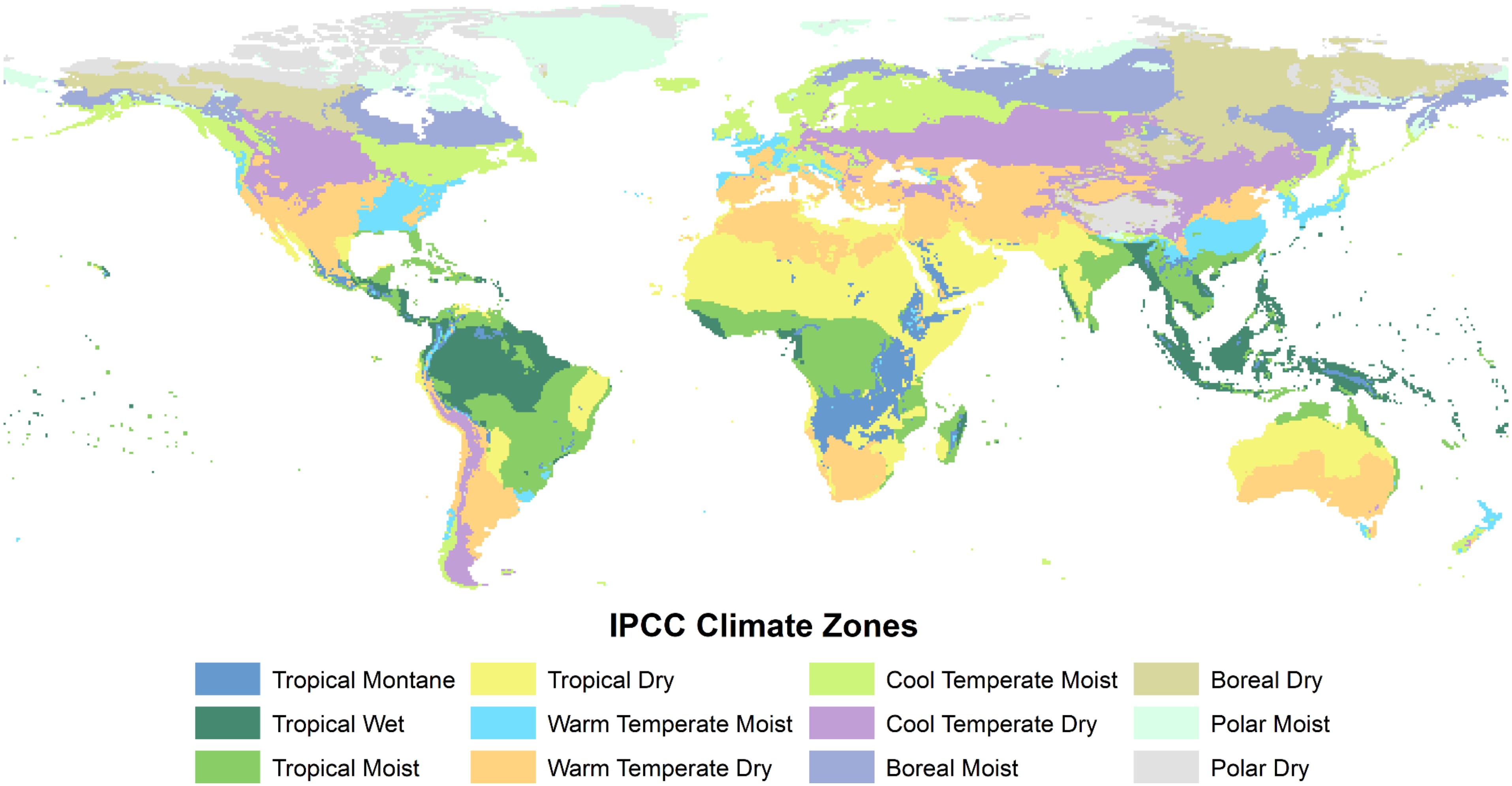


Figure 3A.5.2 Classification scheme for default climate regions. The classification is based on elevation, mean annual temperature (MAT), mean annual precipitation (MAP), mean annual precipitation to potential evapotransporation ratio (MAP:PET), and frost occurrence.

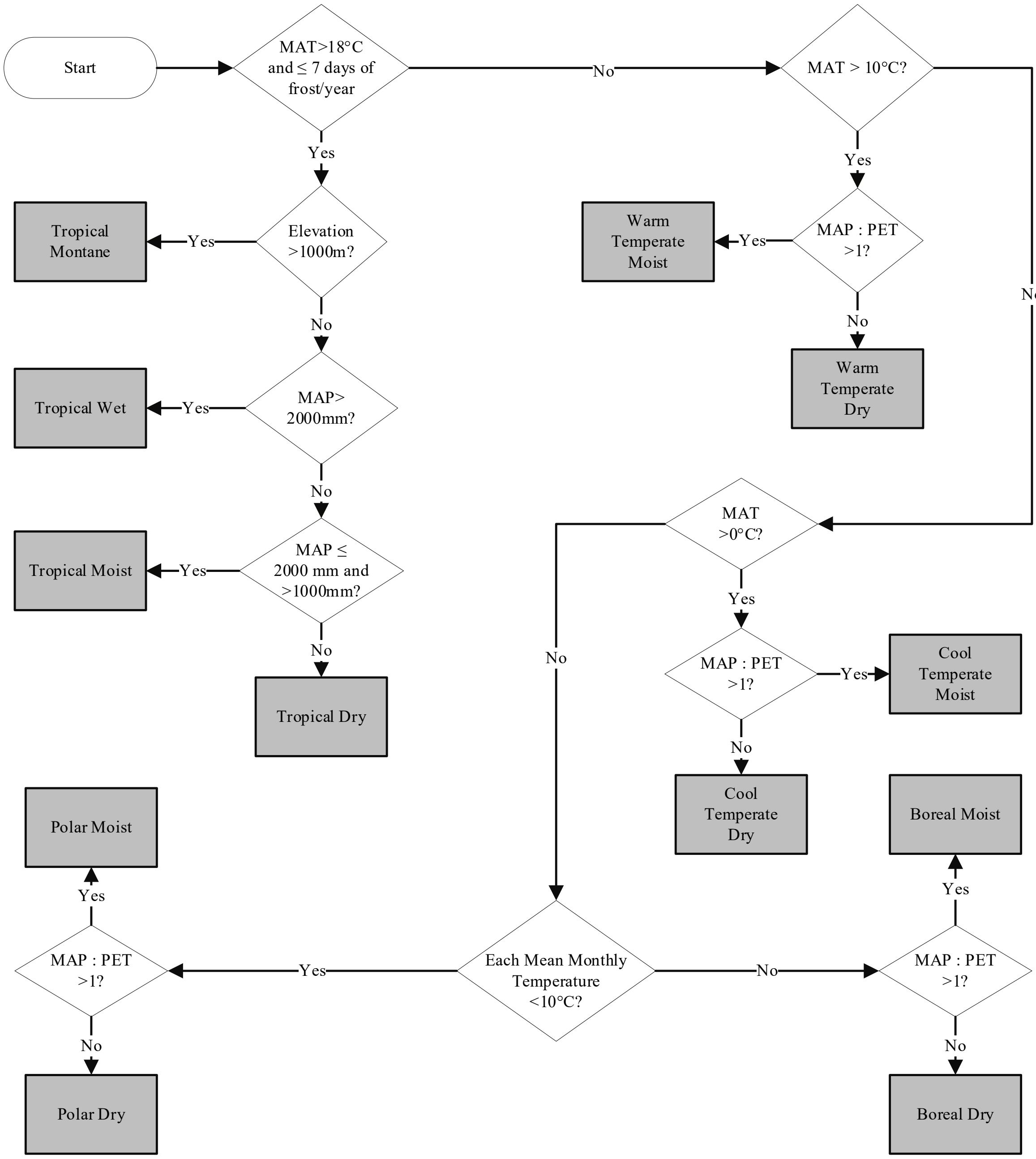


Figure 3A.5.3 Classification scheme for mineral soil types based on USDA taxonomy

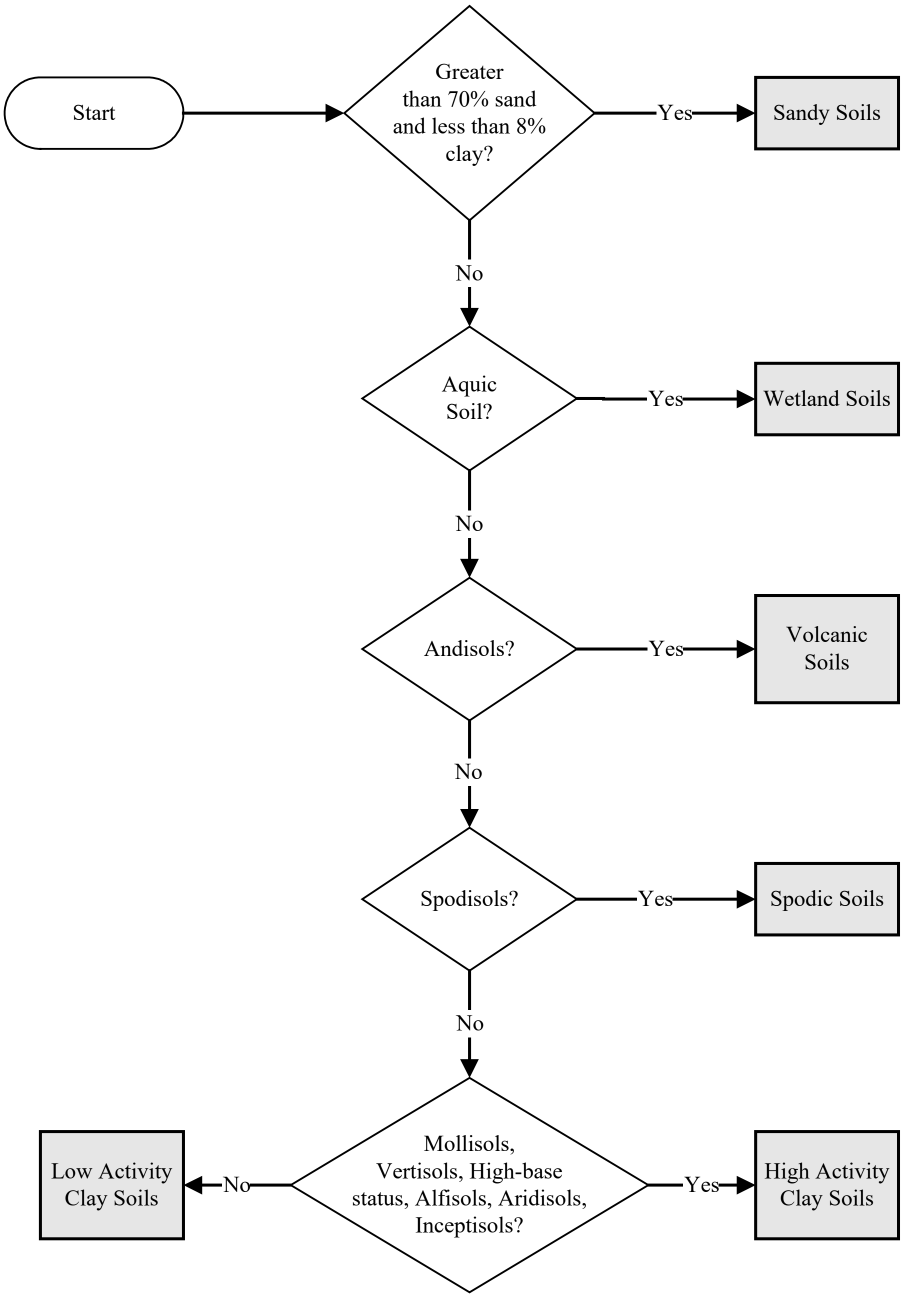
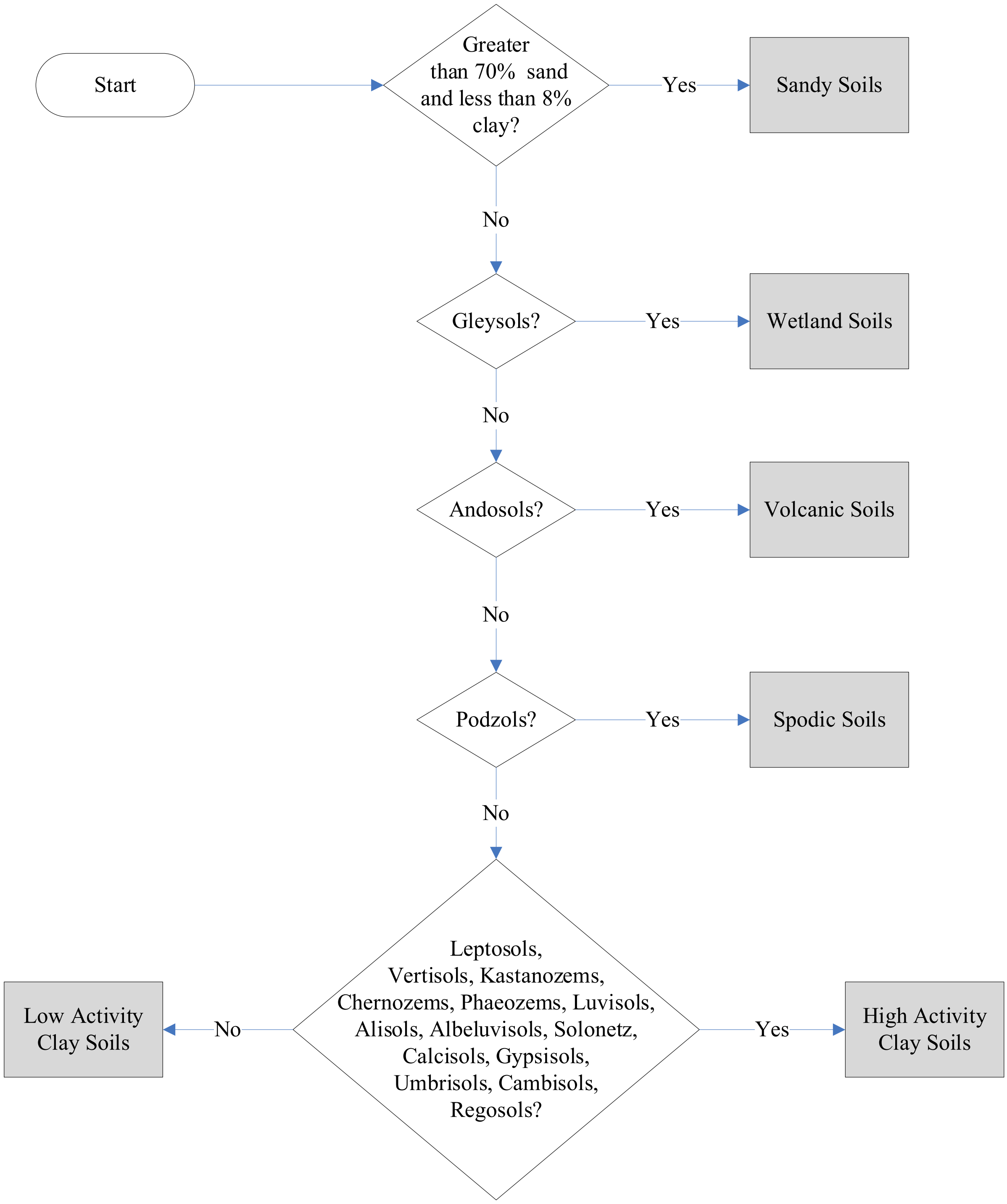


Figure 3A.5.4 Classification scheme for mineral soil types based on World Reference Base for Soil Resources (WRB) classification.



Annex 3A.6 Example process for allocating lands to IPCC land-use classes using Approach 3 wall-to-wall methods.

Figure 3A.6.1 shows a decision tree for allocating lands to the IPCC land-use categories when using Approach 3 wall-to-wall methods (i.e., where every land unit is assumed to have information on land cover over time). This method may also be applicable for some sample-based methods. The process is applied to each area of land (e.g., per pixel or vector unit) for each year of the inventory. The process uses three key types of information: land cover and cover change, auxiliary data and reporting rules. This approach is highly flexible and allows for numerous iterations depending on country circumstance.

Land cover and cover change data are typically obtained from mapping such as from remote sensing (see Appendix 3Ap.2.4). Auxiliary information comprises maps or other spatial and/or non-spatial information (proxies) that provide context to guide assessment of land use from the land cover data. Spatial auxiliary information typically includes maps of management or political boundaries (such as forest management areas or settlements), geophysical conditions (e.g., soils, climate) and disturbances (e.g., fires, harvesting). Spatial auxiliary data can also include analysis of the land cover time-series, looking forward and backward from the current years' data to determine, for example, if the cover change is temporary or part of another land use type. Non-spatial auxiliary data such as management practices by region can also provide valuable context. Finally, reporting rules are used to assign each unit to an IPCC land-use category, including the subcategories of land-use 'remaining' land-use and land-use 'converted to' land-use. These rules include the temporary land cover change period (i.e., the length of time a new land cover type remains in place before the land is considered to have changed land-use). These periods may change for each land use category or sub-category based on country circumstances.

The decision tree can be applied at each year of the inventory. The following clarifying text related to two key decision points will assist in its application:

1. For the first year of data (not the first reporting year), the process assigns each land unit into an IPCC land-use category. All lands are placed into the 'remaining' subcategory as there is no data on conversions prior to the first year of analysis.

Although not represented in this decision tree, where the first year of data is also the first reporting year it may be necessary to assign some lands to conversion categories using other auxiliary information. For example:

- The cover is identified as grass, but auxiliary maps show the land is a park within a residential area. In this case the land may assigned to Settlements.
- The land is identified as grass, but the auxiliary map shows the land is within a forest management area and all the future cover data shows the cover as forest. In this case it is possible to assume that the cover is part of a harvest cycle and the land can be assigned to Forest Land.

2. After the initial year, the cover and auxiliary data are analysed annually (even if the auxiliary data is not updated annually). The process is similar to the first step but includes additional analyses to ensure the lands are placed in the correct remaining or conversion sub-categories. There are two main processes for analysing land use and land use change depending on the cover change.

Land cover does not change.

- Where the cover and auxiliary data do not change, the land remains in the current remaining category.
- Where cover does not change, but auxiliary data does (for example, grass cover remains, but the urban expansion means that the land is now classed as Settlements), the land is placed into the appropriate converted to or remaining sub-category depending on the country specific reporting rules

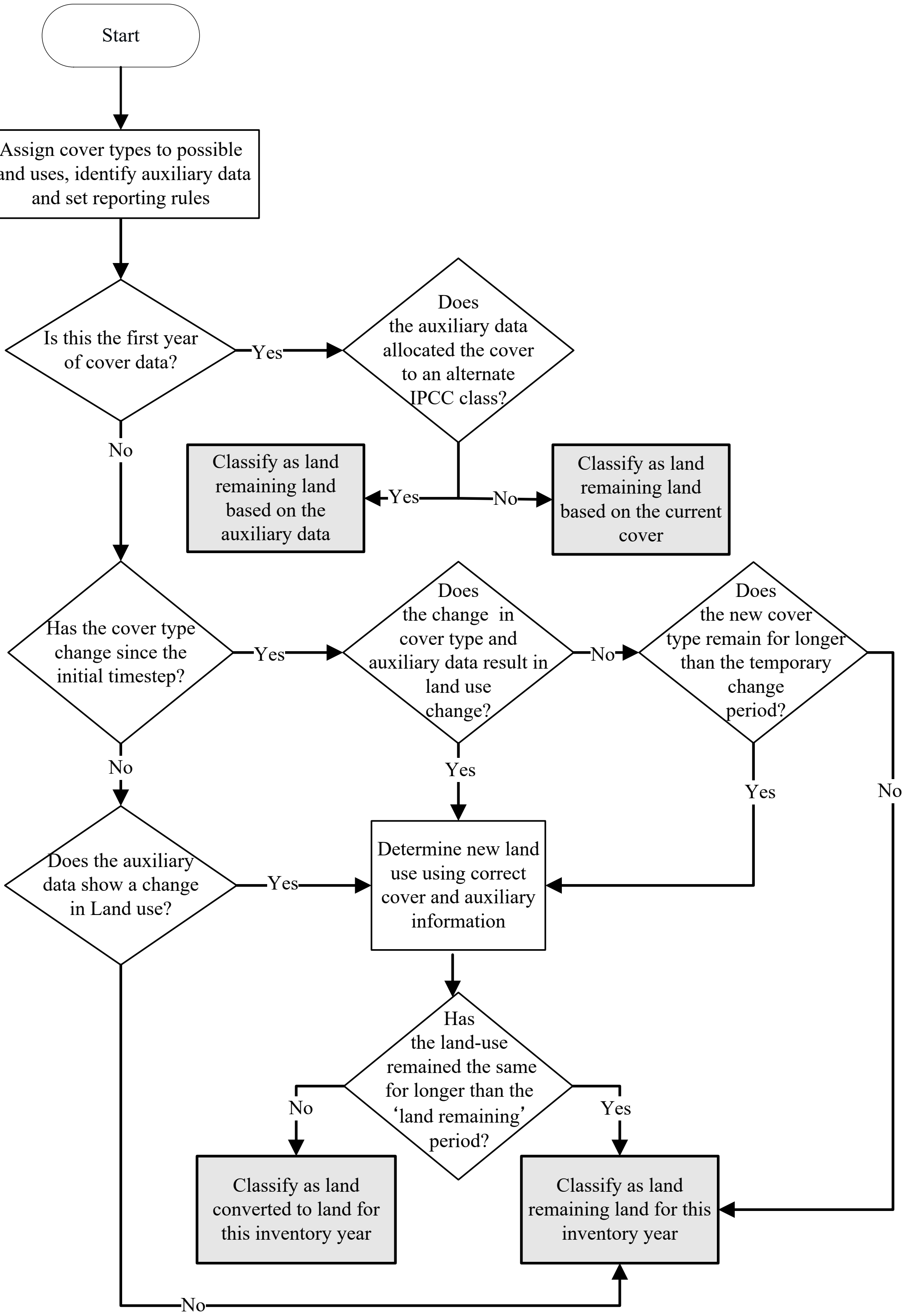
Land cover does change.

- Where cover changes and the auxiliary data suggest a land use change, analyse the time-series of cover data and apply the appropriate reporting rules to allocate the land to the appropriate converted to or remaining sub-category.
- Where the cover data changes but the auxiliary data suggests this is not a land use change (e.g., forest harvesting), analyse the time-series of cover data, apply the temporary destocking reporting rules and allocate the land to the appropriate converted to or remaining sub-category.

Both national data and global datasets can be used to derive IPCC land-use categories from land cover information.

To accurately report the area of land-use change categories in the first year of the time-series of a GHG inventory requires estimates of areas of land-use changes that occurred before the initial reporting year. Since the area to be reported in a land-use change category is the cumulative area of conversions occurred in the period Y-X, where Y is the reporting year and X is the transition period length, in years, it is *good practice t*o report a land-use conversion in an appropriate conversion category. The default length of X is 20 years but may vary depending on country circumstances.

Figure 3A.6.1 (New) Decision tree for classifying land-use and land-use change through time in Approach 3



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CHAPTER 4

FOREST LAND

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Soil Carbon Sections were prepared by lead authors, S. Niinistö, A. Lehtonen, Å. Kasimir, and S.M. Ogle.

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No refinement.

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4.2.2 Dead organic matter

No refinement.

4.2.3 Soil carbon

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

The organic C content of mineral forest soils (to 1 m depth) typically varies between 20 to over 300 tonnes C ha^{-1} depending on the forest type and climatic conditions (Jobbagy and Jackson 2000). Globally, mineral forest soils contain approximately 700 Pg C (Dixon *et al.* 1994), but soil organic C pools are not static due to differences between C inputs and outputs over time. Inputs are largely determined by the forest productivity, the decomposition of litter and its incorporation into the mineral soil and subsequent loss through mineralization/respiration (Pregitzer 2003). Other losses of soil organic C occur through erosion or the dissolution of organic C that is leached to groundwater or loss through overland flow. A large proportion of input is from above-ground litter in forest soils, so soil organic matter tends to concentrate in the upper soil horizons, with roughly half of the soil organic C in the upper 30 cm layer. In some forest ecosystems, rooting zones of trees extend considerable deeper than 30 cm, which can increase the share of soil organic carbon in deeper layers (Nepstad *et al*. 1994). Changes in soil carbon stocks in response to management actions such as thinning and clear-cutting have been detected below 20–30 cm, but not in all studies or all depths (Achat *et al*. 2015a; James and Harrison 2016; Gross *et al*. 2018). Moreover, the scarcity of measurements increases uncertainty related to soil carbon stock changes deeper in soil. The C held in the upper profile is often the most chemically decomposable, and the most directly exposed to natural and anthropogenic disturbances. This section only deals with soil C and does not address decomposing litter (i.e., dead organic matter, see Section 4.2.2).

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

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

To account for changes in soil C stocks associated with *Forest Land Remaining Forest Land*, countries need to have, at a minimum, estimates of the total Forest Land area at the beginning and end of the inventory time period, stratified by climate region and soil type. If land-use and management activity data are limited, Approach 1 activity data (see Chapter 3) can be used as the basis for a Tier 1 approach, but higher Tiers are likely to need more detailed records or knowledge of country experts about the approximate distribution of forest management systems. Forest Land classes must be stratified according to climate regions and major soil types for Tier 1, which can be accomplished with overlays of suitable climate and soil maps. Further stratification may be useful for development of Tier 2 or 3 methodology for a country.

4.2.3.1 CHOICE OF METHOD

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

Mineral soils

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

Tier 1

Current scientific basis is not sufficient to develop Tier 1 default emission factors for quantification of effects of forest management by IPCC climate zones. Thus, it is assumed in the Tier 1 method that forest soil C stocks do not change with management. Recent studies indicate, that effects of forest management actions on soil C stocks can be difficult to quantify and reported effects have been variable and even contradictory (see Box 4.3a). Furthermore, if using Approach 2 or 3 activity data (see Chapter 3), it is not necessary to compute C stock changes for mineral soils (i.e., change in SOC stocks is 0). If using activity data collected via Approach 1 (see Chapter 3), and it is not possible to identify the amount of land converted *from* and *to* Forest Land, then the inventory compiler should estimate soil C stocks for Forest Land using the areas at the beginning and the end of the inventory period in order to estimate the change in soil carbon stock. The changes in soil C stocks for Forest Land are summed with the changes in stocks for other land uses to estimate the influence of land-use change. If the compiler does not compute a stock for Forest Land, it is likely to create systematic errors in the inventory. For example, land converted from Forest Land to Cropland or Grassland will have a soil C stock estimated in the final year of the inventory, but will have no stock in the first year of the inventory (when it was forest). Consequently, conversion to Cropland or Grassland is estimated as a gain in soil C because the soil C stocks are assumed to be 0 in the Forest Land, but not in Cropland and Grassland. This would introduce a bias into the inventory estimates. SOC_0 and SOC_{0-T} are estimated for the top 30 cm of the soil profile using Equation 2.25 (Chapter 2). Note that areas of exposed bedrock in Forest Land are not included in the soil C stock calculation (assume a stock of 0). Further clarification on soil organic carbon estimation is presented in Section 2.3.3.1.

Tier 2

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

Tier 3

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

- Stratification by climatic zones, major forest types and management regimes coherent with those used for other C pools in the inventory, especially biomass;
- Determination of dominant soil types in each stratum;
- Characterization of corresponding soil C pools, identification of determinant processes in SOC input and output rates and the conditions under which these processes occur; and
- Determination and implementation of suitable methods to estimate carbon stock changes from forest soils for each stratum on an operational basis, including model evaluation procedures; methodological considerations

are expected to include the combination of monitoring activities – such as repeated forest soil inventories - and modelling studies, and the establishment of benchmark sites. Further guidance on good soil monitoring practices is available in the scientific literature (Kimble *et al.* 2003, Lal *et al.* 2001, McKenzie *et al.* 2000). It is *good practice* for models developed or adapted for this purpose to be peer-reviewed and validated with observations representative of the ecosystems under study and independent from the calibration data.

More guidance on Tier 3 methods is given in Chapter 2.3.3.1, such as examples of Tier 3 modelling methods in Box 2.2d. The examples provide information about types of data required, brief descriptions of models, methods that are used to apply the models, and how using a Tier 3 model has changed results. General guidance on measurement-based and model-based Tier 3 inventories for the AFOLU sector can be found in Section 2.5.

Organic soils

No refinement.

See guidance in *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*, Chapter 2, Section 2.2.

4.2.3.2 CHOICE OF STOCK CHANGE AND EMISSION FACTORS

Mineral soils

Tier 1

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

Tier 2

In a Tier 2 approach, stock change factors are derived based on a country-specific classification scheme for management, forest types, and natural disturbance regimes. A Tier 2 approach should include the derivation of country-specific reference C stocks, and a more detailed classification of climate and soils than the default categories provided with the Tier 1 method. The depth for evaluating soil C stock changes can differ from 30 cm with the Tier 2 method. However, this will require consistency with the depth of the reference C stocks (SOC_{REF}) and stock change factors (i.e., F_{LU}, F_I, and F_{MG}) to ensure consistent application of methods for determining the impact of land use change on soil C stocks. Box 4.3a provides information and references that can be used as a starting point for developing Tier 2 factors for forest management as well as observations on related challenges.

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

Inventories can also be improved by deriving country-specific reference C stocks (SOC_{REF}), compiled from published studies or surveys. Such values are typically obtained through the development and/or compilation of large soil profile databases (Siltanen *et al.* 1997; Scott *et al.* 2002; Batjes 2011; De Vos *et al.* 2015). Additional guidance for deriving stock change factors and reference C stocks is provided in Section 2.3.3.1 (Chapter 2).

BOX 4.3A (NEW)
DEVELOPING TIER 2 STOCK CHANGE FACTORS FOR FOREST LAND

Although the scientific basis is not sufficient for deriving default stock change factors for forest land, country specific Tier 2 factors can be developed if there is adequate data available to represent national circumstances. Several meta-analyses and reviews provide analyses and references to support incorporation of country-specific data into a Tier 2 method with estimation of management effects and corresponding stock change factors (F_{MG}) for Forest Land Remaining Forest Land. Quantification of management effects becomes increasingly important in cases in which forests represent a significant sink or source or in which changes in management intensity or practices result in gains or losses compared to earlier practices. Increased removal of harvest residues or stumps for bioenergy is one example of changes in management intensity and practices. Most analyses have focused on the effects following harvests of different intensities (e.g., Johnson and Curtis 2001; Achat *et al*. 2015a; James and Harrison 2016; Zhou *et al*. 2013). Response ratios or effect sizes based on measurements of soil carbon stocks reflect all changes associated with a management action; thus, separate carbon stock factors for input of organic matter (F_I) cannot be derived from the existing data.

Most field experiments have been carried out in cool temperate regions, and meta-analyses or reviews on harvest effects can be found to support adaptation of Tier 2 methods for these regions Nave *et al*. 2010; Thiffault *et al*., 2011; Clarke *et al*. 2015; Hume *et al*. 2017). When selecting harvesting experiments on which to base the calculation of stock change factors, several factors need to be considered: intensity of harvest, treatment of harvest residues and other site preparation practices, such as burning, time since the management action, and soil layers and sampling depths (Liao *et al*. 2010; Strömgren *et al*. 2013; Achat *et al*. 2015b; James and Harrison 2016; Dean *et al.* 2017; Hume *et al.* 2017). Tree species composition, i.e., conifers versus broad-leaved or mixed species, could also influence the management effect although the influence can be confounded by other factors (e.g. Hume *et al.* 2017). The question of control conditions for evaluating the management action is of great importance because the control is often not a native reference condition, but rather another managed forest (Dean *et al*. 2017). This should be taken into account when estimating a stock change factor based on several field studies as well as the relationship to country-specific reference soil C stock.

Conclusions on the harvesting effects differ between meta-analyses, which could be partly due to differences in field experiment set-ups and the different data selection and weighting procedures. As an example, whole-tree harvests resulted in average 7.5percent smaller carbon stocks in mineral soil than the stocks measured 10–30 years after stem-only harvests (Achat *et al*. 2015a). However, no effect of whole-tree harvest was found in some other meta-analyses (Clarke *et al.* 2015; Hume *et al.* 2017) or a positive effect was reported (James and Harrison 2016). However, there was a tendency for smaller carbon stocks in forest floor after whole-tree harvesting compared to stem-only harvesting or pre-treatment conditions (Johnson and Curtis 2001; Thiffault *et al*. 2011; Clarke *et al.* 2015).

Considerable spatial variability increases the challenge to detect relatively small management effects in soil C stocks (Jandl *et al*. 2007). However, most studies include only the first one or two decades after the harvest, which may too short to reveal impact of forest management actions on soil carbon stock changes, especially in cool climate regions with long rotation periods (Clarke *et al*. 2015; Dean *et al*. 2017). Non-linearity in the responses has also been observed. For example, an increase in soil C stocks after an initial decrease has been observed for a group of studies on Spodosols from a cool and humid climate with longer monitoring periods, up to eight decades of typical rotation lengths (James and Harrison 2016).

In addition to guidance in this Chapter 4.2.3.2 above, detailed guidance on estimation of country-specific stock change factors and reference C stocks in general is given in Chapter 2, in Section 2.3.3.1., including guidance on using models to derive carbon stock change factors.

Tier 3

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

Organic soils

No refinement.

See guidance in *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*, Chapter 2, Section 2.2.

4.2.3.3 CHOICE OF ACTIVITY DATA

Mineral soils

Tier 1

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

Tier 2

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

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

Tier 3

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

Organic soils

No refinement.

See guidance in *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*, Chapter 2, Section 2.2.

4.2.3.4 CALCULATION STEPS FOR TIER 1

No refinement.

4.2.3.5 UNCERTAINTY ASSESSMENT

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

For Tier 1, uncertainties are provided with the reference C stocks in the first footnote of Table 2.3 (Chapter 2), and emission factor uncertainties for organic soils are provided in Table 4.6, Section 4.5. For organic soils, see guidance in *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*, Chapter 2, Section 2.2. Uncertainties in land-use and management data will need to be addressed by the inventory compiler, and then combined with uncertainties for the default factors and reference C stocks (mineral soils only) using an appropriate method, such as simple error propagation equations. Refer to Section 4.2.1.5 for uncertainty estimate for land area estimates. However, it is *good practice* for the inventory compiler to derive uncertainties from country-specific activity data instead of using a default level.

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

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

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

Tier 3 models are more complex and simple error propagation equations may not be effective at quantifying the associated uncertainty in resulting estimates. Monte Carlo analyses are possible (Smith and Heath 2001), but can be difficult to implement if the model has many parameters (some models can have several hundred parameters) because joint probability distribution functions must be constructed quantifying the variance as well as covariance among the parameters (see e.g. Peltoniemi *et al.* 2006; Metsaranta *et al*. 2017). However, if soil model parameters have been estimated with a Bayesian approach, the resultant joint probability distribution for the parameters can be sampled in a Monte Carlo Analysis to capture parameter uncertainty, along with sampling of probability distribution functions for model inputs and other associated data, see Lehtonen and Heikkinen (2016). Other methods are also available such as empirically-based approaches (Monte *et al.* 1996), which use measurements from a monitoring network to statistically evaluate the relationship between measured and modelled results (Falloon and Smith 2003; Ogle *et al.* 2007). In contrast to modelling, uncertainties in measurement-based Tier 3 inventories can be determined from the sample variance, measurement error and other relevant sources of uncertainty.

4.2.4 Non-CO_2 greenhouse gas emissions from biomass burning

No refinement.

4.3 LAND CONVERTED TO FOREST LAND

4.3.1 Biomass

No refinement.

4.3.2 Dead organic matter

No refinement.

4.3.3 Soil carbon

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

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

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

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

4.3.3.1 CHOICE OF METHOD

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

Mineral soils

Tier 1

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

Tier 2

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

Tier 3

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

Organic soils

No refinement.

See guidance in *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*, Chapter 2, Section 2.3.

4.3.3.2 CHOICE OF STOCK CHANGE AND EMISSION FACTORS

Mineral soils

Tier 1

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

Tier 2

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

Reference C stocks can also be derived from country-specific data in a Tier 2 approach. Reference values in Tier 1 correspond to non-degraded, unimproved lands under native vegetation, but other reference conditions can also be chosen for Tier 2. In general, reference C stocks should be consistent across the land uses (i.e., Forest Land, Cropland, Grassland, Wetlands, Settlements, Other Land) (see section 2.3.3.1). Therefore, the same reference stock should be used for each climate zone and soil type, regardless of the land use. The reference stock is then multiplied by land use, input and management factors to estimate the stock for each land use based on the set of management systems that are present in a country. In addition, the depth for evaluating soil C stock changes can be different with the Tier 2 method. However, this will require consistency with the depth of the reference C stocks (SOC_{REF}) and stock change factors for all land uses (i.e., F_{LU}, F_I, and F_{MG}) to ensure consistency in the application of methods for estimating the impact of land use change on soil carbon stocks. Additional guidance is provided in Chapter 2, Section 2.3.3.1.

The carbon stock estimates may be improved when deriving country-specific factors for F_{LU} and F_{MG}, by expressing carbon stocks on a soil-mass equivalent basis rather than a soil-volume equivalent (i.e., fixed depth) basis. This is because the soil mass in a certain soil depth changes with the various operations associated with land use that affect the density of the soil, such as uprooting, land levelling, tillage, and rain compaction due to the disappearance of the cover of tree canopy. However, it is important to realize that all data used to derive stock change factors across all land uses must be on an equivalent mass basis if this method is applied. This will be challenging to do comprehensively for all land uses. See Box 2.2c in Chapter 2, Section 2.3.3.1 for more information.

Tier 3

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

Organic soils

No refinement.

See guidance in *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*, Chapter 2, Section 2.3.

4.3.3.3 CHOICE OF ACTIVITY DATA

Mineral soils

Tier 1 and Tier 2

For purposes of estimating soil carbon stock change, area estimates of *Land Converted to Forest Land* should be stratified according to major climate regions and soil types. This can be based on overlays with suitable climate and soil maps and spatially-explicit data of the location of land conversions. Detailed descriptions of the default climate and soil classification schemes are provided in Chapter 3. Specific information is provided in the each of the land-use sections regarding treatment of land-use/management activity data (Forest Land in Section 4.2.3.3, Cropland in 5.2.3.3, Grassland in 6.2.3.3, Wetlands in 7.2.3.2, Settlements in 8.2.3.3, and Other Land in 9.3.3.3).

One critical issue in evaluating the impact of Land Converted to Forest Land on soil organic C stocks is the previous land-use and management activity. Activity data gathered using Approach 2 or 3 (see Chapter 3 for discussion about Approaches) provide the underlying basis for determining the previous land use and management for Land Converted to Forest Land. In contrast, aggregate data (Approach 1, Chapter 3) only provide the total amount of area in each land use and do not form a basis for determining specific transitions. Moreover, aggregate data only represent the net changes in land use and management rather than the gross changes, which could be considerably larger and may have an impact on the total soil C stock changes. Regardless, with aggregate data (Approach 1), changes in soil organic C stocks may be computed separately for each land-use category and then combined to obtain the total stock change even if the total changes do not capture the full dynamics occurring with land use change. Using this approach, it will be necessary for coordination among each land-use category to ensure the total land base is remaining constant over time, given that some land area will be lost and gained within individual land-use category during each inventory year due to land-use change. Further clarification on soil organic C estimation methods in case of land-use change is presented in Section 2.3.3.1.

Tier 3

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

Organic soils

No refinement.

See guidance in *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*, Chapter 2, Section 2.3.

4.3.3.4 CALCULATION STEPS FOR TIER 1

Mineral soils

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

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

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

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

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

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

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

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

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

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

Organic soils

No refinement.

See guidance in *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*, Chapter 2, Section 2.3.

4.3.3.5 UNCERTAINTY ASSESSMENT

No refinement.

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

4.4.1 Completeness

No refinement.

4.4.2 Developing a consistent time series

It is *good practice* to develop a consistent time series of inventories of anthropogenic emissions and removals of greenhouse gases for all AFOLU categories using the guidance in Volume 1, Chapter 5. Because forest-related activity data and emission factors may only be available every few years, achieving time series consistency may require interpolation or extrapolation from longer timeseries or trend.

In addition to the general guidance on gap filling (e.g. on linear interpolation or extrapolation) in Volume 1, Chapter 5, further guidance is provided here on how to ensure methodological consistency in the case of the Forest Land category. When extrapolation may allow reflecting the evolution of the main drivers of emissions and removals during the period to be gap filled, including forest increment and harvest, with a greater level of accuracy than a linear interpolation or extrapolation.

Generally, these functional relationships are expressed in models which are applied to simulate the dynamics of carbon stocks in different pools, taking into account a number of interrelated variables.These variables include: forest characteristics (i.e. forest types, soil types, tree species composition, growing stock, age-class structure) and management practices (i.e. regeneration modality, rotation lengths, thinning frequency, etc.); the carbon pools and gases; the estimation parameters for HWP; the treatment of natural disturbances; the possible inclusion of impact of “indirect human-induced effects” (see Section 2.5), such as human-induced climate and environmental changes (e.g., temperature, precipitation, CO_2 and nitrogen deposition feedbacks) that affect growth, mortality, decomposition rates and natural disturbances regimes.

Among these, harvest volume is a key driver of emissions and removals. To this regard, if the actual harvest volume for the period to be extrapolated is known with confidence, then the model may directly apply this harvest volume, in combination with the other variables above. However, sometimes no reliable statistics on harvest volume (or other suitable proxies) are available for the period to be gap-filled. In this case, it is *good practice* to assume that the historical management practices continue during the period to be gap-filled. These practices should be those applied (and documented) in the existing time series, e.g. for the “calibration period” (see below). The functional relationships between available timber stocks, age structure dynamics, the increment and the harvest volume under the continuation of management practices (which is the basis of yield tables for forest management) can be used to calculate a consistent time series of annual C stock gains (forest net increment) and annual C stock losses (e.g. harvest, etc.). For example, if a given tree species is typically harvested at 80 years, the extrapolation based on functional relationships will apply this harvesting age (i.e. the historical forest management practice) also in the period to be gap-filled, taking into account the age structure dynamics (e.g. if the forest is getting older, more area reaching 80 years may be available); the carbon gains will be calculated using the forest net increment associated with the age structure and harvest volume simulated for the period to be gap-filled. An example of resolving data gaps in Forest Land through an extrapolation based on functional relationships is provided in Box 4.3b.

It is *good practice* that the model used for extrapolation utilizes information on the methodological elements above that is consistent with those used in the rest of the time series.

A change in any of the variables above used in the existing (non-extrapolated) time series (e.g., adding a new carbon pool) triggers a methodological inconsistency, to be addressed through a re-run, for the entire time series, of the model used for the extrapolation. Such re-run should ensure consistency in the variables described above.

As a general check for the consistency, it is *good practice* to demonstrate that the model used for the extrapolation reproduces the existing time series, for a selected “calibration period”. The length of this calibration period may depend on various factors, but it is preferable to have at least 5 or 10 years of comparison between the model’s results and the existing time series. If the model results for the calibration period fall within the estimated range of uncertainty of the existing time series (as documented in the GHG inventory), any remaining discontinuity between the existing time series and the portion extrapolated may be addressed through the application of the “overlap” technique (Volume 1, Chapter 5.3.3.1) to extrapolated data. This procedure will affect the level of modelled GHG estimates, but not their trend. If, for the calibration period, the model’s results do not fall within the reported range of uncertainty of the existing time series, it is *not good practice* to use these results for extrapolating the time series. An example of resolving forest data gaps through extrapolation based on functional relationships is provided in Box 4.3b

BOX 4.3B (NEW)
EXAMPLE OF RESOLVING FOREST DATA GAPS THROUGH EXTRAPOLATION BASED ON FUNCTIONAL RELATIONSHIPS

Consider a case in which the stock difference method (see Volume 4, Chapter 2.3) is applied to construct a consistent time series between 1990 and 2015. Suppose that the next complete forest inventory will be reported in 2025, and that no reliable harvest data after 2015 is available. Until this inventory becomes available, the GHG emissions after 2015 may need to be extrapolated.

One option is to apply a linear extrapolation to the historical time series. Another option, to be considered especially when age structure dynamics exert a relevant impact on the trend of forest CO_2 fluxes, is to extrapolate the historical GHG emissions through functional relationships. To this aim, a model may be used to calculate, for the period to be gap-filled, the net increment and the harvest volumes associated with the continuation of historical management practices.

A theoretical example of the impact of different extrapolation approaches is provided in the following table, for selected years and for the living biomass of forests that are assumed to approach maturity.

For the purpose of extrapolating based on functional relationships, a model calculates the harvest volumes in the period to be gap-filled through the intersection between the continuation of historical forest management practices and the available timber stocks as affected by the age-related forest dynamics.

Historical period			**Linear extrapolation**	**Extrapolation based on functional relationships**
(ktC yr-1)	**2000**	**2015**	**2020**	**2020**
Net increment	20.0	26.0	28.0	26.0
Harvest	14.0	17.0	18.0	22.0
Net change	6.0	9.0	10.0	4.0

In this example, the net forest increment has increased in the historical period (2000-2015) more than the increase in harvest volumes. As a result, the sink (net change in C) has also increased. A linear extrapolation of this trend would lead to a further increase on the sink in 2020. However, in this example, the forests are aging, i.e. more forest area reaches maturity. As a consequence, assuming the continuation of the historical forest management practices, in 2020 the net increment is expected to saturate (i.e. in the table it remains at the 2015 levels) and the total harvest volume is expected to increase (because more area will reach maturity, and thus more biomass will be ready to be harvested). The resulting sink would also decline, in contrast with what obtained by the linear extrapolation. In this theoretical case, the extrapolation based on functional relationships may be considered to provide a more realistic estimate of GHG emissions in the period to be gap-filled.

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

4.4.3 Quantity Assurance and Quality Control

No refinement.

4.4.4 Reporting and Documentation

No refinement.

4.5 TABLES

Table 4.1

No refinement.

Table 4.2

No refinement.

Table 4.3

No refinement.

TABLE 4.4 (UPDATED)
RATIO OF BELOW-GROUND BIOMASS TO ABOVE-GROUND BIOMASS (R) [TONNE ROOT D.M. (TONNE SHOOT D.M.)$^{-1}$]

Domain	Ecological zone[1]	Continent	Origin (Natural/Plantation)	Above-ground biomass (tonnes ha^{-1})	R [tonne root d.m. (tonne shoot d.m.)$^{-1}$]	Uncertainty	Uncertainty type	References
Tropical	Tropical Rainforest	Africa	Natural	≤ 125	0.825	±90%	default	1, 2
			Natural	> 125	0.532	±90%	default	2, 3
		North and South America	Natural	≤ 125	0.221	0.036	SD	4
			Planted	≤ 125	0.170	0.11	SD	5
			Natural	> 125	0.221	0.036	SD	4
			Planted	> 125	0.170	0.11	SD	5
		Asia	Natural	≤ 125	0.207	0.072	SD	6, 7, 8
			Planted	≤ 125	0.325	0.025	SD	8
			Natural	> 125	0.212	0.077	SD	7, 8, 9, 10, 11
	Tropical Moist	Africa	Natural	≤ 125	0.232	±90%	default	12
			Natural	> 125	0.232	±90%	default	12
		North and South America	Natural	≤ 125	0.2845	0.061	SD	12
			Natural	> 125	0.284	0.061	SD	12
		Asia	Natural	≤ 125	0.323	0.073	SD	1, 13, 14, 5
			Natural	> 125	0.246	0.036	SD	12, 16
	Tropical Dry	Africa	Natural	≤ 125	0.332	0.247	SD	1, 12, 17, 18, 19
			Natural	> 125	0.379	0.040	SD	12
		North and South America	Natural	≤ 125	0.334	0.040	SD	4, 12, 20
			Natural	> 125	0.379	0.040	SD	12
		Asia	Natural	≤ 125	0.440	±90%	default	12
			Natural	> 125	0.379	0.040	SD	12
	Tropical Mountain	North and South America	Natural	≤ 125	0.348	±90%	default	4
			Planted	≤ 125	0.205	±90%	default	12
			Natural	> 125	0.283	0.16	SD	21
		Asia	Natural	≤ 125	0.322	0.084	SD	22, 23
			Natural	> 125	0.345	0.280	SD	22, 23

TABLE 4.4 (UPDATED) (CONTINUED) RATIO OF BELOW-GROUND BIOMASS TO ABOVE-GROUND BIOMASS (R) [TONNE ROOT D.M. (TONNE SHOOT D.M.)$^{-1}$]								
Domain	**Ecological zone[1]**	**Continent**	**Origin (Natural/ Plantation)**	**Above-ground biomass (tonnes ha^{-1})**	**R [tonne root d.m. (tonne shoot d.m.)$^{-1}$]**	**Uncertainty**	**Uncertainty type**	**References**
Sub-tropical	Sub-tropical Humid	Africa	Natural	≤ 125	0.232	±90%	default	12
			Natural	> 125	0.232	±90%	default	12
		North and South America	Natural	≤ 125	0.175	±90%	default	12
			Natural	> 125	0.284	±90%	default	12
		Asia	Natural	≤ 125	0.230	±90%	default	12
			Natural	> 125	0.246	±90%	default	12
	Sub-tropical Dry	North and South America	Natural	≤ 125	0.336	±90%	default	12
			Natural	> 125	0.352	0.047	SD	12
		Asia	Natural	≤ 125	0.440	0.184	SD	12
			Natural	> 125	0.440	0.184	SD	12
	Sub-tropical Steppe	North and South America	Natural	≤ 125	1.338	±90%	default	12
		Asia	Natural	> 125	1.338	±90%	default	12
			Planted	≤ 125	2.158	±90%	default	12
Temperate	Oceanic	Europe	Natural/Planted (Other Broadleaf)	all size classes	0.192	±90%	default	24
			Natural (Conifer)	≤ 125	0.359	±90%	default	12
			Natural (Other Broadleaf)	>125	0.172	±90%	default	12
			Planted (Conifer)	>125	0.206	±90%	default	12, 25, 26, 27
			Planted (Conifer)	all size classes	0.359	0.145	SD	28
			Planted (Quercus)	≤ 125	1.400	±90%	default	29
		North and South America	Natural (Conifer)	≤ 125	0.337	±90%	default	12
			Natural (Conifer)	>125	0.338	±90%	default	12
			Natural (Other Broadleaf)	≤ 125	0.466	±90%	default	12, 30
			Natural (Other Broadleaf)	>125	0.190	±90%	default	12, 31
			Planted (Conifer)	>125	0.203	±90%	default	12, 32

TABLE. 4.4 (UPDATED) (CONTINUED)
RATIO OF BELOW-GROUND BIOMASS TO ABOVE-GROUND BIOMASS (R) [TONNE ROOT D.M. (TONNE SHOOT D.M.)$^{-1}$]

Domain	Ecological zone[1]	Continent	Origin (Natural/Plantation)	Above-ground biomass (tonnes ha^{-1})	R [tonne root d.m. (tonne shoot d.m.)$^{-1}$]	Uncertainty	Uncertainty type	References
Temperate	Oceanic	Oceania	Natural (Eucalyptus)	≤ 125	0.464	±90%	default	12
			Natural (Eucalyptus)	>125	0.257	±90%	default	12
			Natural (Other Broadleaf)	≤ 125	0.213	±90%	default	34-36
			Natural (Other Broadleaf)	>125	0.313	±90%	default	37, 38
			Planted (Conifer)	all size classes	0.190	±90%	default	39
			Planted (Conifer)	≤ 125	0.634	±90%	default	12
			Planted (Conifer)	>125	0.294	±90%	default	12
			Planted (Eucalyptus)	≤ 125	0.391	±90%	default	12
			Planted (Eucalyptus)	>125	0.188	±90%	default	12, 40
	Continental	Europe	Natural (Quercus)	>125	0.477	±90%	default	12
			Planted (Conifer)	≤ 125	0.340	±90%	default	12
		North and South America	Natural (Other Broadleaf)	≤ 125	0.481	±90%	default	12
			Natural (Other Broadleaf)	>125	0.277	±90%	default	12
			Planted (Conifer)	≤ 125	0.237	±90%	default	12

TABLE. 4.4 (UPDATED) (CONTINUED)
RATIO OF BELOW-GROUND BIOMASS TO ABOVE-GROUND BIOMASS (R) [TONNE ROOT D.M. (TONNE SHOOT D.M.)$^{-1}$]

Domain	Ecological zone[1]	Continent	Origin (Natural/Plantation)	Above-ground biomass (tonnes ha^{-1})	R [tonne root d.m. (tonne shoot d.m.)$^{-1}$]	Uncertainty	Uncertainty type	References
Temperate	Oceanic Continental Mountain	Asia	Natural (Conifer)	≤ 125	0.243	±90%	default	33
			Natural (Conifer)	>125	0.262	±90%	default	33
			Natural (Other Broadleaf)	≤ 125	0.225	±90%	default	33
			Natural (Other Broadleaf)	>125	0.229	±90%	default	33
			Planted (Conifer)	≤ 125	0.224	±90%	default	33
			Planted (Conifer)	>125	0.232	±90%	default	33
			Planted (other Broadleaf)	≤ 125	0.307	±90%	default	33
			Planted (other Broadleaf)	>125	0.248	±90%	default	33
Boreal	Coniferous, tundra woodland, mountain systems	-	-	≤ 75	0.390	0.23 - 0.96	Range	12, 46
				>75	0.240	0.15 - 0.37	Range	12, 46

[1] Forest Resources Assessment (FRA). (2015). Global Eological Zones for FAO Forest Reporting 2010 Update. Forest Resources Assessment Working Paper 179.

References:

1 Masota, A.M., *et al*., 2016; 2 Njana, M.A., *et al*., 2015; 3 Masota, A.M., *et al*., 2015; 4 FAO, 2015; 5 Sanquetta, *et al*., 2011; 6 Saner, P., *et al*., 2012; 7 Murdiyarso, M., *et al*., 2015; 8 Kotowska, M.M., *et al*., 2015; 9 Lu, X.T., *et al*., 2010; 10 Niiyama K, *et al*., 2010; 11 Krisnawati, H., *et al*., 2014; 12 Mokany, K., *et al*., 2006; 13 Wang, X.P., *et al*., 2008; 14 Li, X., *et al*., 2010; 15 Monda, Y., *et al*., 2016; 16 Gautum, T.P., Mandal, T.N., 2016; 17 Mugasha, W.A., *et al*., 2013; 18 Malimbwi, R.E., *et al*., 2016; 19 Makero, *et al*., 2016; 20 Sato, T., *et al*., 2015; 21 Moser, G., 2011; 22 Iqbal, K., *et al*., 2014; 23 Sharma, D.P., 2009; 24 Skovsgaard, J.P., Nord-Larsen, T., 2012; 25 Green C., *et al*., 2007; 26 Urban, J., *et al*., 2015; 27 Xiao, C.W., *et al*., 2003; 28 Levy, P.E., *et al*., 2004; 29 Cotillas, M., *et al*., 2016; 30 Gargaglione, *et al*., 2010; 31 Frangi, J.L., *et al*., 2005; 32 Miller, A.T., *et al*., 2006; 33 Luo, Y., *et al*., 2014; 34 Schwendenmann, L., Mitchell, N., 2014; 35 Watson, A,. O'Loughlin, C., 1985; 36 Watson, A., 1995; 37 Beets, P.N., 1980; 38 Miller, R. B. 1963; 39 Beets PN, *et al*., 2007; 40 Oliver GR, *et al*., 2009; 41 Battles, J. J., *et al*., 2002; 42 Laclau P. 2003; 43 Grimm, U., Fassbender, H., 1981; 44 Edwards, P., Grubb, P., 1977; 45 Scott, N.A., *et al*., 2005; 46 Li, et al., 2003.

Table 4.5

No refinement.

Table 4.6

No refinement.

TABLE 4.7 (UPDATED) ABOVE-GROUND BIOMASS IN NATURAL FORESTS (TONNES D.M. HA^{-1})							
Domain	**Ecological zone [1]**	**Continent**	**Status/condition[2]**	**Above-ground biomass [tonnes d.m. ha^{-1}]**	**Uncer tainty**	**Uncerta inty type**	**References**
Tropical	Tropical rainforest	Africa	Primary	404.2	120.4	SD	1-12
			Secondary >20 years	212.9	143.1	SD	5-7, 11, 13-16
			Secondary ≤20 years	52.8	35.6	SD	9-11, 14, 15, 17
		North and South America	Primary	307.1	104.9	SD	3, 4, 9, 10, 18-21
			Secondary >20 years	206.4	80.4	SD	9, 10, 22-28
			Secondary ≤20 years	75.7	34.5	SD	9, 10, 14, 22, 23, 28-32
		Asia	Primary	413.1	128.5	SD	3, 4, 9, 10, 33-35
			Secondary >20 years	131.6	20.7	SD	9, 10, 36, 37
			Secondary ≤20 years	45.6	20.6	SD	9, 10, 37-39
	Tropical moist deciduous forest	Africa	Primary	236.6	104.7	SD	1, 2, 16
			Secondary >20 years	72.8	36.4	SD	9, 10, 16, 40-47
			Secondary ≤20 years				
		North and South America	Primary	187.3	94.0	SD	3, 4, 9, 10, 18-21
			Secondary >20 years	131.0	54.2	SD	9, 10, 22-26
			Secondary ≤20 years	55.7	28.7	SD	9, 10, 22, 23, 25, 26
		Asia	Primary	67.7	93.4	SD	9, 10, 35, 48-50
			Secondary >20 years				
			Secondary ≤20 years				
	Tropical dry forest	Africa	Primary	69.6	47.5	SD	1, 2, 43, 44, 51-53
			Secondary >20 years				
			Secondary ≤20 years				
		North and South America	Primary	127.5	72.6	SD	18-21
			Secondary >20 years	118.9	81.3	SD	9, 10, 22, 23, 54
			Secondary ≤20 years	32.2	24.2	SD	9, 10, 22, 23, 54, 55
		Asia	Primary	184.6	144.5	SD	9, 10, 35, 48, 56
			Secondary >20 years				
			Secondary ≤20 years				
	Tropical shrublands	Africa	Primary	48.4	45.8	SD	44, 57, 58
			Secondary >20 years				
			Secondary ≤20 years				
		North and South America	Primary	71.5	46.4	SD	59
			Secondary >20 years				
			Secondary ≤20 years				
		Asia	Primary	38.3	33.0	SD	59
			Secondary >20 years				
			Secondary ≤20 years				

TABLE 4.7 (UPDATED) (CONTINUED)
ABOVE-GROUND BIOMASS IN NATURAL FORESTS (TONNES D.M. HA^{-1})

Domain	Ecological zone [1]	Continent	Status/condition[2]	Above-ground biomass [tonnes d.m. ha^{-1}]	Uncertainty	Uncertainty type	References
Tropical	Tropical mountain systems	Africa	Primary				
			Secondary >20 years	190.0	131.2	SD	1-4, 9, 10, 42-44, 47, 53, 60-68
			Secondary ≤20 years				
		North and South America	Primary	195.0	95.6	SD	3, 4, 9, 10, 18-21
			Secondary >20 years	184.4	111.0	SD	9, 10, 22, 23, 26, 69
			Secondary ≤20 years	75.9	51.1	SD	9, 10, 22, 23, 26, 69, 70
		Asia	Primary	433.5	147.5	SD	3, 4, 9, 10, 34, 35
			Secondary >20 years	66.4	61.0	SD	9, 10, 50, 71-73
			Secondary ≤20 years				
Sub-tropical	Sub-tropical humid forests	Africa	Primary				
			Secondary >20 years	54.1	20.6	SD	59
			Secondary ≤20 years				
		North and South America	Primary				
			Secondary >20 years	84.5	42.9	SD	59
			Secondary ≤20 years				
		Asia	Primary	323.0	157.7	SD	9, 10
			Secondary >20 years	258.4	128.1	SD	9, 10
			Secondary ≤20 years				
	Sub-tropical dry forests	Africa	Primary				
			Secondary >20 years	65.2	27.1	SD	59
			Secondary ≤20 years				
		North and South America	Primary				
			Secondary >20 years	115.9	46.2	SD	59
			Secondary ≤20 years				
		Asia	Primary				
			Secondary >20 years	70.9	26.2	SD	59
			Secondary ≤20 years				
	Sub-tropical steppe	Africa	Primary				
			Secondary >20 years	50.5	23.9	SD	59
			Secondary ≤20 years				
		North and South America	Primary				
			Secondary >20 years	44.0	26.0	SD	59
			Secondary ≤20 years				
		Asia	Primary				
			Secondary >20 years	41.6	24.7	SD	59
			Secondary ≤20 years				

TABLE 4.7 (UPDATED) (CONTINUED)
ABOVE-GROUND BIOMASS IN NATURAL FORESTS (TONNES D.M. HA^{-1})

Domain	Ecological zone [1]	Continent	Status/condition[2]	Above-ground biomass [tonnes d.m. ha^{-1}]	Uncertainty	Uncertainty type	References
Sub-tropical	Sub-tropical mountain systems	Africa	Primary	35.1	22.2	SD	59
			Secondary >20 years				
			Secondary ≤20 years				
		North and South America	Primary	74.6	40.1	SD	59
			Secondary >20 years				
			Secondary ≤20 years				
		Asia	Primary	250.2	59.4	SD	9, 10
			Secondary >20 years	155.2	41.7	SD	9, 10
			Secondary ≤20 years				
Temperate	Mountain	Asia	Primary	n.a	n.a	n.a	
			Secondary >20 years	170.4	±57.85	95% CI	75
			Secondary ≤20 years	n.a	n.a	n.a	
		Europe	Primary	301.1	±90%	default	76-79
			Secondary >20 years	214.7	±90%	default	77
			Secondary ≤20 years	27.8	±90%	default	77
		North and South America	Primary	n.a	n.a	n.a	
			Secondary >20 years	185.9	153.8	SD	80
			Secondary ≤20 years	57.9	78.6	SD	80
	Continental	Asia	Primary	n.a	n.a	n.a	
			Secondary >20 years	116.0	±18.37	95% CI	75
			Secondary ≤20 years	90.9	±40.43	95% CI	75
		Europe	Primary	332.4	±90%	default	77-79
			Secondary >20 years	162.0	±90%	default	77, 81-83
			Secondary ≤20 years	51.6	±90%	default	77, 81-83
		North and South America	Primary	n.a	n.a	n.a	
			Secondary >20 years	128.9	240.3	SD	80
			Secondary ≤20 years	46.0	99.5	SD	80
	Oceanic	Asia	Primary	289.8	±90%	default	84
			Secondary >20 years	n.a	n.a	n.a	
			Secondary ≤20 years				
		Europe	Primary	126.1	±90%	default	77
			Secondary >20 years	153.9	±90%	default	77,85-90
			Secondary ≤20 years	22.3	±90%	default	77
		Oceania	Primary	352.7	±17	95%CI	91
			Secondary >20 years	120.5	±22.3	95%CI	91
			Secondary ≤20 years	57.5	±14.28	95%CI	92

TABLE 4.7 (UPDATED) (CONTINUED)
ABOVE-GROUND BIOMASS IN NATURAL FORESTS (TONNES D.M. HA^{-1})

Domain	Ecological zone [1]	Continent	Status/condition[2]	Aboveground biomass [tonnes d.m. ha^{-1}]	Uncertainty	Uncertainty type	References
Temperate	Oceanic	North and South America	Primary	n.a	n.a	n.a	
			Secondary >20 years	354.1	455.7	SD	80
			Secondary ≤20 years	213.9	227.1	SD	80
	Desert	North and South America	Primary	n.a	n.a	n.a	
			Secondary >20 years	44.0	39.7	SD	80
			Secondary ≤20 years	25.6	35.1	SD	80
	Steppe	North and South America	Primary	n.a	n.a	n.a	
			Secondary >20 years	118.5	459.9	SD	80
			Secondary ≤20 years	42.9	76.5	SD	80
Boreal	Coniferous	North and South America	Primary	62.9	28.1	SD	93
			Secondary >20 years	n.a	n.a	n.a	
			Secondary ≤20 years	n.a	n.a	n.a	
	Tundra woodland	North and South America	Primary	63.7	30.1	SD	93
			Secondary >20 years	104.2	±90%	default	94
			Secondary ≤20 years	n.a	n.a	n.a	
	Mountain	North and South America	Primary	n.a	n.a	n.a	
			Secondary >20 years	n.a	n.a	n.a	
			Secondary ≤20 years	1.9	±90%	default	94

[1] Forest Resources Assessment (FRA). (2015). Global Eological Zones for FAO Forest Reporting 2010 Update. Forest Resources Assessment Working Paper 179.

[2] Some categories include sub-strata for primary forests, which are defined as old-growth forests that are intact or with no active human intervention, and secondary forests which include all other forests. The table considers a forest definition of at least 10% tree canopy cover (74).

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TABLE 4.8 (UPDATED) ABOVEGROUND BIOMASS (AGB) IN FOREST PLANTATIONS (TONNES D.M. HA^{-1})							
Domain	**Ecological Zone[1]**	**Continent**	**Species**	**Age (yr)**	**AGB (Tonnes d.m. ha^{-1})**	**SD**	**References**
Tropical	Tropical rain forest	Africa	Broadleaf	≤20	100	±90%	10
		Africa	Broadleaf	>20	300	±90%	10
		Africa	*Pinus* sp.	≤20	60	±90%	10
		Africa	*Pinus* sp.	>20	200	±90%	10
		Americas	*Eucalyptus* sp.		200	±90%	10
		Americas	Other Broadleaf		150	±90%	10
		Americas	*Pinus* sp.		300	±90%	10
		Americas	*Tectona grandis*	>20	240	±90%	13
		Asia	*Acacia auriculiformis*	≤20	99-119	±90%	20
		Asia	*Acacia mangium*	<20	93.6	64.20	28
		Asia	Broadleaf		220	±90%	10
		Asia	*Dipterocarp* sp.	>20	452.2	149.90	14
		Asia	*Eucalyptus* sp.	≤20	46-161	43.70	20
		Asia	*Gmelina arborea*	<20	97.6	23.60	14
		Asia	*Hevea brasiliensis*	<20	113-132	±90%	18
		Asia	*Mangifera indica*	<20	13.5	4.90	7
		Asia	*Rhizophora sp.*	>20	152.2	±90%	1
		Asia	Mixed	>20	69	±90%	3
		Asia	Oil Palm	<20	18.4-35.4	±90%	33
		Asia	Oil Palm	>20	48.5	9.20	33
		Asia	*Paraserianthes falcataria*	<20	64.4	38.80	14
		Asia	*Sweitenia macrophylla*	>20	512.8	170.40	14
	Tropical moist deciduous	Africa	Broadleaf	>20	150	±90%	10
		Africa	Broadleaf	≤20	80	±90%	10
		Africa	*Rhizophora sp.*		111-483	±90%	34
		Africa	*Pinus* sp.	≤20	40-166	±90%	10,1
		Africa	*Tectona grandis*	<20	195.5	±90%	16
		Africa	*Tectona grandis*	>20	428.9	±90%	16
		Africa	*Pinus* sp.	>20	120-193.3	±90%	10,16
		Americas	*Anthocephalus chinensis*	<20	144	±90%	2
		Americas	*Coffea sp.*		46.9-57.5	±90%	15
		Americas	*Eucalyptus* sp.	>20	90	±90%	31
		Americas	Other Broadleaf		100	±90%	10
		Americas	*Pinus* sp.	>20	270	±90%	10

Table 4.8 (Updated) (Continued) Aboveground biomass (AGB) in forest plantations (tonnes d.m. ha^{-1})							
Domain	**Ecological Zone[1]**	**Continent**	**Species**	**Age (yr)**	**AGB (Tonnes d.m. ha^{-1})**	**SD**	**References**
Tropical	Tropical moist deciduous	Americas	*Swietenia macrophylla*	<20	94	±90%	2
		Americas	*Swietenia macrophylla*	>20	121	±90%	2
		Americas	*Tectona grandis*	<20	84	±90%	24
		Americas	*Tectona grandis*	>20	284	±90%	24
		Asia	*Acacia auriculiformis*	>20	177	7.60	6
		Asia	*Acaica mangium*	>20	211	3.30	6
		Asia	Broadleaf	≤20	93.33-147.76	21.90	5
		Asia	Broadleaf	>20	107.05-224.48	55.60	5
		Asia	*Cassia montana*	<20	5.71	±90%	4
		Asia	*Cedeus libani*	≤20	15.1	±90%	8
		Asia	*Eucalyptus* sp.	<20	41.78	±90%	4
		Asia	*Eucalyptus* sp.	>20	260	97.40	6
		Asia	Oil Palm	<20	124-202	±90%	29
		Asia	Other		100	±90%	10
		Asia	*Swietenia macrophylla*	>20	193	17.00	6
		Asia	*Tectona grandis*	<20	121.88	±90%	9
		Asia	*Tectona grandis*	>20	93.72	64.70	6
	Tropical dry forest	Africa	Broadleaf	≤20	30	±90%	10
		Africa	Broadleaf	>20	70	±90%	10
		Africa	*Pinus* sp.	≤20	20-75.6	±90%	10,16
		Africa	*Pinus* sp.	>20	60-193.9	±90%	10,16
		Africa	*Tectona grandis*	<20	38.33	0.40	22
		Americas	*Eucalyptus* sp.		90	±90%	31
		Americas	Oil Palm	<20	40-62	±90%	26
		Americas	Oil Palm	>20	50-100	±90%	12
		Americas	Other Broadleaf		60	±90%	10
		Americas	*Pinus* sp.		110	±90%	10
		Americas	*Tectona grandis*		90	±90%	10
		Asia	*Acacia* sp.	<20	7.54-58.21	±90%	4
		Asia	*Adina cordifolia*		14.8	±90%	11
		Asia	*Adansonia digitata*		28.6	±90%	11
		Asia	*Albizia procera*	<20	4.9	±90%	11
		Asia	*Azadirachta indica*	<20	30.6-55.64	±90%	11,19
		Asia	*Bombax ceiba*		64.7	±90%	11
		Asia	Broadleaf		90	±90%	10

TABLE 4.8 (UPDATED) (CONTINUED) ABOVEGROUND BIOMASS (AGB) IN FOREST PLANTATIONS (TONNES D.M. HA^{-1})							
Domain	**Ecological Zone**[1]	**Continent**	**Species**	**Age (yr)**	**AGB (Tonnes d.m. ha^{-1})**	**SD**	**References**
Tropical	Tropical dry forest	Asia	*Courapita guianensis*		5.5	±90%	11
		Asia	*Dalbergia sissoo*	≤20	11.07	6.79	35
		Asia	*Dendrocalamus strictus*	<20	48.2	±90%	19
		Asia	*Eucalyptus* sp.	≤20	21.67	±90%	37
		Asia	*Ficus* sp.		25.4	±90%	11
		Asia	*Gmelina arborea*	≤20	6.65	1.37	35
		Asia	*Leucaena leucocephala*	<20	53.35	±90%	19
		Asia	*Madhuca indica*		35.2	±90%	11
		Asia	*Mangifera indica*		24.2	±90%	11
		Asia	*Rhizophora sp.*	<20	125.5	2.60	25
		Asia	*Manilkara elengi*	<20	7.4	±90%	11
		Asia	*Miliusa tomentosa*	<20	4.8	±90%	11
		Asia	*Mitragyna parviflora*		18.1	±90%	11
		Asia	Other		60	±90%	10
		Asia	*Pongamia pinnata*	≤20	8.57	2.00	35
		Asia	*Populus deltoides*	<20	37.5	34.40	21
		Asia	*Prosopis juliflora*	<20	3.56	±90%	4
		Asia	*Salvadora oleoides*		12.2	±90%	11
		Asia	*Samanea saman*		30.9	±90%	11
		Asia	*Sterculia urens*	<20	8.2	±90%	11
		Asia	*Swietenia mahogani*		28.7	±90%	11
		Asia	*Tamarindus indica*		88.8	±90%	11
		Asia	*Tectona grandis*	<20	21.8	±90%	19
		Asia	*Terminalia* sp.	>20	45.5-71.1	±90%	11
		Asia	*Terminalia* sp.	<20	8.2	±90%	11
		Asia	*Ziziphus mauritiana*	<20	8	±90%	11
	Tropical shrubland	Africa	Broadleaf		20	±90%	10
		Africa	*Pinus sp.*	≤20	15	±90%	10
		Africa	*Pinus sp.*	>20	20	±90%	10
		Americas	*Eucalyptus* sp.		60	±90%	10
		Americas	Other Broadleaf		30	±90%	10
		Americas	*Pinus* sp.		60	±90%	10
		Americas	*Tectona grandis*		50	±90%	10
		Asia	*Acacia* sp.	≤20	11.78-47.99	±90%	27,32
		Asia	*Azadirachta indica*	≤20	53.32	±90%	32

Table 4.8 (Updated) (Continued) Aboveground biomass (AGB) in forest plantations (tonnes d.m. ha^{-1})							
Domain	**Ecological Zone[1]**	**Continent**	**Species**	**Age (yr)**	**AGB (Tonnes d.m. ha^{-1})**	**SD**	**References**
Tropical	Tropical shrubland	Asia	Broadleaf		40	±90%	10
		Asia	Broadleaf	>20	263.3	±90%	17
		Asia	*Casuarina equisetifolia*	≤20	9.12	±90%	32
		Asia	Other		30	±90%	10
		Asia	*Pongamia pinnata*	≤20	9.03	±90%	32
		Asia	*Tectona grandis*	≤20	31.66	±90%	32
	Tropical mountain systems	Africa	*Broadleaf*	≤20	40-100	±90%	10
		Africa	Broadleaf	>20	60-150	±90%	10
		Africa	*Pinus* sp.	≤20	30-40	±90%	10
		Africa	*Pinus* sp.	>20	30-100	±90%	10
		Americas	*Eucalyptus* sp.		30-120	±90%	10
		Americas	Other Broadleaf		30-80	±90%	10
		Americas	*Pinus* sp.		60-170	±90%	10
		Americas	*Tectona grandis*		30-130	±90%	10
		Asia	Broadleaf		40-150	±90%	10
		Asia	Other		25-80	±90%	10
Sub-tropical	Subtropical humid forest	Americas	*Eucalyptus* sp.		140	±90%	10
		Americas	Other Broadleaf		100	±90%	10
		Americas	*Pinus* sp.		270	±90%	10
		Americas	*Tectona grandis*		120	±90%	10
		Asia	Broadleaf		180	±90%	10
		Asia	Other		100	±90%	10
		North America	*Populus sp.*	<20	23.07	20.40	36
		North America	*Eucalyptus* sp.	<20	2.45	2.99	36
		North America	Oaks and other hardwoods	<20	7.88	12.05	36
		North America	Oaks and other hardwoods	≥20	11.09	20.56	36
		North America	*Pinus* sp.	<20	19.65	17.01	36
		North America	*Pinus* sp.	≥20	45.53	24.66	36
	Subtropical dry forest	Africa	Broadleaf	≤20	30	±90%	10
		Africa	Broadleaf	>20	70	±90%	10
		Africa	*Pinus* sp.	≤20	20	±90%	10
		Africa	*Pinus* sp.	>20	60	±90%	10
		Americas	*Eucalyptus* sp.		110	±90%	10
		Americas	Other Broadleaf		60	±90%	10
		Americas	*Pinus* sp.		110	±90%	10
		Americas	*Tectona grandis*		90	±90%	10

TABLE 4.8 (UPDATED) (CONTINUED)
ABOVEGROUND BIOMASS (AGB) IN FOREST PLANTATIONS (TONNES D.M. HA^{-1})

Domain	Ecological Zone[1]	Continent	Species	Age (yr)	AGB (Tonnes d.m. ha^{-1})	SD	References
Sub-tropical	Subtropical dry forest	Asia	Broadleaf	<20	69.45	48.89	39
		Asia	Broadleaf	>20	137.64	77.29	39
		Asia	Coniferous	<20	63.18	38.07	39
		Asia	Coniferous	>20	127.61	63.31	39
		Asia	*Cunninghamia* sp.	<20	62.96	37.38	39
		Asia	*Cunninghamia* sp.	>20	148.6	72.32	39
		Asia	*Eucalyptus* sp.	<20	68.72	55.05	39
		Asia	Other		60	±90%	39
		Asia	*Picea abies*	>20	138.23	47.42	39
		Asia	*Pinus massoniana*	<20	54.75	40.55	39
		Asia	*Pinus massoniana*	>20	163.45	66.07	39
	Subtropical steppe	Africa	Broadleaf		20	±90%	10
		Africa	*Pinus* sp.	≤20	15	±90%	10
		Africa	*Pinus* sp.	>20	20	±90%	10
		Americas	*Eucalyptus* sp.		60	±90%	10
		Americas	Other Broadleaf		30	±90%	10
		Americas	*Pinus* sp.		60	±90%	10
		Americas	*Tectona grandis*		50	±90%	10
		Asia	Broadleaf	≤20	10	±90%	10
		Asia	Broadleaf	>20	80	±90%	10
		Asia	Coniferous	≤20	100-120	±90%	10
		Asia	Coniferous	>20	20	±90%	10
		North America	Oaks and other hardwoods	<20	3.59-8.75	±90%	36
		North America	*Pinus* sp.	<20	22.8	19.91	36
		North America	*Pinus* sp.	≥20	46.69	16.55	36
	Subtropical mountain systems	Asia	*Acer velutinum*	<20	90.03	±90%	23
		Asia	*Alnus subcordata*	<20	103.53	±90%	23
		Asia	*Arizone cypress*	<20	25.72	0.11	30
		Asia	*Robinia pseudoacacia*	<20	8.85	0.54	30
		Asia	*Pinus brutia*	<20	50.62	0.52	30
		Asia	*Fraxinus excelsior*	<20	56.07	±90%	23
		Asia	*Morus sp.*	<20	9.87	0.33	30
		Asia	*Pinus nigra*	≤20	20.05-38.46	±90%	23,8
		Asia	*Prunus avium*	<20	37.92	±90%	23
		Asia	*Quercus castanifolia*	<20	72.82	±90%	23

TABLE 4.8 (UPDATED) (CONTINUED)
ABOVEGROUND BIOMASS (AGB) IN FOREST PLANTATIONS (TONNES D.M. HA^{-1})

Domain	Ecological Zone[1]	Continent	Species	Age (yr)	AGB (Tonnes d.m. ha^{-1})	SD	References
Sub-tropical	Subtropical mountain systems	Asia	*Tilia begonifolia*	<20	71.88	±90%	23
		North America	*Pseudotsuga menziesii*	<20	53.93	±90%	36
		North America	Oaks and other hardwoods	<20	3.68	4.53	36
		North America	*Pinus* sp.	<20	14.51	14.54	36
		North America	*Pinus* sp.	≥20	24.87	25.85	36
		Africa	Broadleaf	≤20	40-100	±90%	10
		Africa	Broadleaf	>20	60-150	±90%	10
		Africa	*Pinus* sp.	≤20	10-40	±90%	10
		Africa	*Pinus* sp.	>20	30-100	±90%	10
		Americas	*Eucalyptus* sp.		30-120	±90%	10
		Americas	Other Broadleaf		30-80	±90%	10
		Americas	*Pinus* sp.		60-170	±90%	10
		Americas	*Tectona grandis*		30-130	±90%	10
		Asia	Broadleaf		40-150	±90%	10
		Asia	Other		25-80	±90%	10
Temperate	Temperate oceanic forest	Asia, Europe	Broadleaf	≤20	30	±90%	10
		Asia, Europe	Broadleaf	>20	200	±90%	10
		Asia, Europe	Coniferous	≤20	40	±90%	10
		Asia, Europe	Coniferous	>20	150-250	±90%	10
		North America	*Populus sp.*	≥20	76.19	51.72	36
		North America	*Pseudotsuga menziesii*	<20	15.35	18.86	36
		North America	*Pseudotsuga menziesii*	≥20	95.8	73.39	36
		North America	*Pinus* sp.	<20	3.87	±90%	36
		North America	*Pinus* sp.	≥20	131.27	143.75	36
		South America	Coniferous		90-120	±90%	10
	Temperate continental forest and mountain systems	Asia, Europe	Broadleaf	≤20	15	±90%	10
		Asia, Europe	Broadleaf	>20	200	±90%	10
		Asia, Europe	Coniferous	≤20	25-30	±90%	10
		Asia, Europe	Coniferous	>20	150-200	±90%	10
		North America	Coniferous		50-300	±90%	10
		North America	Coniferous		50-300	±90%	10
		South America	Coniferous		90-120	±90%	10
	Temperate continental forest	North America	*Populus sp.*	<20	88.35	±90%	36
		North America	*Populus sp.*	≥20	55.71	14.47	36

TABLE 4.8 (UPDATED) (CONTINUED)
ABOVEGROUND BIOMASS (AGB) IN FOREST PLANTATIONS (TONNES D.M. HA^{-1})

Domain	Ecological Zone[1]	Continent	Species	Age (yr)	AGB (Tonnes d.m. ha^{-1})	SD	References
Temperate	Temperate continental forest	North America	*Pseudotsuga menziesii*	≥20	42.62-96.65	±90%	36
		North America	*Abies sp.*	<20	5.62	6.63	36
		North America	*Abies sp.*	≥20	21.49	10.62	36
		North America	Oaks and other hardwoods	<20	6.7	12.63	36
		North America	Oaks and other hardwoods	≥20	23.72	46.23	36
		North America	*Pinus* sp.	<20	31.45	28.87	36
		North America	*Pinus* sp.	≥20	80.94	68.21	36
		North America	*Picea sp.*	<20	9.89	8.14	36
		North America	*Picea sp.*	≥20	77.34	131.88	36
		Asia	*Larix* sp.	<20	57.49	32.16	39
		Asia	*Larix* sp.	>20	112.88	56.21	39
		Asia	*Pinus koraiensis*	<20	58.23	18.89	39
		Asia	*Pinus koraiensis*	>20	132.13	72.18	39
		Asia	*Pinus sylvestris*	<20	18	8.95	39
		Asia	*Pinus sylvestris*	>20	58.6	18.57	39
		Asia	*Pinus tabuliformis*	<20	34.02	14.15	39
		Asia	*Pinus tabuliformis*	>20	59.39	35.26	39
		Asia	*Poplar* sp.	<20	66.74	45.30	39
		Asia	*Robinia pseudoacacia*	<20	29.44	13.20	39
		Asia	*Robinia pseudoacacia*	>20	54.46	16.99	39
	Temperate mountain system	North America	*Populus sp.*	<20	55.98	±90%	36
		North America	Douglas fir	<20	13.56	18.81	36
		North America	Douglas fir	≥20	89.22	71.32	36
		North America	*Abies sp.*	<20	3.02	3.11	36
		North America	*Abies sp.*	≥20	40.48	71.99	36
		North America	Oaks and other hardwoods	<20	3.77	5.76	36
		North America	*Pinus* sp.	<20	6.93	14.26	36
		North America	*Pinus* sp.	≥20	29.07	35.39	36
		North America	*Picea sp.*	<20	5.92	11.25	36
		North America	*Picea sp.*	≥20	50.27	38.11	36
		Asia	*Acacia crassicarpa*	<20	31.5	±90%	38
		Asia	*Castanopsis hystrix*	<20	16.6	±90%	38

TABLE 4.8 (UPDATED) (CONTINUED)
ABOVEGROUND BIOMASS (AGB) IN FOREST PLANTATIONS (TONNES D.M. HA^{-1})

Domain	Ecological Zone[1]	Continent	Species	Age (yr)	AGB (Tonnes d.m. ha^{-1})	SD	References
Temperate	Temperate mountain system	Asia	*Eucalyptus sp.*	<20	34.6	±90%	38
		Asia	Mixed Plantation	<20	19.2	±90%	38
	Temperate steppe	North America	*Populus sp.*	≥20	51.8-60.05	±90%	36
		North America	*Quercus* and other hardwoods	≥20	41.06	29.99	36
		North America	*Pinus* sp.	<20	48.57	65.55	36
		North America	*Pinus* sp.	<20	4.75	6.72	36
		North America	*Pinus* sp.	≥20	84.88	24.75	36
		North America	*Pinus* sp.	≥20	3.6	4.70	36
Boreal	Boreal coniferous forest and mountain systems	Asia, Europe	Coniferous	≤20	5	±90%	10
		Asia, Europe	Coniferous	>20	40	±90%	10
		North America	Coniferous		40-50	±90%	10
	Boreal tundra woodland	Asia, Europe	Coniferous	≤20	5	±90%	10
		Asia, Europe	Coniferous	>20	25	±90%	10

[1] Forest Resources Assessment (FRA). (2015). Global Eological Zones for FAO Forest Reporting 2010 Update. Forest Resources Assessment Working Paper 179.

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TABLE 4.9 (UPDATED) ABOVE-GROUND NET BIOMASS GROWTH IN NATURAL FORESTS[1,2,3,4] (TONNES D.M. HA^{-1} YR^{-1})							
Domain	**Ecological Zone[4]**	**Continent**	**Status/ Condition**	**Aboveground biomass growth [tonnes d.m. ha^{-1} yr^{-1}]**	**Uncertainty**	**Uncertainty type**	**References**
Tropical	Tropical rainforest	Africa	Primary	1.3	3.5	SD	1, 2
			Secondary> 20 years	3.5	3.3	SD	3-8
			Secondary≤ 20 years	7.6	5.9	SD	3-7, 9
		North and South America	Primary	1.0	2.0	SD	2, 10, 11
			Secondary> 20 years	2.3	1.1	SD	3, 4, 12-15
			Secondary≤ 20 years	5.9	2.5	SD	3, 4, 6, 12-14
		Asia	Primary	0.7	2.2	SD	2, 16
			Secondary> 20 years	2.7	3.1	SD	3, 4, 17
			Secondary≤ 20 years	3.4	3.9	SD	3, 4, 17-19
	Tropical moist deciduous forest	Africa	Primary[6]	0.4	±90%	default	
			Secondary> 20 years	0.9	0.7	SD	20, 21
			Secondary≤ 20 years	2.9	1.0	SD	20, 21
		North and South America	Primary	0.4	2.1	SD	2, 10, 11
			Secondary> 20 years	2.7	1.7	SD	3, 4, 12, 13, 15, 22
			Secondary≤ 20 years	5.2	2.3	SD	3, 4, 12, 13, 22
		Asia	Primary	0.4	±90%	default	7
			Secondary> 20 years	0.9	±90%	default	8
			Secondary≤ 20 years	2.4	0.3	SD	3, 4
	Tropical dry forest	Africa	Primary	-	-	-	
			Secondary> 20 years	1.6	±90%	default	9
			Secondary≤ 20 years	3.9	±90%	default	10
		North and South America	Primary	-	-	-	
			Secondary> 20 years	1.6	1.1	SD	12, 13
			Secondary≤ 20 years	3.9	2.4	SD	12, 13, 23

TABLE 4.9 (UPDATED) (CONTINUED) ABOVE-GROUND NET BIOMASS GROWTH IN NATURAL FORESTS[1,2,3,4] (TONNES D.M. HA^{-1} YR^{-1})							
Domain	**Ecological Zone[4]**	**Continent**	**Status/ Condition**	**Aboveground biomass growth [tonnes d.m. ha^{-1} yr^{-1}]**	**Uncer tainty**	**Uncertainty type**	**References**
Tropical	Tropical dry forest	Asia	Primary	-	-	-	
			Secondary> 20 years	1.6	±90%	default	11
			Secondary≤ 20 years	3.9	±90%	default	12
	Tropical shrublands	Africa	Primary	0.9 (0.2-1.6)*	±90%	default	24
			Secondary> 20 years	0.9 (0.2-1.6)*	±90%	default	24
			Secondary≤ 20 years	0.2-0.7	±90%	default	24
		North and South America	Primary	1.0*	±90%	default	24
			Secondary> 20 years	1.0*	±90%	default	24
			Secondary≤ 20 years	4.0	±90%	default	24
		Asia (Continental)	Primary	1.3 (1.0-2.2)*	±90%	default	24
			Secondary> 20 years	1.3 (1.0-2.2)*	±90%	default	24
			Secondary≤ 20 years	5.0	±90%	default	24
		Asia (Insular)	Primary	1.0*	±90%	default	24
			Secondary> 20 years	1.0*	±90%	default	24
			Secondary≤ 20 years	2.0	±90%	default	24
	Tropical mountain system	Africa	Primary	0.5	±90%	default	13
			Secondary> 20 years	1.8	±90%	default	14
			Secondary≤ 20 years	5.5	6.8	SD	25-27
		North and South America	Primary	0.5	1.9	SD	2, 10, 11
			Secondary> 20 years	1.8	0.8	SD	3, 4, 12, 13
			Secondary≤ 20 years	4.4	1.6	SD	3, 4, 12, 13, 22
		Asia	Primary	-0.7	3.1	SD	2, 16
			Secondary> 20 years	1.1	0.4	SD	3, 4, 28, 29
			Secondary≤ 20 years	2.9	0.1	SD	3, 4, 28-30

TABLE 4.9 (UPDATED) (CONTINUED) ABOVE-GROUND NET BIOMASS GROWTH IN NATURAL FORESTS[1,2,3,4] (TONNES D.M. HA^{-1} YR^{-1})							
Domain	**Ecological Zone[4]**	**Continent**	**Status/ Condition**	**Aboveground biomass growth [tonnes d.m. ha^{-1} yr^{-1}]**	**Uncertainty**	**Uncertainty type**	**References**
Subtropical	Subtropical humid forest	Africa	Primary	-	-	-	
			Secondary> 20 years	1.0	±90%	default	15
			Secondary≤ 20 years	2.5	±90%	default	16
		North and South America	Primary	-	-	-	
			Secondary> 20 years	1.0	±90%	default	17
			Secondary≤ 20 years	2.5	±90%	default	18
		Asia	Primary	-	-	-	
			Secondary> 20 years	1.0	0.9	SD	3, 4, 31
			Secondary≤ 20 years	2.5	0.8	SD	3, 4, 31
	Subtropical dry forest	Africa	Primary	1.8 (0.6-3.0)*	±90%	default	24
			Secondary> 20 years	1.8 (0.6-3.0)*	±90%	default	24
			Secondary≤ 20 years	2.4 (2.3-2.5)	±90%	default	24
		North and South America	Primary	1.0*	±90%	default	24
			Secondary> 20 years	1.0*	±90%	default	24
			Secondary≤ 20 years	4.0	±90%	default	24
		Asia (continental)	Primary	1.5*	±90%	default	24
			Secondary> 20 years	1.5*	±90%	default	24
			Secondary≤ 20 years	6.0	±90%	default	24
		Asia (insular)	Primary	2.0*	±90%	default	24
			Secondary> 20 years	2.0*	±90%	default	24
			Secondary≤ 20 years	7.0	±90%	default	24
	Subtropical steppe	Africa	Primary	0.9 (0.2-1.6)*	±90%	default	24
			Secondary> 20 years	0.9 (0.2-1.6)*	±90%	default	24
			Secondary≤ 20 years	1.2 (0.8-1.5)	±90%	default	24
		North and South America	Primary	1.0*	±90%	default	24
			Secondary> 20 years	1.0*	±90%	default	24
			Secondary≤ 20 years	4.0	±90%	default	24

TABLE 4.9 (UPDATED) (CONTINUED) ABOVE-GROUND NET BIOMASS GROWTH IN NATURAL FORESTS[1,2,3,4] (TONNES D.M. HA^{-1} YR^{-1})							
Domain	**Ecological Zone[4]**	**Continent**	**Status/ Condition**	**Aboveground biomass growth [tonnes d.m. ha^{-1} yr^{-1}]**	**Uncertainty**	**Uncertainty type**	**References**
Subtropical	Subtropical steppe	Asia (continental)	Primary	1.3 (1.0-2.2)*	±90%	default	24
			Secondary >20 years	1.3 (1.0-2.2)*	±90%	default	24
			Secondary ≤20 years	5.0	±90%	default	24
		Asia (insular)	Primary	1.0*	±90%	default	24
			Secondary >20 years	1.0*	±90%	default	24
			Secondary ≤20 years	2.0	±90%	default	24
	Subtropical mountain system	Africa	Primary	-	-	-	
			Secondary >20 years	0.5	±90%	default	19
			Secondary ≤20 years	2.5	±90%	default	20
		North and South America	Primary	-	-	-	
			Secondary >20 years	0.5	±90%	default	21
			Secondary ≤20 years	2.5	±90%	default	22
		Asia	Primary	-	-	-	
			Secondary >20 years	0.5	0.3	SD	3, 4, 32
			Secondary ≤20 years	2.5	0.03	SD	3, 4, 32
Temperate	Oceanic	New Zealand	Primary	0.37	±0.85	95%CI	33
			Secondary >20 years	2.12	±0.82	95%CI	33
			Secondary ≤20 years	3.12	0.83	SE	34
		Europe	All	2.3	-	-	35
		North and South America	Secondary >20 years	4.94	0.25	SD	36
			Secondary ≤20 years	3.5	0.87	SD	36
	Continental	North and South America	Secondary >20 years	1.97	0.01	SD	36
			Secondary ≤20 years	1.96	0.04	SD	36
	Mountain	North and South America	Secondary >20 years	2.09	0.02	SD	36
			Secondary ≤20 years	1.38	0.07	SD	36

TABLE 4.9 (UPDATED) (CONTINUED)
ABOVE-GROUND NET BIOMASS GROWTH IN NATURAL FORESTS[1,2,3,4] (TONNES D.M. HA^{-1} YR^{-1})

Domain	Ecological Zone[4]	Continent	Status/ Condition	Aboveground biomass growth [tonnes d.m. ha^{-1} yr^{-1}]	Uncertainty	Uncertainty type	References
Temperate	Desert	North and South America	Secondary>20 years	0.2	0.02	SD	36
			Secondary≤20 years	-	-	SD	36
	Steppe	North and South America	Secondary>20 years	1.43	0.05	SD	36
			Secondary≤20 years	0.64	0.1	SD	36
Boreal	Coniferous	Asia, Europe, North America	All	0.1-2.1	-	-	35
	Tundra woodland	Asia, Europe, North America	All	0.4	(0.2-0.5)	Range	24
	Mountain	Asia, Europe, North America	Primary or secondary>20 years	1.1-1.5	-	-	24
			Secondary≤20 years	1.0-1.1	-	-	24

[1] Aboveground net biomass growth is defined as net change in total aboveground biomass over time. In this respect, both forest productivity and mortality are accounted for.

[2] Some categories include sub-strata for primary forests defined as old growth forests that are intact or with no active human intervention, and secondary forests which include all other forests. The table considers a forest definition of at least 10% tree canopy cover.

[3] For above-ground biomass growth rates with no standard deviation, IPCC Tier 1 default uncertainties apply.

[4] Forest Resources Assessment (FRA). (2015). *Global Eological Zones for FAO Forest Reporting 2010 Update. Forest Resources Assessment Working Paper 179.*

Observations on ecological zone and continent columns

Above-ground biomass growth rate was taken from: Tropical moist deciduous forest - North and South America (Primary); Tropical moist deciduous forest - North and South America (Primary); Tropical moist deciduous forest - Africa (Secondary>20 years); Tropical dry forest – North and South America (Secondary>20 years); Tropical dry forest – North and South America (Secondary≤20 years); Tropical dry forest – North and South America (Secondary>20 years); Tropical dry forest – North and South America (Secondary≤20 years); Tropical mountain system – North and South America (Primary); Tropical mountain system – North and South America (Secondary>20 years); Subtropical humid forest – Asia (Secondary>20 years); Subtropical humid forest – Asia (Secondary≤20 years)

Subtropical humid forest – Asia (Secondary>20 years); Subtropical humid forest – Asia (Secondary≤20 years); Subtropical mountain system – Asia (Secondary>20 years); Subtropical mountain system – Asia (Secondary≤20 years); Subtropical mountain system – Asia (Secondary>20 years); Subtropical mountain system – Asia (Secondary≤20 years).

Note: SD = standard deviation, CI = confidence interval, SE = standard error.

*Recommendation based on IPCC 2006 estimates for Forests > 20 years.

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TABLE 4.10 (UPDATED)
ABOVE-GROUND NET BIOMASS GROWTH IN TROPICAL AND SUB-TROPICAL PLANTATION FORESTS (TONNES D.M. HA^{-1} YR^{-1})

Domain	Ecological zone[1]	Continent	Species	Above-ground biomass [tonnes d.m. ha^{-1} yr^{-1}]	Range [tonnes d.m. ha^{-1} yr^{-1}][2]	References
Tropical	Tropical rainforest	Africa	*Pinus* sp. ≤ 20 y	20		1
			Other ≤ 20 y	6	5-8	1
		North and South America	*Eucalyptus* sp.	20	6-40	1
			Pinus sp.	20		1
			Tectona grandis	15		1
			Other broadleaf	20	5-35	1
		Asia	*Eucalyptus* sp.	5	4-8	1
			Other	5	2-8	1
	Tropical moist deciduous forest	Africa	*Eucalyptus* sp. >20 y	25		1
			Eucalyptus sp. ≤20 y	20		1
			Other ≤ 20 y	9	3-15	1
		North and South America	*Eucalyptus* sp.	16		2
			Tectona grandis	8	4-12	1
			Other broadleaf	6-20	6-20	3
		Asia		8		1
	Tropical dry forest	Africa	*Eucalyptus* sp. ≤20 y	13		1
			Pinus sp. > 20 y	9	7-10	4
			Pinus sp. ≤ 20 y	6	5-8	4
			Other ≤ 20 y	10	4-20	1
		North and South America	*Eucalyptus* sp.	20	6-30	1
			Pinus sp.	7	4-10	1
			Tectona grandis	8	4-12	1
			Other broadleaf	10	3-12	1
		Asia	*Eucalyptus* sp.	15	5-25	1
			Other	7	2-13	1
	Tropical shrubland	Africa	*Eucalyptus* sp. >20 y	8	5-14	1
			Eucalyptus sp. ≤20 y	5	3-7	1
			Pinus sp. > 20 y	2.5		1
			Pinus sp. ≤ 20 y	3	0.5-6	1
			Other > 20 y	10		1
			Other ≤ 20 y	15		1
		North and South America	*Eucalyptus* sp.	20		1
			Pinus sp.	5		1
		Asia		6	1-12	1

TABLE 4.10 (UPDATED) (CONTINUED)
ABOVE-GROUND NET BIOMASS GROWTH IN TROPICAL AND SUB-TROPICAL PLANTATION FORESTS (TONNES D.M. HA^{-1} YR^{-1})

Domain	Ecological zone[1]	Continent	Species	Above-ground biomass [tonnes d.m. ha^{-1} yr^{-1}]	Range [tonnes d.m. ha^{-1} yr^{-1}][2]	References
Tropical	Tropical mountain systems	Africa		10		1
		North and South America	Eucalyptus sp.	10	8-18	1
			Pinus sp.	10		1
		Asia	Tectona grandis	2		1
			Other broadleaf	4		1
			Eucalyptus sp.	3		1
			Other	5	1-10	1
Sub-tropical	Subtropical humid forest	North and South America	Eucalyptus sp.	20	6-32	1
			Pinus sp.	7	4-10	1
			Tectona grandis	8	4-12	1
			Other broadleaf	10	3-12	1
		Asia		8		1
	Subtropical dry forest	Africa	Eucalyptus sp. ≤20 y	13		1
			Pinus sp. > 20 y	10		1
			Pinus sp. ≤ 20 y	8		1
			Other ≤ 20 y	10	4-20	1
		North and South America	Eucalyptus sp.	20	6-30	1
			Pinus sp.	7	4-10	1
			Tectona grandis	8	4-12	1
			Other broadleaf	10	3-12	1
		Asia	Eucalyptus sp.	15	5-25	1
			Other	7	2-13	1
	Subtropical steppe	Africa	Eucalyptus sp. >20 y	8	5-14	1
			Eucalyptus sp. ≤20 y	5	3-7	1
			Pinus sp. > 20 y	2.5		1
			Pinus sp. ≤ 20 y	3	0.5-6	1
			Other > 20 y	10		1
			Other ≤ 20 y	15		1
		North and South America	Eucalyptus sp.	20		1
			Pinus sp.	5		1
		Asia		6	1-12	1
	Subtropical mountain systems	Africa		10		1
		North and South America	Eucalyptus sp.	10	8-18	1
			Pinus sp.	10		1
			Tectona grandis	2		1
			Other broadleaf	4		1

TABLE 4.10 (UPDATED) (CONTINUED)
ABOVE-GROUND NET BIOMASS GROWTH IN TROPICAL AND SUB-TROPICAL PLANTATION FORESTS (TONNES D.M. HA^{-1} YR^{-1})

Domain	Ecological zone[1]	Continent	Species	Above-ground biomass [tonnes d.m. ha^{-1} yr^{-1}]	Range [tonnes d.m. ha^{-1} yr^{-1}][2]	References
Subtropical	Subtropical mountain systems	Asia	Eucalyptus sp.	3		1
			Other	5	1-10	1
Temperate	Continental	North and South America	Secondary >20 years	2.9	0.1	5
			Secondary ≤20 years	4.1	0.2	5
	Mountain	North and South America	Secondary >20 years	7.7	0.1	5
			Secondary ≤20 years	5.5	0.3	5
	Oceanic	North and South America	Secondary >20 years	8.3	0.5	5
			Secondary ≤20 years	4.2	0.6	5
	Steppe	North and South America	Secondary >20 years	1.7	0.3	5
			Secondary ≤20 years	3	0.8	5
Boreal	Coniferous	Asia, Europe, North America	Secondary >20 years	1.0		1
			Secondary ≤20 years	1.0		1
	Tundra woodland	Asia, Europe, North America	Secondary >20 years	0.4		1
			Secondary ≤20 years	0.4		1
	Mountain	Asia, Europe, North America	Secondary >20 years	1.0		1
			Secondary ≤20 years	1.0		1

[1] Forest Resources Assessment (FRA) (2015). Global Eological Zones for FAO Forest Reporting 2010 Update. Forest Resources Assessment Working Paper 179.

[2] If a single estimate is included in this column it refers to the standard deviation of the mean estimate.

References

1 IPCC 2003; 2 Stape *et al*. 2004; 3 Lugo *et al*. 1990; 4 Masota *et al*. 2016; 5 June 18, 2018. Forest Inventory and Analysis Database, St. Paul, MN: U.S. Department of Agriculture, Forest Service, Northern Research Station (Available only on internet: http://apps.fs.fed.us/fiadb-downloads/datamart.html).

TABLE 4.11 (UPDATED)
REPORTED MEAN ANNUAL INCREMENT (GROWTH RATE OF MERCHANTABLE VOLUME) VALUES FOR SOME PLANTATION FOREST SPECIES (M^3 HA^{-1} YR^{-1})

Continent	Region/ Country	Tree species	Plantation Purpose	MAI min	MAI max	S.D.[2]	Reference
World	General	*Acacia auriculiformis*	Productive	6	20	3.5	5, 8
		Acacia mearnsii	Productive	14	25	2.8	5, 8
		Araucaria angustifolia	Productive	8	24	4.0	5, 8
		Araucaria cunninghamii	Productive	10	18	2.0	5, 8
		Casuarina equisetifolia	Productive	6	20	3.5	5, 8
		Casuarina junghuhniana	Productive	7	11	1.0	5, 8
		Cordia alliodora	Productive	10	20	2.5	5, 8
		Cupressus lusitanica	Productive	8	40	8.0	5, 8
		Dalbergia sissoo	Productive	5	8	0.8	5, 8
		Eucalyptus camaldulensis	Productive	15	30	3.8	5, 8
		Eucalyptus deglupta	Productive	14	50	9.0	5, 8
		Eucalyptus globulus	Productive	10	40	7.5	5, 8
		Eucalyptus grandis	Productive	15	50	8.8	5, 8
		Eucalyptus robusta	Productive	10	40	7.5	5, 8
		Eucalyptus saligna	Productive	10	55	11.3	5, 8
		Eucalyptus urophylla	Productive	20	60	10.0	5, 8
		Gmelina arborea	Productive	12	50	9.5	5, 8
		Leucaena leucocephala	Productive	30	55	6.3	5, 8
		Pinus caribaea var. *caribaea*	Productive	10	28	4.5	5, 8
		Pinus caribaea var. *hondurensis*	Productive	20	50	7.5	5, 8
		Pinus oocarpa	Productive	10	40	7.5	5, 8
		Pinus patula	Productive	8	40	8.0	5, 8
		Pinus radiata	Productive	10	50	10.0	5, 8
		Swietenia macrophylla	Productive	7	30	5.8	5, 8
		Tectona grandis	Productive	6	18	3.0	5, 8
		Terminalia ivorensis	Productive	8	17	2.3	5, 8
		Terminalia superba	Productive	10	14	1.0	5, 8
Africa	General	*Acacia mellifera*	Productive	2.2	4.0	0.5	6, 8
		Acacia nilotica	Productive	15.0	20.0	1.3	6, 8
		Acacia senegal	Productive	1.4	2.6	0.3	6, 8
		Acacia seyal	Productive	2.0	6.0	1.0	6, 8
		Ailanthus excelsa	Productive	6.6	9.4	0.7	6, 8
		Bamboos	Productive	5.0	7.5	0.6	6, 8
		Cupressus spp.	Productive	15.0	24.0	2.3	6, 8
		Eucalyptus spp.	Productive	12.0	14.0	0.5	6, 8
		Khaya spp.	Productive	8.5	12.0	0.9	6, 8
		Tectona grandis	Productive	2.5	3.5	0.3	6, 8

TABLE 4.11 (UPDATED) (CONTINUED) REPORTED MEAN ANNUAL INCREMENT (GROWTH RATE OF MERCHANTABLE VOLUME) VALUES FOR SOME PLANTATION FOREST SPECIES (M^3 HA^{-1} YR^{-1})							
Continent	**Region/ Country**	**Tree species**	**Plantation Purpose**	**MAI min**	**MAI max**	**S.D.[2]**	**Reference**
Africa	General	*Acacia albida*	Productive semi-natural	4.0	6.1	0.5	6, 8
		Acacia mellifera	Productive semi-natural	1.9	3.5	0.4	6, 8
		Acacia nilotica	Productive semi-natural	12.5	20.0	1.9	6, 8
		Acacia senegal	Productive semi-natural	1.1	2.4	0.3	6, 8
		Acacia seyal	Productive semi-natural	1.8	3.2	0.4	6, 8
		Acacia tortilis	Productive semi-natural	1.2	3.7	0.6	6, 8
		Acacia tortilis var. *siprocarpa*	Productive semi-natural	1.5	2.4	0.2	6, 8
		Balanites aegyptiaca	Productive semi-natural	1.2	1.5	0.1	6, 8
		Sclerocarya birrea	Productive semi-natural	1.5	1.7	0.1	6, 8
		Ziziphus mauritiana	Productive semi-natural	0.9	1.0	0.0	6, 8
		Acacia mellifera	Protective	2.0	6.0	1.0	6, 8
		Acacia nilotica	Protective	13.0	21.0	2.0	6, 8
		Acacia senegal	Protective	1.4	2.8	0.4	6, 8
		Acacia seyal	Protective	1.9	4.3	0.6	6, 8
		Ailanthus spp.	Protective	6.0	12.0	1.5	6, 8
		Bamboos	Protective	4.0	8.0	1.0	6, 8
		Cupressus spp.	Protective	14.0	20.0	1.5	6, 8
		Eucalyptus spp.	Protective	10.0	14.0	1.0	6, 8
		Khaya spp.	Protective	7.0	16.0	2.3	6, 8
		Tectona grandis	Protective	5.0	8.0	0.8	6, 8
	E and S	*Acacia mearnsii / melanoxylon*	Productive	10	12	0.5	6, 8
	N	*Acacia nilotica*	Productive	15	20	1.3	6, 8
	N	*Acacia nilotica*	Productive semi-natural	12.5	20	1.9	6, 8
	N	*Acacia senegal*	Productive	1.4	2.6	0.3	6, 8
	N	*Acacia senegal*	Productive semi-natural	1.1	2.4	0.3	6, 8
	N	*Acacia seyal*	Productive	2	6	1.0	6, 8
	N	*Acacia seyal*	Productive semi-natural	1.8	3.2	0.4	6, 8
	E and S	*Eucalyptus grandis*	Productive	18	24	1.5	6, 8
	E and S	*Eucalyptus nitens*	Productive	22	28	1.5	6, 8

TABLE 4.11 (UPDATED) (CONTINUED) REPORTED MEAN ANNUAL INCREMENT (GROWTH RATE OF MERCHANTABLE VOLUME) VALUES FOR SOME PLANTATION FOREST SPECIES (M^3 HA^{-1} YR^{-1})							
Continent	**Region/ Country**	**Tree species**	**Plantation Purpose**	**MAI min**	**MAI max**	**S.D.[2]**	**Reference**
Africa	N	*Eucalyptus* spp.	Productive	12	14	0.5	6, 8
	E and S	*Pinus elliottii*	Productive	12	18	1.5	6, 8
	N and C	*Pinus elliottii*	Productive	7	8	0.3	6, 8
	N	*Pinus halapensis*	Productive semi-natural	1	2	0.3	6, 8
	Africa	*Pinus patula*	Productive	12	18	1.5	6, 8
	Africa	*Pinus pinaster*	Productive semi-natural	1	2	0.3	6, 8
	Africa	*Pinus radiata*	Productive	12	16	1.0	6, 8
	Congo	*Eucalyptus* spp.	Experimental	13.8	25	2.8	10
Asia	Asia	*Eucalyptus camaldulensis*	Productive	21.0	43.0	5.5	6, 8
	Asia	*Pinus* spp.	Productive	4.0	15.0	2.8	6, 8
	S and SE	*Acacia mangium*	Productive	19	40	5.3	6, 8
	E and S	*Castanea molissima*	Productive	1	6	1.3	6, 8
	E and S	*Cunninghamia lanceolata*	Productive	2.5	13.5	2.8	6, 8
	E and S	*Cunninghamia lanceolata*	Productive semi-natural	2.5	13.5	2.8	6, 8
	E	*Eucalyptus* spp.	Productive	1.6	8.7	1.8	6, 8
	S and SE	*Eucalyptus* spp.	Productive	7	12	1.3	6, 8
	S and SE	*Eucalyptus* spp.	Productive semi-natural	8	12	1.0	6, 8
	W and C	*Eucalyptus* spp.	Productive	4	10	1.5	6, 8
	Asia	*Pinus massoniana*	Productive semi-natural	2.8	16.3	3.4	6, 8
	Asia	*Populus* spp. and cultivars	Productive	3.7	18.5	3.7	6, 8
	Asia	*Populus* spp. and cultivars	Productive semi-natural	3.7	17.7	3.5	6, 8
	Asia	*Populus* spp. and cultivars	Productive	5	12	1.8	6, 8
	Asia	*Tectona grandis*	Productive	4	17.3	3.3	6, 8
	Asia	*Tectona grandis*	Productive semi-natural	4	6	0.5	6, 8
	China	*Dalbergia sissoo*	Productive	4	6	0.5	1
	China	*Eucalyptus* spp.	Productive	8	12	1.0	1
	China	*Gmelina arborea*	Productive	10	15	1.3	1
	China	*Acacia nilotica*	Productive	3	4	0.3	1
	China	*Populus* spp.	Productive	20	25	1.3	1
	China	*Tectona grandis*	Productive	0.6	7	1.6	1
	Turkey	*Pinus pinaster*	Productive	9.8	22.4	3.2	4
	Turkey	*Eucalyptus camaldulensis*	Productive	18.3	24.1	1.5	4
	Turkey	*Populus* spp. and cultivars	Productive	23.5	55.1	7.9	4

TABLE 4.11 (UPDATED) (CONTINUED)
REPORTED MEAN ANNUAL INCREMENT (GROWTH RATE OF MERCHANTABLE VOLUME) VALUES FOR SOME PLANTATION FOREST SPECIES (M^3 HA^{-1} YR^{-1})

Continent	Region/ Country	Tree species	Plantation Purpose	MAI min	MAI max	S.D.[2]	Reference
Asia	Turkey	*Pinus brutia*	Productive	1	15.4	3.6	4
	Vietnam	*Acacia* hybrid	Experimental	24.4	39.4	3.8	3
	Vietnam	*Acacia mangium*	Productive	11	23	3.0	9
	Vietnam	*Melia azedarach*	Productive	15	17	0.5	9
Europe	Europe	*Fagus sylvatica*	Productive	4	14	2.5	6, 8
	Europe	*Fagus sylvatica*	Productive semi-natural	2	14	3.0	6, 8
	Europe	*Larix decidua*	Productive	7	13	1.5	6, 8
	Europe	*Larix decidua*	Productive semi-natural	2	11	2.3	6, 8
	Europe	*Picea abies*	Productive	3.5	6	0.6	6, 8
	Europe	*Picea abies*	Productive semi-natural	1.5	15	3.4	6, 8
	Europe	*Pinus pinaster*	Productive	4.7	13.8	2.3	6, 8
	Europe	*Pinus sylvestris*	Productive	2.5	14	2.9	6, 8
	Europe	*Pinus sylvestris*	Productive semi-natural	1	10	2.3	6, 8
	Europe	*Quercus robur*	Productive	3	9	1.5	6, 8
	Europe	*Quercus robur*	Productive semi-natural	1.5	10	2.1	6, 8
	Sweden	*Pinus sylvestris*	Productive semi-natural	3.3	5.3	0.5	7
	Sweden	*Picea abies*	Productive semi-natural	3.4	10	1.7	7
	Sweden	*Larix sibirica*	Productive semi-natural	4	5.9	0.5	7
	Sweden	*Pinus contorta*	Productive semi-natural	4.6	6.9	0.6	7
	Sweden	*Betula pendula*	Productive semi-natural	3	8	1.3	7
	Sweden	*Populus* spp. and cultivars	Productive semi-natural	12	16	1.0	7
	Sweden	*Quercus robur*	Productive semi-natural	3.9	5.2	0.3	7
	Finland	*Pinus sylvestris*	Productive semi-natural	2	5	0.8	7
	Finland	*Picea abies*	Productive semi-natural	3	7	1.0	7
	Finland	*Betula pendula*	Productive semi-natural	3	7	1.0	7
	Norway	*Pinus sylvestris*	Productive semi-natural	1.5	3.5	0.5	7
	Norway	*Picea abies*	Productive semi-natural	4	8.5	1.1	7
	Norway	*Picea sitchensis*	Productive semi-natural	12	18	1.5	7
North and Central America	North and Central America	*Pinus taeda*	Productive	9	10	0.3	6, 8
Oceania	Oceania	*Eucalyptus globulus*	Productive	15.6	25	2.4	6, 8
	Oceania	*Pinus radiata*	Productive	15.7	21	1.3	6, 8

TABLE 4.11 (UPDATED) (CONTINUED) REPORTED MEAN ANNUAL INCREMENT (GROWTH RATE OF MERCHANTABLE VOLUME) VALUES FOR SOME PLANTATION FOREST SPECIES (M^3 HA^{-1} YR^{-1})							
Continent	**Region/ Country**	**Tree species**	**Plantation Purpose**	**MAI min**	**MAI max**	**S.D.[2]**	**Reference**
South America	South America	*Tectona grandis*	Productive	7.3	17.3	2.5	6, 8
	South America	*Xylia xylocarpa*	Productive	3.0	8.8	1.5	6, 8
	South America	*Acacia* spp.	Productive	15.0	30.0	3.8	6, 8
	South America	*Araucaria angustifolia*	Productive	15.0	30.0	3.8	6, 8
	South America	*Eucalyptus* spp.	Productive	20.0	70.0	12.5	6, 8
	South America	*Hevea brasiliensis*	Productive	10.0	20.0	2.5	6, 8
	South America	*Mimosa scabrella*	Productive	10.0	25.0	3.8	6, 8
	South America	*Pinus* spp.	Productive	25.0	40.0	3.8	6, 8
	South America	*Populus* spp.	Productive	10.0	30.0	5.0	6, 8
	South America	*Tectona grandis*	Productive	15.0	35.0	5.0	6, 8
	South America	*Eucalyptus* spp.	Productive	15	70	13.8	6, 8
	South America	*Pinus radiata*	Productive	14	34	5.0	6, 8
	Brazil	*Khaya ivorensis*	Productive	18	25	1.8	11
	Brazil	*Schizolobium amazonicum*	Productive	10	33	5.8	2

[1] Updated and replaced former Table 4.11A and 4.11B from the *2006 IPCC Guidelines*

[2] Standard deviation estimated from the min and max estimates.

Note: E: East, S: South, N: North, SE: Southeast, W: West, C: Central

References

1 Chuande X. 2001; 2 Cordeiro *et al*. 2015; 3 Dell B., Daping X., Thu P.Q. 2012; 4 Erkan, N., 2003; 5 FAO, 2001; 6 FAO, 2006; 7 Haapanen, M., *et al*., 2015; 8 IPCC, 2006; 9 Kien, N.D., 2014; 10 Nzila, J.D., *et al*., 2004; 11 Silva, L.F., *et al*., 2016.

TABLE 4.12 (UPDATED)
BIOMASS VALUES FROM TABLES 4.7–4.10

Domain	Ecological zone[1]	Continent	Status/ condition	Above-ground biomass in natural forests (tonnes d.m. ha^{-1})[2]	Above-ground biomass in forest plantations (tonnes d.m. ha^{-1})[3]	Above-ground net biomass growth in natural forests (tonnes d.m. ha^{-1} yr^{-1})[4]	Above-ground net biomass growth in forest plantations (tonnes d.m. ha^{-1} yr^{-1})[5]
Tropical	Tropical rainforest	Africa	Primary	404.2	n.a.	1.3	n.a.
			Secondary >20 years	212.9	200-300	3.5	n.a.
			Secondary ≤ 20 years	52.8	60-100	7.6	5-8
		North and South America	Primary	307.1	n.a.	1.0	n.a.
			Secondary >20 years	206.4	150-300	2.3	5-40
			Secondary ≤20 years	75.7	150-300	5.9	5-40
		Asia	Primary	413.1	n.a.	0.7	n.a.
			Secondary >20 years	131.6	48.5-512.8	2.7	2-8
			Secondary ≤20 years	45.6	13.5-161	3.4	2-8
	Tropical moist deciduous forest	Africa	Primary	236.6	n.a.	0.4	n.a.
			Secondary >20 years	72.8	120-483	0.9	n.a.
			Secondary ≤ 20 years	72.8	40-195	2.9	3-15
		North and South America	Primary	187.3	n.a.	0.4	n.a.
			Secondary >20 years	131.0	46.9-284	2.7	4-20
			Secondary ≤20 years	55.7	46.9-195	5.2	4-20
		Asia	Primary	67.7	n.a.	0.4	n.a.
			Secondary >20 years	67.7	93.7-260	0.9	8
			Secondary ≤20 years	67.7	5.7-202	2.4	8
	Tropical dry forest	Africa	Primary	69.6	n.a.	n.a.	n.a.
			Secondary >20 years	69.6	60-193.9	1.6	6-13
			Secondary ≤ 20 years	69.6	20-75.6	3.9	4-20
		North and South America	Primary	127.5	n.a.	n.a.	n.a.
			Secondary >20 years	118.9	50-110	1.6	4-30
			Secondary ≤20 years	32.2	40-62	3.9	4-30

TABLE 4.12 (UPDATED) (CONTINUED) BIOMASS VALUES FROM TABLES 4.7–4.10							
Domain	**Ecological zone[1]**	**Continent**	**Status/ condition**	**Above-ground biomass in natural forests (tonnes d.m. ha^{-1})[2]**	**Above-ground biomass in forest plantations (tonnes d.m. ha^{-1})[3]**	**Above-ground net biomass growth in natural forests (tonnes d.m. ha^{-1} yr^{-1})[4]**	**Above-ground net biomass growth in forest plantations (tonnes d.m. ha^{-1} yr^{-1})[5]**
Tropical	Tropical dry forest	Asia	Primary	184.6	n.a.	n.a.	n.a.
			Secondary >20 years	184.6	45.5-88.8	1.6	2-25
			Secondary ≤20 years	184.6	3.56-125.5	3.9	2-25
	Tropical shrublands	Africa	Primary	48.4	n.a.	0.9	n.a.
			Secondary >20 years	48.4	20	0.9	2.5-14
			Secondary ≤ 20 years	48.4	15-20	0.2-0.7	3-7
		North and South America	Primary	71.5	n.a.	1.0	n.a.
			Secondary >20 years	71.5	30-60	1.0	5-20
			Secondary ≤20 years	71.5	30-60	4.0	5-20
		Asia	Primary	38.3	n.a.	1.0-1.3	n.a.
			Secondary >20 years	38.3	30-263.3	1.0-1.3	1-12
			Secondary ≤20 years	38.3	9.0-53.3	2.0-5.0	1-12
	Tropical mountain systems	Africa	Primary	190.0	n.a.	0.5	n.a.
			Secondary >20 years	190.0	30-150	1.8	10
			Secondary ≤ 20 years	190.0	30-100	5.5	10
		North and South America	Primary	195.0	n.a.	0.5	n.a.
			Secondary >20 years	184.4	30-170	1.8	8-18
			Secondary ≤20 years	75.9	30-170	4.4	8-18
		Asia	Primary	433.5	n.a.	-0.7	n.a.
			Secondary >20 years	66.4	25-150	1.1	1-10
			Secondary ≤20 years	66.4	25-150	2.9	1-10

TABLE 4.12 (UPDATED) (CONTINUED) BIOMASS VALUES FROM TABLES 4.7–4.10							
Domain	**Ecological zone[1]**	**Continent**	**Status/ condition**	**Above-ground biomass in natural forests (tonnes d.m. ha^{-1})[2]**	**Above-ground biomass in forest plantations (tonnes d.m. ha^{-1})[3]**	**Above-ground net biomass growth in natural forests (tonnes d.m. ha^{-1} yr^{-1})[4]**	**Above-ground net biomass growth in forest plantations (tonnes d.m. ha^{-1} yr^{-1})[5]**
Sub-tropical	Sub-tropical humid forests	Africa	Primary	54.1	n.a.	n.a.	n.a.
			Secondary >20 years	54.1	n.a.	1.0	n.a.
			Secondary ≤ 20 years	54.1	n.a.	2.5	n.a.
		North and South America	Primary	84.5	n.a.	n.a.	n.a.
			Secondary >20 years	84.5	11.1-270	1.0	3-32
			Secondary ≤20 years	84.5	2.45-270	2.5	3-32
		Asia	Primary	323.0	n.a.	n.a.	n.a.
			Secondary >20 years	258.4	100-180	1.0	8
			Secondary ≤20 years	258.4	100-180	2.5	8
	Sub-tropical dry forests	Africa	Primary	65.2	n.a.	1.8	n.a.
			Secondary >20 years	65.2	60-70	1.8	8
			Secondary ≤ 20 years	65.2	20-30	2.4	4-20
		North and South America	Primary	115.9	n.a.	1.0	n.a.
			Secondary >20 years	115.9	60-110	1.0	3-30
			Secondary ≤20 years	115.9	60-110	4.0	3-30
		Asia	Primary	70.9	n.a.	1.5-2.0	n.a.
			Secondary >20 years	70.9	60-163.5	1.5-2.0	2-25
			Secondary ≤20 years	70.9	54.8-69.5	6.0-7.0	2-25
	Sub-tropical steppe	Africa	Primary	50.5	n.a.	0.9	n.a.
			Secondary >20 years	50.5	15-20	0.9	2.5-14
			Secondary ≤ 20 years	50.5	15-20	1.2	0.5-15
		North and South America	Primary	44.0	n.a.	1.0	n.a.
			Secondary >20 years	44.0	30-60	1.0	5-20
			Secondary ≤20 years	44.0	3.6-60	4.0	5-20

TABLE 4.12 (UPDATED) (CONTINUED) BIOMASS VALUES FROM TABLES 4.7–4.10							
Domain	**Ecological zone[1]**	**Continent**	**Status/ condition**	**Above-ground biomass in natural forests (tonnes d.m. ha^{-1})[2]**	**Above-ground biomass in forest plantations (tonnes d.m. ha^{-1})[3]**	**Above-ground net biomass growth in natural forests (tonnes d.m. ha^{-1} yr^{-1})[4]**	**Above-ground net biomass growth in forest plantations (tonnes d.m. ha^{-1} yr^{-1})[5]**
Sub-tropical	Sub-tropical steppe	Asia	Primary	41.6	n.a.	1.0-1.3	n.a.
			Secondary >20 years	41.6	20-80	1.0-1.3	1-12
			Secondary ≤20 years	41.6	10-120	2.0-5.0	1-12
	Sub-tropical mountain systems	Africa	Primary	35.1	n.a.	n.a.	n.a.
			Secondary >20 years	35.1	30-150	0.5	10
			Secondary ≤ 20 years	35.1	10-100	2.5	10
		North and South America	Primary	74.6	n.a.	n.a.	n.a.
			Secondary >20 years	74.6	24.9-170	0.5	2-18
			Secondary ≤20 years	74.6	3.7-170	2.5	2-18
		Asia	Primary	250.2	n.a.	n.a.	n.a.
			Secondary >20 years	155.2	n.a.	0.5	1-12
			Secondary ≤20 years	155.2	8.9-103.5	2.5	1-12
Temperate	Mountain	Asia	Primary	n.a.	n.a.	n.a.	n.a.
			Secondary >20 years	170.4	n.a.	n.a.	3.0
			Secondary ≤ 20 years	n.a.	16.6-34.6	n.a.	3.0
		Europe	Primary	301.1	n.a.	n.a.	n.a.
			Secondary >20 years	214.7	n.a.	n.a.	3.0
			Secondary ≤20 years	27.8	n.a.	n.a.	3.0
		North and South America	Primary	n.a.	n.a.	n.a.	n.a.
			Secondary >20 years	185.9	29.1-89.2	4.4	9
			Secondary ≤20 years	57.9	3.0-56.0	3.1	10

TABLE 4.12 (UPDATED) (CONTINUED)
BIOMASS VALUES FROM TABLES 4.7–4.10

Domain	Ecological zone[1]	Continent	Status/ condition	Above-ground biomass in natural forests (tonnes d.m. ha^{-1})[2]	Above-ground biomass in forest plantations (tonnes d.m. ha^{-1})[3]	Above-ground net biomass growth in natural forests (tonnes d.m. ha^{-1} yr^{-1})[4]	Above-ground net biomass growth in forest plantations (tonnes d.m. ha^{-1} yr^{-1})[5]
Temperate	Continental	Asia	Primary	n.a.	n.a.	n.a.	n.a.
			Secondary >20 years	116	54.5-132.1	n.a.	4.0
			Secondary ≤ 20 years	90.9	18-66.7	n.a.	4.0
		Europe	Primary	332.4	n.a.	n.a.	n.a.
			Secondary >20 years	162	n.a.	n.a.	4.0
			Secondary ≤20 years	51.6	n.a.	n.a.	4.0
		North and South America	Primary	n.a.	n.a.	n.a.	n.a.
			Secondary >20 years	128.9	21.5-96.7	3.6	4
			Secondary ≤20 years	46	5.688.35	3.3	5
	Oceanic	Asia	Primary	289.8	n.a.	n.a.	n.a.
			Secondary >20 years	n.a.	150-200	n.a.	4.4
			Secondary ≤ 20 years	n.a.	30-40	n.a.	4.4
		Europe	Primary	126.1	n.a.	2.3	n.a.
			Secondary >20 years	153.9	150-200	2.3	4.4
			Secondary ≤20 years	22.3	30-40	2.3	4.4
		Oceania	Primary	352.7	n.a.	0.37	n.a.
			Secondary >20 years	120.5	n.a.	2.12	4.4
			Secondary ≤20 years	57.5	n.a.	3.12	4.4
		North and South America	Primary	n.a.	n.a.	n.a.	n.a.
			Secondary >20 years	354.1	76.2-131.3	9.1	10
			Secondary ≤20 years	213.9	3.9-120	6.3	6
	Desert	Asia Europe North and South America	Primary	n.a.	n.a.	n.a.	n.a.
			Secondary >20 years	44	n.a.	0.6	n.a.
			Secondary ≤20 years	25.6	n.a.	0.5	n.a.

TABLE 4.12 (UPDATED) (CONTINUED)
BIOMASS VALUES FROM TABLES 4.7–4.10

Domain	Ecological zone[1]	Continent	Status/ condition	Above-ground biomass in natural forests (tonnes d.m. ha^{-1})[2]	Above-ground biomass in forest plantations (tonnes d.m. ha^{-1})[3]	Above-ground net biomass growth in natural forests (tonnes d.m. ha^{-1} yr^{-1})[4]	Above-ground net biomass growth in forest plantations (tonnes d.m. ha^{-1} yr^{-1})[5]
Temperate	Steppe	Asia Europe North and South America	Primary	n.a.	n.a.	n.a.	n.a.
			Secondary >20 years	118.5	3.6-84.9	3.5	11
			Secondary ≤20 years	42.9	4.8-48.8	2.3	4
Boreal	Coniferous Tundra woodland Mountain	Asia Europe North America	Primary	62.9	n.a.	0.1-2.1	n.a.
			Secondary >20 years	n.a.	40-50	0.1-2.2	1.0
			Secondary ≤20 years	n.a.	5.0-50	0.1-2.3	1.0
		Asia Europe North America	Primary	n.a.	n.a.	0.4	n.a.
			Secondary >20 years	63.7	25	0.4	0.4
			Secondary ≤20 years	104.2	5	0.4	0.4
		Asia Europe North America	Primary	n.a.	n.a.	n.a.	n.a.
			Secondary >20 years	n.a.	40-50	1.1-1.5	1.0
			Secondary ≤20 years	1.9	5.0-50	1.0-1.1	1.0

[1] Forest Resources Assessment (FRA) (2015). Global Ecological Zones for FAO Forest Reporting 2010 Update. Forest Resources Assessment Working Paper 179.

[2] For information related to uncertainties and references refer to table 4.7

[3] For information related to uncertainties and references refer to table 4.8

[4] For information related to uncertainties and references refer to table 4.9

[5] For information related to uncertainties and references refer to table 4.10

Annex 4A-1 Glossary for Forest Land

No refinement.

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CHAPTER 5

CROPLAND

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5 CROPLAND

5.1 INTRODUCTION

No refinement.

5.2 CROPLAND REMAINING CROPLAND

No refinement.

5.2.1 Biomass

5.2.1.1 CHOICE OF METHODS

Carbon can be stored in the biomass of croplands that contain perennial woody vegetation including, but not limited to, monocultures such as tea, coffee, oil palm, coconut, rubber plantations, fruit and nut orchards, and polycultures such as agroforestry systems. The default methodology for estimating carbon stock changes in woody biomass is provided in Chapter 2, Section 2.2.1. This section elaborates this methodology with respect to estimating changes in carbon stocks in biomass in *Cropland Remaining Cropland*.

The change in biomass is only estimated for perennial woody crops. For annual crops, increase in biomass stocks in a single year is assumed equal to biomass losses from harvest and mortality in that same year - thus there is no net accumulation of biomass carbon stocks.

Changes in carbon in cropland biomass (ΔC_{CC_B}) may be estimated from either: (a) annual rates of biomass gain and loss (Chapter 2, Equation 2.7) or (b) carbon stocks at two points in time (Chapter 2, Equation 2.8). The first approach (gain-loss method) provides the default Tier 1 method and can also be used at Tier 2 or 3 with refinements described below. The second approach (the stock-difference method) applies either at Tier 2 or Tier 3, but not Tier 1. It is *good practice* to improve inventories by using the highest feasible tier given national circumstances. It is *good practice* for countries to use a Tier 2 or Tier 3 method if carbon emissions and removals in *Cropland Remaining Cropland* is a *key category* and if the sub-category of biomass is considered significant. It is *good practice* for countries to use the decision tree in Figure 2.2 in Chapter 2 to identify the appropriate tier to estimate changes in carbon stocks in biomass.

Tier 1

The default method is to multiply the area of perennial woody cropland by a net estimate of biomass accumulation from growth and subtract losses associated with harvest or gathering or disturbance (according to Equation 2.7 in Chapter 2). Losses are estimated by multiplying a carbon stock value by the area of cropland on which perennial woody crops are harvested.

Default Tier 1 assumptions are: all carbon in perennial woody biomass removed (e.g., biomass cleared and replanted with a different crop) is emitted in the year of removal; and perennial woody crops accumulate carbon for an amount of time equal to a nominal harvest/maturity cycle. The latter assumption implies that perennial woody crops accumulate biomass for a finite period until they are removed through harvest or reach a steady state where there is no net accumulation of carbon in biomass because growth rates have slowed and incremental gains from growth are offset by losses from natural mortality, pruning or other losses.

Under Tier 1, updated default factors shown in updated Table 5.1, Table 5.2 and Table 5.3, are applied to nationally derived estimates of land areas. For perennial cropland C uptake, multiply unharvested area that is still younger than the age of maturity by the above-ground growth rate. If harvest and immature areas are unknown, it is assumed that in cropland remaining cropland, the annual harvest area is equal to total area divided by rotation length in years. For perennial cropland C losses, the updated tables provide two types of carbon stocks of perennial woody biomass per area. One is maximum carbon stock at harvest/maturity state (L_{max}). This is appropriate for estimating harvest loss due to crop renewal. The other is the mean carbon stock over the whole lifetime of the crop (L_{mean}). This is used for loss due to conversion to another land use where the age of converted cropland is unknown. These values should be used appropriately to calculate carbon losses following the guidance in 5.2.1.2.

Tier 2

Two methods can be used for Tier 2 estimation of changes in biomass. Method 1 (also called the **Gain-Loss Method**) requires the biomass carbon loss to be subtracted from the biomass carbon increment for the reporting year (Chapter 2, Equation 2.7). Method 2 (also called the **Stock-Difference Method**) requires biomass carbon stock inventories for a given land-use area at two points in time (Chapter 2, Equation 2.8).

A Tier 2 estimate, in contrast, will generally develop estimates for the major woody crop types by climate zones, using country-specific carbon accumulation rates and stock losses where possible or country-specific estimates of carbon stocks at two points in time. Under Tier 2, carbon stock changes are estimated for above-ground and below-ground biomass in perennial woody vegetation. Tier 2 methods involve country-specific or region-specific estimates of biomass stocks by major cropland types and management system and estimates of stock change as a function of major management system (e.g., dominant crop, productivity management). To the extent possible, it is *good practice* for countries to incorporate changes in perennial crop or tree biomass using country-specific or region-specific data. Where data are missing, default data may be used.

Tier 3

A Tier 3 estimate will use a highly disaggregated Tier 2 approach or a country-specific method involving process modelling and/or detailed measurement. Tier 3 involves inventory systems using statistically-based sampling of carbon stocks over time and/or process models, stratified by climate, cropland type and management regime. For example, validated species-specific growth models that incorporate management effects such as harvesting and fertilization, with corresponding data on management activities, can be used to estimate net changes in cropland biomass carbon stocks over time. Models, perhaps accompanied by measurements like those in forest inventories, can be used to estimate stock changes and extrapolate to entire cropland areas, as in Tier 2.

Key criteria in selecting appropriate models are that they are capable of representing all of the management practices that are represented in the activity data. It is critical that the model be validated with independent observations from country-specific or region-specific field locations that are representative of climate, soil and cropland management systems in the country.

5.2.1.2 CHOICE OF EMISSION FACTORS

Emission and removal factors required to estimate the changes in carbon stocks include (a) annual biomass accumulation or growth rate, and (b) biomass loss factors which are influenced by such activities as removal (harvesting), fuelwood gathering and disturbance.

Above-ground woody biomass growth rate

Tier 1

Updated Tables 5.1 to 5.3 provide estimates of biomass stocks and/or biomass growth rates and losses for major climatic regions and agricultural systems. Updated Table 5.1 provides default values of biomass growth and losses applicable to agroforestry cropping systems in broad climate regions. Agroforestry systems are defined in Table 5.5. Updated Table 5.2 provides default sequestration rates in above- and below-ground biomass for agro-forestry systems by region and climate zone. Updated Table 5.3 provides default values of biomass growth and losses for perennial cropping monoculture systems. Countries should use appropriate default values of above-ground biomass growth rate relative to each climate region and cropping system from updated Table 5.1, Table 5.2 or Table 5.3. However, given the large variation in cropping systems, incorporating trees or tree crops, it is *good practice* to seek national data on above-ground woody biomass growth rate.

Tier 2

Annual woody biomass growth rate data can be, at a finer or disaggregated scale, based on national data sources for different cropping and agroforestry systems. Rates of change in annual woody biomass growth rate should be estimated in response to changes in specific management/land-use activities (e.g., fertilization, harvesting, thinning). Results from field research should be compared to estimates of biomass growth from other sources to verify that they are within documented ranges. It is important, in deriving estimates of biomass accumulation rates, to recognize that biomass growth rates will occur primarily during the first 20 years following changes in management, after which time the rates will tend towards a new steady-state level with little or no change occurring unless further changes in management conditions occur.

TABLE 5.1 (UPDATED[1])
DEFAULT COEFFICIENTS FOR ABOVE-GROUND BIOMASS AND HARVEST/MATURITY CYCLES IN AGROFORESTRY SYSTEMS CONTAINING PERENNIAL SPECIES[2]

Climate Region	Agroforestry system[3]	N	Tree density (Stems ha^{-1})	Maximum above-ground biomass carbon stock at harvest ***L_{max} (tonnes C ha^{-1})	Harvest /Maturity cycle** (yr)	Biomass accumulation rate (G)* (tonnes C ha^{-1} yr^{-1})	Mean biomass carbon loss *** (L_{mean}) (tonnes C ha^{-1} yr^{-1})
Tropical	Fallow	69	6074	22.1 ± 52%	5 ± 50%	4.42 ± 15%	11.1 ± 26%
	Hedgerow[4]	3	1481	9.4 ± 59%	20 ± 50%	0.47 ± 31%	4.7 ± 29%
	Alley cropping	90	8568	47.4 ± 52%	20 ± 50%	2.37 ± 13%	23.7 ± 26%
	Multistrata	51	929	65.0 ± 54%	20 ± 50%	3.25 ± 21%	32.5 ± 27%
	Parkland	7	152	11.8 ± 76%	20 ± 50%	0.59 ± 58%	5.9 ± 38%
	Shaded Perennial	28	4236	48.0 ± 55%	20 ± 50%	2.4 ± 24%	24.0 ± 28%
	Silvoarable	22	880	72.2 ± 60%	20 ± 50%	3.61± 33%	36.1 ± 30%
	Silvopasture	18	1609	58.2 ± 80%	20 ± 50%	2.91 ± 63%	29.1 ± 40%
Temperate	Hedgerow[4]	12	816	26.1 ± 59%	30 ± 33%	0.87 ± 49%	13.1 ± 29%
	Silvoarable	14	202	27.3 ± 62%	30 ± 33%	0.91 ± 52%	13.7 ± 31%
	Silvopasture	10	854	69.9 ± 61%	30 ± 33%	2.33 ± 52%	35.0 ± 31%

*Source: biomass carbon accumulation rate, G, from Cardinael *et al*. (2018). Uncertainty = 95% CI.

** Harvest/Maturity cycle and uncertainty are nominal estimates.

*** calculated (L_{max} = G * Maturity cycle; Lmean = L_{max}/2)

[1] Replaces Table 5.1 from the *2006 IPCC Guidelines*

[2] See Table 5.3 for monocultures

[3] See Table 5.4 for agroforestry system definitions

[4] Biomass storage rates and tree density for hedgerows are presented per kilometer of hedgerows, not per hectare of agricultural field or per hectare of hedgerow

Tier 3

For Tier 3, highly disaggregated factors for biomass accumulation are needed. These may include categorisation of species, specific for growth models that incorporate management effects such as harvesting and fertilization. Measurement of above-ground biomass, similar to forest inventory with periodic measurement of above-ground biomass accumulation, is necessary.

TABLE 5.2 (UPDATED[1])
DEFAULT COEFFICIENTS FOR ABOVE- AND BELOW-GROUND BIOMASS IN AGROFORESTRY SYSTEMS CONTAINING PERENNIAL SPECIES[2]

Climate Region	Region	Agroforestry system	N	Tree density (stems ha^{-1})	Above-ground biomass accumulation rate (G) (tonnes C ha^{-1} yr^{-1})	Below-ground biomass accumulation rate (tonnes C ha^{-1} yr^{-1})
Cool Temperate	Asia	Silvoarable	2	833	2.97 ± 75%	0.77
	Europe	Silvopasture	4	225	2.17 ± 47%	0.56
	North America	Hedgerow[3]	12	816	0.87 ± 49%	0.23
		Silvoarable	7	111	0.59 ± 29%	0.14
		Silvopasture	1	571	0.97 ± 75%	0.11
	South America	Silvopasture	1	400	1.18 ± 75%	0.52
	All regions	Hedgerow[3]	12	816	0.87 ± 49%	0.23
		Silvoarable	9	271	1.12 ± 62%	0.28
		Silvopasture	6	312	1.81 ± 44%	0.48
Warm Temperate	Europe	Silvoarable	5	76	0.52 ± 102%	0.14
		Silvopasture	4	1667	3.11 ± 91%	1.03
Temperate (ALL)	All Regions	Hedgerow[3]	12	816	0.87 ± 49%	0.23
		Silvoarable	14	202	0.91 ± 54%	0.23
		Silvopasture	10	854	2.33 ± 52%	0.70
Tropical Dry	Africa	Fallow	22	-	5.61 ± 21%	2.54
		Hedgerow[3]	2	1667	0.48 ± 75%	0.12
		Alley cropping	20	1000	1.88 ± 28%	0.45
		Multistrata	3	2771	1.63 ± 26%	0.46
		Parkland	7	152	0.59 ± 58%	0.21
	Asia	Fallow	9	1250	5.61 ± 59%	0.53
		Alley cropping	15	10430	2.79 ± 24%	0.67
		Silvoarable	6	540	6.24 ± 36%	1.62
		Silvopasture	17	1609	3.07 ± 62%%	0.84
	All Regions	Fallow	31	1250	5.61 ± 22%	1.95
		Hedgerow[3]	2	1667	0.48 ± 75%	0.12
		Alley cropping	35	5041	2.27 ± 19%	0.54
		Multistrata	3	2771	1.63 ± 26%	0.46
		Parkland	7	152	0.59 ± 58%	0.21
		Silvoarable	6	540	6.24 ± 36%	1.62
		Silvopasture	17	1609	3.07 ± 62%	0.84
Tropical Moist	Africa	Alley cropping	28	7233	2.75 ± 22%	0.59
		Multistrata	3	1902	2.98 ± 28%	0.72
		Shaded Perennial	5	-	1.82 ± 34%	0.44
		Silvoarable	5	-	5.09 ± 39%	1.22

TABLE 5.2 (UPDATED) (CONTINUED) DEFAULT COEFFICIENTS FOR ABOVE- AND BELOW-GROUND BIOMASS IN AGROFORESTRY SYSTEMS CONTAINING PERENNIAL SPECIES[2]						
Climate Region	**Region**	**Agroforestry system**	**N**	**Tree density** **(stems ha^{-1})**	**Above-ground biomass accumulation rate (G)** **(tonnes C ha^{-1} yr^{-1})**	**Below-ground biomass accumulation rate** **(tonnes C ha^{-1} yr^{-1})**
Tropical Moist	Asia	Fallow	1	-	5.30 ± 75%	1.27
		Multistrata	21	628	3.03 ± 30%	0.73
		Shaded Perennial	2	1481	2.07 ± 36%	0.50
		Silvoarable	11	1065	1.5 ± 44%	0.35
	Central America	Alley cropping	15	25000	2.28 ± 23%	0.55
	South America	Shaded Perennial	6	4131	3.06 ± 66%	0.71
	All Regions	Fallow	1	-	5.30 ± 75%	1.27
		Alley cropping	43	13733	2.59 ± 17%	0.58
		Multistrata	24	802	3.02 ± 26%	0.73
		Shaded Perennial	13	3071	2.43 ± 40%	0.57
		Silvoarable	16	1065	2.63 ± 42%	0.62
Tropical montane	Africa	Fallow	30	7521	3.12 ± 15%	1.12
Tropical Wet	Africa	Fallow	3	-	6.21 ± 53%	1.49
		Multistrata	2	-	2.89 ± 75%	0.69
		Shaded Perennial	1	1477	3.16 ± 75%	0.71
	Asia	Fallow	2	-	2.00 ± 75%	0.48
		Multistrata	11	-	4.83 ± 50%%	1.16
		Shaded Perennial	2	1608	1.79 ± 75%	0.42
		Silvopasture	1	-	0.06 ± 75%	0.01
	Central America	Hedgerow[3]	1	1110	0.43 ± 75%	0.10
		Alley cropping	12	1203	1.88 ± 51%	0.45
		Multistrata	1	-	3.25 ± 75%	0.78
		Shaded Perennial	10	5967	2.28 ± 42%	0.51
	South America	Fallow	2	-	4.76 ± 75%	1.14
		Multistrata	10	475	2.6 ± 42%	0.70
		Shaded Perennial	2	-	2.96 ± 75%	0.71
	All Regions	Fallow	7	-	4.59 ± 45%	1.10
		Hedgerow[3]	1	1110	0.43 ± 75%	0.10
		Alley cropping	12	1203	1.88 ± 51%	0.45
		Multistrata	24	475	3.25 ± 31%	0.91
		Shaded Perennial	15	4766	2.36 ± 29%	0.54
		Silvopasture	1	-	0.06 ± 75%	0.01

TABLE 5.2 (UPDATED) (CONTINUED)
DEFAULT COEFFICIENTS FOR ABOVE- AND BELOW-GROUND BIOMASS IN AGROFORESTRY SYSTEMS CONTAINING PERENNIAL SPECIES[2]

Climate Region	Region	Agroforestry system	N	Tree density (stems ha^{-1})	Above-ground biomass accumulation rate (G) (tonnes C ha^{-1} yr^{-1})	Below-ground biomass accumulation rate (tonnes C ha^{-1} yr^{-1})
Tropical All	All Regions	Fallow	69	6074	4.42 ± 15%	1.49
		Hedgerow[3]	3	1481	0.47 ± 31%	0.11
		Alley cropping	90	8568	2.37 ± 13%	0.55
		Multistrata	51	929	3.25 ± 21%	0.80
		Parkland	7	152	0.59 ± 58%	0.21
		Shaded Perennial	28	4236	2.40 ± 24%	0.55
		Silvoarable	22	880	3.61 ± 33%	0.89
		Silvopasture	18	1609	2.91 ± 63%	0.79

Source: Cardinael *et al*. (2018).

[1] Replaces Tables 5.2 and 5.3 from the *2006 IPCC Guidelines*

[2] See Table 5.3 for monocultures.

[4] Biomass storage rates and tree density for hedgerows are presented per kilometer of hedgerows, not per hectare of agricultural field or per hectare of hedgerow

* Where N < 3 a nominal uncertainty estimate of ± 75% is given.

TABLE 5.3 (UPDATED[1])
DEFAULT MAXIMUM AND TIME-AVERAGED MEAN ABOVE-GROUND BIOMASS AND ABOVE GROUND BIOMASS ACCUMULATION RATE FOR PERENNIAL CROPLAND MONOCULTURES (TONNES HA^{-1})

Domain	Cropping system	Maximum above-ground biomass carbon stock at harvest (L_{max}) (tonnes C ha^{-1})	Harvest /Maturity cycle (yr)	Above-ground biomass accumulation rate (G) (tonnes C ha^{-1} yr^{-1})	Mean biomass carbon stock (L_{mean}) (tonnes C ha^{-1})	References
Temperate	Olive	9.1 ± 15%	20 ± 23%	0.46 ± 27%	6.9 ± 25%	[1]
	Orchard e.g. apple	8.5 ± 19%	20 ± 42%	0.43 ± 46%	6.4 ± 25%	[1]
	Vine e.g. grape	5.5 ± 18%	20 ± 18%	0.28 ± 26%	2.8 ± 25%	[1]
	Short Rotation Coppice	12.69 ± 40%	4	3.2 ± 40%	6.35 ± 40%	[2] + adjust-ment from [3]
Tropical	Oil palm *Elaeis guineensis*	60.0 ± 41%	25	2.4 ± 41%	30.0 ± 41%	[4]
	Rubber *Hevea brasiliensis*	80.2 ± 15%	27	3.0 ± 13%	40.1 ± 15%	[5]
All	Tea *Camelia sinensis*	20.7 ± 50%	30	0.7 ± 25%	18.3 ± 25%	[6]

[1] Canaveira, P. *et al*. 2018.
[2] Hauk S, Knoke T, Wittkopf S 2013
[3] Krasuska E, Rosenqvist H. 2012
[4] Chave, J. 2015
[5] Blagodatsky, S., Xu, J., Cadisch, G. 2016
[6] Zhang M, *et al*. 2017
[1] Updated Table 5.3 from *2006 IPCC Guidelines*

Below-ground biomass accumulation

Tier 1

The default assumption is that there is no change in below-ground biomass of perennial trees in agricultural systems. There are limited below-ground biomass data for agricultural systems.

Tier 2

This includes the use of actually measured below-ground biomass data from perennial woody vegetation. Estimating below-ground biomass accumulation is recommended for Tier 2 calculation. Estimates are provided in Table 5.2. Root-to-shoot ratios show wide ranges in values at both individual species (e.g., Anderson *et al.* 1972*)* and community scales (e.g., Jackson *et al.* 1996; Cairns *et al.* 1997*)*. Limited data is available for below ground biomass thus, as far as possible, empirically-derived root-to-shoot ratios specific to a region or vegetation type should be used.

Tier 3

This includes the use of data from field studies identical to forest inventories and modelling studies, if stock difference method is adopted.

Biomass losses from removal, fuelwood and disturbance

Tier 1

The default assumption is that all biomass lost is assumed to be emitted in the same year. Limited biomass removal, fuelwood gathering and disturbance loss data from cropland source are available. Food and Agriculture Organization of the United Nations (FAO) provides total roundwood and fuelwood consumption data, but not separated by source (e.g., Cropland, Forest Land, etc.). It is recognized that statistics on fuelwood are extremely poor and uncertain worldwide. Default removal and fuelwood gathering statistics (discussed in Chapter 4, Section 4.2) may include biomass coming from cropland such as when firewood is harvested from home gardens. Thus, it is necessary to ensure no double counting of losses occurs. If no data are available for roundwood or fuelwood sources from Cropland, the default approach will include losses in Forest Land (Section 4.2) and will exclude losses from Cropland. Updated Tables 5.1 and 5.3 provide default values of maximum carbon stock per area (L_{max}) and mean carbon stock per area (L_{mean}). Countries should use L_{max} in updated Table 5.1 and 5.3 in the case that perennial woody biomass is replaced at or over the year of harvest/maturity under a nominal harvest/maturity cycle assuming that perennial cropland is harvested and regenerated back into perennial cropland. Carbon losses are estimated by multiplying annual area of harvested/replaced cropland by L_{max}. Countries should use L_{mean} in updated Table 5.1 and 5.3 in the case that carbon removal has occurred by land use change where the age of the perennial crop removed is unknown. Carbon losses are estimated by multiplying the annual area of land conversion by L_{mean}. When perennial cropland is converted to another type of cropland, losses are reported in cropland remaining cropland. When perennial cropland is converted to non-cropland land uses, losses are reported in relevant land converted categories

Tiers 2 and 3

National level data at a finer scale, based on inventory studies or production and consumption studies according to different sources, including agricultural systems, can be used to estimate biomass loss. These can be obtained through a variety of methods, including estimating density (crown coverage) of woody vegetation from air photos (or high-resolution satellite imagery) and ground-based measurement plots. Species composition, density and above-ground vs. below-ground biomass can vary widely for different cropland types and conditions and thus it may be most efficient to stratify sampling and survey plots by cropland types. General guidance on survey and sampling techniques for biomass inventories is given in Chapter 3, Annex 3A.3.

5.2.1.3 CHOICE OF ACTIVITY DATA

Activity data in this section refer to estimates of land areas of growing stock and harvested land with perennial woody crops. The area data are estimated using the approaches described in Chapter 3. They should be regarded as strata within the total cropland area (to keep land-use data consistent) and should be disaggregated depending on the tier used and availability of growth and loss factors. Examples of Cropland subcategories are given in updated Table 5.4.

Tier 1

Under Tier 1, annual or periodic surveys are used in conjunction with the approaches outlined in Chapter 3 to estimate the average annual area of established perennial woody crops and the average annual area of perennial woody crops that are harvested or removed. The area estimates are further sub-divided into general climate regions or soil types to match the default biomass gain and loss values. Under Tier 1 calculations, international statistics such as FAO databases, and other sources can be used to estimate the area of land under perennial woody crops.

Tier 2

Under Tier 2, more detailed annual or periodic surveys are used to estimate the areas of land in different classes of perennial woody biomass crops. Areas are further classified into relevant sub categories such that all major combinations of perennial woody crop types and climatic regions are represented with each area estimate. These area estimates must match any country-specific biomass carbon increment and loss values developed for the Tier 2 method. If country-specific finer resolution data are only partially available, countries are encouraged to extrapolate to the entire land base of perennial woody crops using sound assumptions from best available knowledge.

Tier 3

Tier 3 requires high-resolution activity data disaggregated at sub-national to fine grid scales. Similar to Tier 2, land area is classified into specific types of perennial woody crops by major climate and soil categories and other potentially important regional variables (e.g., regional patterns of management practices). Furthermore, it is *good practice* to relate spatially explicit area estimates with local estimates of biomass increment, loss rates, and management practices to improve the accuracy of estimates.

TABLE 5.4 (UPDATED[1])
EXAMPLES OF CLASSIFICATION OF PERENNIAL CROP SYSTEMS

	Crop system	Description
Agroforestry	Fallows	Land rested from cultivation, but comprises planted and managed trees, often leguminous, shrubs and herbaceous cover crops before it is cultivated again. Includes improved and natural fallows and can be implemented before any of the following systems.
	Hedgerows	Linear plantation around fields, including shelterbelts, windbreaks, boundary plantings and live fences.
	Alley cropping	Fast-growing, usually leguminous, woody species (mainly shrubs) grown in crop fields, usually at high densities. The woody species are regularly pruned and the prunings are applied as mulch into the alleys as a source of organic matter and nutrients. Also known as intercropping.
	Multistrata systems	Multistorey combinations of a large number of various trees and perennial and annual crops. They include home gardens and agroforests.
	Parklands	Intercropping of agricultural crops or grazing land under low density mature scattered trees. Typical of dry areas like Sahel (e.g. *Faidherbia albida*).
	Shaded perennial-crop systems	Growing shade-tolerant species such as cacao and coffee under, or in between, overstorey shade trees that can be used for timber or other commercial tree products
	Silvoarable systems	Woody species planted in parallel tree rows to allow mechanization and intercropped with an annual crop; usually used for timber (e.p. *Juglans* spp), but also for fuel (e.p. *Populus* spp). Usually low tree density per hectare.
	Silvopastoral systems	Woody species planted on permanent grasslands, often grazed.
Monoculture	Plantations	Monoculture plantation crops such as tea, coffee and cacao grown without shade trees, as well as oil palms, rubber and coconuts.
	Vine systems	A plantation of vines, typically producing grapes used for winemaking, but also kiwifruit or passionfruit.
	Orchards systems	Land planted with woody vegetation, often fruit trees (eg. apple, pear, plum, nut trees). Understory vegetation is usually mowed or grazed.

Source: Cardinael *et al*. (2018), adapted from Nair *et al*. (2009)
Within the FAOSTAT land use classification system most perennial crop systems will be classified under 6650 (Land under permanent crops). Fallows may be reported under 6655 (Land with temporary fallow), and parklands and silvopastoral systems under 6655 (Land under permanent meadows and pastures), Land that meets the forest definition will be reported as Forest land.

[1]Updated Table 5.4 in the *2006 IPCC Guidelines*

5.2.1.4 CALCULATION STEPS FOR TIER 1 AND TIER 2

No refinement.

5.2.1.5 UNCERTAINTY ASSESSMENT

No refinement.

5.2.2 Dead organic matter

No refinement.

5.2.3 Soil carbon

Cropland management modifies soil C stocks to varying degrees depending on how specific practices influence C input and output from the soil system (Paustian *et al*. 1997a; Bruce *et al*. 1999; Ogle *et al*. 2005). The main management practices that affect soil C stocks in croplands are the type of residue management, tillage management, fertilizer management (both mineral fertilizers and organic amendments), choice of crop and intensity of cropping management (e.g., continuous cropping versus cropping rotations with periods of bare fallow), irrigation management, and mixed systems with cropping and pasture or hay in rotating sequences. In addition, drainage and cultivation of organic soils reduces soil C stocks (Armentano and Menges, 1986).

General information and guidance for estimating changes in soil C stocks are found in Section 2.3.3 of Chapter 2 (including equations). That section should be read before proceeding with specific guidelines dealing with Cropland soil C stocks. The total change in soil C stocks for Cropland is estimated using Equation 2.24 (Chapter 2), which combines the change in soil organic C stocks for mineral soils and organic soils; and stock changes associated with soil inorganic C pools (Tier 3 only). This section provides specific guidance for estimating soil organic C stock changes. Soil inorganic C is fully covered by Section 2.3.3.1.

To account for changes in soil C stocks associated with *Cropland Remaining Cropland*, countries need at a minimum, estimates of the Cropland area at the beginning and end of the inventory time period. If land-use and management data are limited, aggregate data, such as FAO statistics on Cropland, can be used as a starting point, along with expert knowledge about the approximate distribution of land management systems (e.g., medium, low and high input cropping systems, etc.). Cropland management classes must be stratified according to climate regions and major soil types, which can either be based on default or country-specific classifications. This can be accomplished with overlays of land use on suitable climate and soil maps.

5.2.3.1 CHOICE OF METHOD

Inventories can be developed using a Tier 1, 2, or 3 method, with each successive Tier requiring more detail and resources than the previous one. It is also possible that countries will use different tiers to prepare estimates for the separate subcategories of soil C (i.e., soil organic C stocks changes in mineral soils and organic soils, and stock changes associated with soil inorganic C pools). Decision trees are provided for mineral soils (Figure 2.5) and organic soils (Figure 2.6) in Section 2.3.3.1 (Chapter 2) to assist inventory compilers with selection of the appropriate tier for their soil C inventory.

Mineral soils

Tier 1

For mineral soils, the estimation method is based on changes in soil organic C stocks over a finite period following changes in management that impact soil organic C. Equation 2.25 (Chapter 2) is used to estimate change in soil organic C stocks in mineral soils by subtracting the C stock in the last year of an inventory time period (SOC_0) from the C stock at the beginning of the inventory time period ($SOC_{(0-T)}$) and dividing by the time dependence of the stock change factors (D). In practice, country-specific data on land use and management must be obtained and classified into appropriate land management systems (e.g., high, medium and low input cropping), including tillage management, and then stratified by IPCC climate regions and soil types. Soil organic C stocks (SOC) are estimated for the beginning and end of the inventory time period using default reference carbon stocks (SOC_{ref}) and default stock change factors (F_{LU}, F_{MG}, F_I).

Tier 2

Developing Country-Specific Factors for the Default Equations

For Tier 2, the same basic equations are used as in Tier 1 (Equation 2.25), but country-specific information is incorporated to specify better the stock change factors and reference C stocks with more disaggregation of climate regions, soil types, and/or the land management classification. See Section 2.3.3.1, Chapter 2, Volume IV for more information.

Biochar C Amendments

Tier 2 methods for biochar C amendments utilize a top-down approach in which the total amount of biochar generated and added to mineral soil is used to estimate the change in soil organic C stocks with country-specific factors. See Section 2.3.3.1, Chapter 2, Volume IV for more information.

Steady-State Method

The Tier 2 steady-state method is a three sub-pool steady-state C model that provides an optional alternative method for estimating soil C stock changes in the 0-30 cm layer of mineral soils in *Cropland Remaining Cropland.*[2] This Tier 2 steady-state method estimates C stock changes from combinations of tillage and C-input management activities under conditions defined by the soil texture and the weather. The method is not appropriate for rice cultivation and is not parameterised to estimate the change in soil organic C stocks due to biochar C amendments.

[2] The Tier2 Steady state method may be applicable to other land uses, but this will require further development and parameterisation than provided in this section.

This is an approach with intermediate complexity between Tier 1 and Tier 3 methods, and is based on a steady-state solution to the three soil organic C sub-pools in the Century ecosystem model (Ogle *et al*. 2012; Parton *et al*. 1987; Paustian *et al.* 1997b).

The Tier 2 steady-state method addresses more complexity in soil C dynamics than Tier 1 or Tier 2 using default equations, by subdividing soil organic C into three separate sub-pools with fast (Active sub-pool), intermediate (Slow sub-pool), and long turnover times (Passive sub-pool). The turnover time of C within each sub-pool determines the length of time that C remains in the soil. The Tier 2 steady-state method incorporates spatial and temporal variation in climate, organic carbon inputs to soils, soil properties and management practices. However, compilers can further develop and/or parameterise this model given appropriate datasets, which would be a Tier 3 method (See Section 2.5.2 for more information about developing a Tier 3 model-based approach). See Boxes 5.1A and 5.1B for more information about the method.

BOX 5.1A (NEW)
UNDERSTANDING THE BASIS FOR THE TIER 2 STEADY STATE METHOD

The Tier 2 steady-state method, based on a soil C model, features intermediate complexity between Tier 1 and Tier 3 methods. It allows a compiler to estimate C stock changes in a more disaggregated way compared to Tier 1, but lacks the full complexity of Tier 3 methods. The model parameters were determined using a Bayesian Calibration method (See Annex 5A.3), and application of this method will generate SOC stock change factor that are specific to climate, soil and management conditions in a country. Consequently, the resulting stock change factors are more disaggregated than the default Tier 1 methods that are derived at a global scale with limited disaggregation to broadly-defined climate regions.

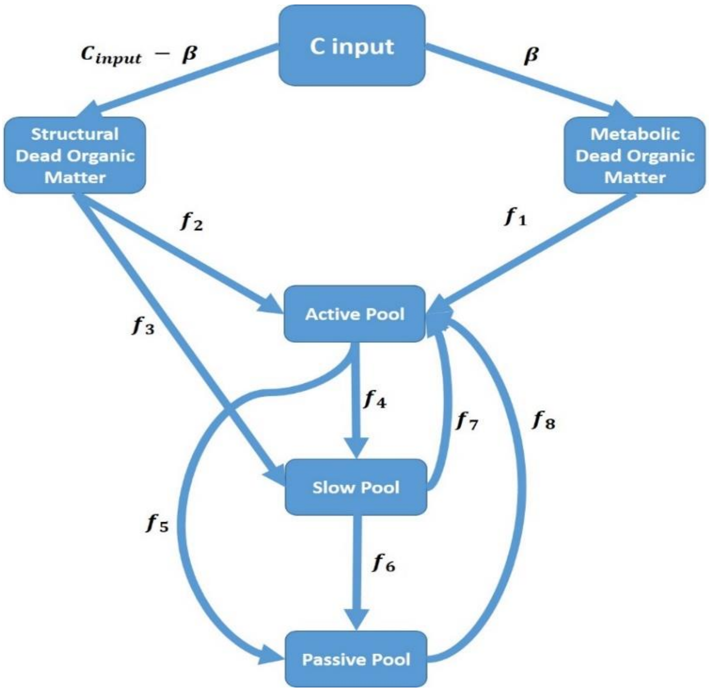
It is noteworthy that Tier 2 methods are often based directly on the Tier 1 equations with country-specific factors, but this is not a requirement for a Tier 2 method (See Volume 4, Chapter 1, Box 1.1). This method is analogous to the Tier 2 methods for estimating CH_4 emissions from enteric fermentation (Volume 4, Chapter 10), with a set of equations for calculating gross energy intake in order to derive a country-specific emission factor. The Tier 2 equations are used to derive stock change factors from country-specific data on crop type, yields, tillage, organic amendments, soil texture, and weather. The Tier 2 steady-state method uses management activity data that are typically more available in a country than that required to apply the methods for the default equations. The method gives the countries with these data an option to develop C stock change that are more responsive to their particular conditions than the Tier 1 approach. The Tier 1 equations require detailed information on the combination of crops types, tillage practices, manure amendments, mineral fertilization, irrigation management, grazing management, green manures, and fallows for individual parcels of land in the inventory. Although several of these activity data are needed for the Tier 2 steady-state method, much of the data requirements with the default equations are represented by the C inputs to the soil that are derived from crop yields, thereby eliminating several data requirements.

This method differs from Tier 3 methods that utilize process-based models that yield a fully dynamic time series by simulating changes in management and environmental conditions through time. This Tier 2 method does not simulate C change but simply calculates an annual C stock change from the current C stock to the future steady-state soil C stock calculated based on current conditions. In addition, the steady-state method is much less complex with about 20 parameters compared to the 100s to 1000s parameters that are often found in Tier 3 process-based models. Consequently, the data and resource requirements are considerably less intensive than typical process-based model applications (See examples in Box 2.2d, Chapter 2, Volume IV).

The Tier 2 steady state method introduces additional interannual variation into the final results compared to Tier 1, by representing the impact of drivers such as weather on C inputs to soils and losses associated with decomposition of soil organic matter. Using this method may require additional quality assurance, quality control and verification (see Volume 1, Chapter 6, Section 6.11).

BOX 5.1B (NEW)
DESCRIPTION OF THE TIER 2 STEADY STATE METHOD FOR ESTIMATING MINERAL SOIL ORGANIC CARBON STOCK CHANGES

The Tier 2 steady-state method is adapted from the Century Ecosystem Model (Parton *et al.* 1987) and estimates changes in soil organic C for the top 30cm of the soil profile. In this model, the stock of the soil carbon sub-pools is initialised by running the model with climate and carbon input data associated for a period of 5-20 years prior to the start of the inventory (or longer if data are available). A proportion of biomass C (C input to the soil) is transferred to soil litter, and then divided into fraction, β, that goes to metabolic components with the remaining fraction (C_{input}- β) going to structural components [1]. The structural component is composed of more recalcitrant, ligno-cellulose plant materials. The metabolic component is composed of more readily decomposed organic matter. Decomposition products are transferred according to calculated fractional transfer coefficients (f_1 to f_8) to and between three soil organic matter sub-pools, active, slow and passive. The active sub-pool is microbial (bacteria and fungi) biomass and associated metabolites with a rapid turnover (months to years), the slow sub-pool has intermediate stability and turnover (decades), and the passive sub-pool is mineral-protected C and microbial decomposition products with long turnover times (centuries). Irrespective of the turnover time the approach is used to estimate the stock of each sub-pool and how they change over time. The total soil organic carbon stock and stock change is calculated as the sum of the values derived for each sub-pool.



Decomposition rates for sub-pools depend on the decay rate constants, temperature effects, and moisture effects. Decomposition of the active and slow sub-pools is also influenced by the soil texture (sand content) and tillage practice. Sub-pools with longer turnover times imply that the C remains in the soil for more years before the organic matter is decomposed and carbon is respired as CO_2 by the soil decomposer community. As decomposition occurs in each sub-pool, some of the decomposing C is transferred to other sub-pools and components (arrows in the diagram) and some of the C is converted into CO_2 and lost from the soil (not identified with arrows). The transfer of C to the next sub-pool or component at steady state is determined by the transfer coefficients (f). Higher transfer coefficients imply that more of the C is transferred to the next sub-pool or component rather than converted into CO_2. The steady-state solution for this model is discussed further in Paustian *et al*. (1997) and Ogle *et al*. (2012).

[1] This approach is not intended to be used for estimation of dead organic matter. Compilers should apply the dead organic matter methods in section 5.2.2.

The land base is stratified as fine as possible to include the spatial variation in climate, soil properties, irrigation, and tillage practices. However, there will be practical limits to the level of stratification given the resolution of data and national circumstances for inventory compilation. The method can be applied by subdividing the country into grid cells or regions, such as counties, districts or municipalities. Each grid cell or region would contain a single combination of climate, soil properties and tillage practices and have an area of land assigned to the unit. Within each grid cell or region, the compiler will determine the C input using country-specific equations, or alternatively a generic equation can be used (Equation 5.0h). Compilers will also need values for the parameters defining the quality of the C input (lignin and nitrogen content) or use generic values available in Tables 5.5b and 5.5c. The type of tillage applied within each grid cell or region will need to be compiled to determine the correct value for tillage parameter. Monthly average temperature, precipitation and potential evapotranspiration is needed for each grid cell or region. This information is available from global datasets, such as the Climatic Research Unit (CRU) climate dataset[3], if country-specific data are not available. The average sand content is needed for each grid cell or region, which is available from Harmonized World Soil Database[4] or from Soil Grids[5], if country-specific data are not available. If global data sources are used, it is important to understand and acknowledge the uncertainty associated with these data products to estimate confidence intervals for the resulting changes in soil C stocks.

The following sections provide the equations and steps involved with application of the method within a grid cell or region (e.g., counties, districts or municipalities). The equations estimate water and temperature effects on decomposition; the size of the active, slow and passive soil carbon sub-pools; and the change in total SOC. The values of default parameters are given in Table 5.5a. All constants in the equations are considered globally applicable and should not be altered when applying this Tier 2 steady-state method. The change in soil C stock is calculated annually, multiplied by the area of the grid cell or region and the product summed across all grid cells or regions to determine the annual inventory soil C stock change.

Equations for the Tier 2- Steady State Method for Mineral Soils

Calculate SOC Stock Changes

The change in SOC stock is calculated using Equation 5.0a.

EQUATION 5.0A (NEW)
ANNUAL CHANGE IN SOIL C STOCK FOR MINERAL SOILS USING THE STEADY STATE METHOD

$$\Delta C_{Mineral} = \sum_i F_{SOC_i} \bullet A_i$$

$$F_{SOC_i} = SOC_{yi} - SOC_{(y-1)i}$$

$$SOC_{yi} = ACTIVE_{yi} + SLOW_{yi} + PASSIVE_{yi}$$

Where:

$\Delta C_{Mineral}$ = annual SOC stock change factor for mineral soil, summed across all i grid cells or regions, tonnes C

F_{SOC_i} = annual stock change factor for mineral soils in grid cell or region i, tonnes C ha^{-1}

A_i = Area of grid cell or region i, ha

SOC_{yi} = SOC stock at the end of the current year y for grid cell or region i , tonnes C ha^{-1}

$SOC_{(y-1)i}$ = SOC stock at the end of the previous year for grid cell or region i, tonnes C ha^{-1}

$ACTIVE_{yi}$ = active sub-pool SOC stock in year y for grid cell or region i, tonnes C ha^{-1} (see Equation 5.0b)

$SLOW_{yi}$ = slow sub-pool SOC stock in year y for grid cell or region i, tonnes C ha^{-1} (see Equation 5.0c)

$PASSIVE_{yi}$ = passive sub-pool SOC stock in year y for grid cell or region i, tonnes C ha^{-1} (see Equation 5.0d)

[3] https://crudata.uea.ac.uk/cru/data/hrg/ (23/10/2018)

[4] http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/ (23/10/2018)

[5] https://soilgrids.org/#!/?layer=TAXNWRB_250m&vector=1 (23/10/2018)

All subsequent equations associated with the steady state method (Equations 5.0b – 5.0g) are to be completed separately using data derived for each grid cell or region to yield values specific to the grid cell or region. The subscripts i have been left off the equations to simplify the presentation of the equations. All calculations denoted in Equations 5.0b – 5.0g will need to be completed for each individual grid cell or region included in the inventory process.

Calculate the size of the Active SOC Sub-pool

The size of the active SOC sub-pool is calculated using Equation 5.0b. The calculations for each sub-pool

EQUATION 5.0B (NEW)
ACTIVE SUB-POOL SOIL C STOCK FOR MINERAL SOILS USING THE STEADY-STATE METHOD

$$ACTIVE_y = ACTIVE_{y-1} + \left(ACTIVE_{y^*} - ACTIVE_{y-1}\right) \bullet 1yr \bullet k_a$$

$$ACTIVE_{y^*} = \frac{\alpha}{k_a}$$

$$k_a = k_{fac_a} \bullet t_{fac} \bullet w_{fac} \bullet \left(0.25 + \left(0.75 \bullet sand\right)\right) \bullet till_{fac}$$

Where:

$ACTIVE_y$ = active sub-pool SOC stock in year y, tonnes C ha^{-1}

$ACTIVE_{y-1}$ = active sub-pool SOC stock in previous year, tonnes C ha^{-1}

$ACTIVE_{y^*}$ = steady state active sub-pool SOC stock given conditions in year y, tonnes C ha^{-1}

k_a = decay rate for active SOC sub-pool, year^{-1}

α = C input to the active SOC sub-pool, tonnes C ha^{-1} year^{-1} (see Equation 5.0g)

k_{fac_a} = decay rate constant under optimal conditions for decomposition of the active SOC sub-pool, year^{-1} (see Table 5.5a)

t_{fac} = temperature effect on decomposition, dimensionless (see Equation 5.0e)

w_{fac} = water effect on decomposition, dimensionless (see Equation 5.0f)

$till_{fac}$ = tillage disturbance modifier on decay rate for active and slow sub-pools, dimensionless (see Table 5.5a)

$sand$ = fraction of 0-30 cm soil mass that is sand (0.050 – 2mm particles), dimensionless

NOTE: If the estimated k_a value is above 1, then set the value of k_a to 1 in the equation for calculating $ACTIVE_y$ in the first equation. The '1 year' designation in the equation is because the model is applied to estimate changes over a single year, which is needed so that units cancel appropriately in the calculation.

Calculate the size of the Slow SOC Sub-pool

The size of the slow SOC sub-pool is calculated using Equation 5.0c.

EQUATION 5.0C (NEW)
SLOW SUB-POOL SOIL C STOCK FOR MINERAL SOILS USING THE STEADY-STATE METHOD

$$SLOW_y = SLOW_{y-1} + \left(SLOW_{y^*} - SLOW_{y-1}\right) \bullet 1yr \bullet k_s$$

$$SLOW_{y^*} = \frac{[\left(C_{input} \bullet LC\right) \bullet f_3] + \left[\left(ACTIVE_{y^*} \bullet k_a\right) \bullet f_4\right]}{k_s}$$

$$k_s = k_{fac_s} \bullet t_{fac} \bullet w_{fac} \bullet till_{fac}$$

$$f_4 = 1 - f_5 - \left(0.17 + 0.68 \bullet \ sand\right)$$

Where:

$SLOW_y$ = slow sub-pool SOC stock in y, tonnes C ha^{-1}

$SLOW_{y-1}$ = slow sub-pool SOC stock in previous year, tonnes C ha^{-1}

$SLOW_{y^*}$ = steady state slow sub-pool SOC stock given conditions in year y, tonnes C ha^{-1}

k_s = decay rate for slow SOC sub-pool, year^{-1}

C_{input} = total carbon input, tonnes C ha^{-1} year^{-1}

LC = lignin content of carbon input, proportion (see Table 5.5b and 5.5c) for default values, otherwise compile country-specific values)

$ACTIVE_{y^*}$ = steady state active sub-pool SOC stock given conditions in year y, tonnes C ha^{-1}

k_a = decay rate for active carbon sub-pool in the soil, year^{-1}

k_{fac_s} = decay rate constant under optimal condition for decomposition of the slow carbon sub-pool, year^{-1} (see Table 5.5a)

t_{fac} = temperature effect on decomposition, dimensionless (see Equation 5.0e)

w_{fac} = water effect on decomposition, dimensionless (see Equation 5.0f)

$till_{fac}$ = tillage disturbance modifier on decay rate for active and slow sub-pools, dimentionless (see Table 5.5a)

f_3 = fraction of structural component decay products transferred to the slow sub-pool, proportion (see Table 5.5a)

f_4 = fraction of active sub-pool decay products transferred to the slow sub-pool, proportion (see Equation 5.0c)

f_5 = fraction of active sub-pool decay products transferred to the passive sub-pool, proportion (see Table 5.5a)

$sand$ = fraction of 0-30 cm soil mass that is sand (0.050 – 2mm particles), proportion

NOTE: If the estimated k_s value is above 1, then set the value of k_s to 1 in the equation for calculating $SLOW_y$ in the first equation. The '1 year' designation in the equation is because the model is applied to estimate changes over a single year, which is needed so that units cancel appropriately in the calculation.

Calculate the size of the Passive C Sub-pool

The size of the slow SOC sub-pool is calculated using Equation 5.0d.

EQUATION 5.0D (NEW)
PASSIVE SUB-POOL SOIL C STOCK FOR MINERAL SOILS USING THE STEADY-STATE METHOD

$$PASSIVE_y = PASSIVE_{y-1} + \left(PASSIVE_{y^*} - PASSIVE_{y-1}\right) \bullet 1yr \bullet k_p$$

$$PASSIVE_{y^*} = \frac{\left[\left(ACTIVE_{y^*} \bullet k_a\right) \bullet f_5\right] + \left[\left(SLOW_{y^*} \bullet k_s\right) \bullet f_6\right]}{k_p}$$

$$k_P = k_{fac_p} \bullet t_{fac} \bullet w_{fac}$$

Where:

$PASSIVE_y$ = passive sub-pool SOC stock in year y, tonnes C ha^{-1}

$PASSIVE_{y-1}$ = passive sub-pool SOC stock in previous year, tonnes C ha^{-1}

$PASSIVE_{y^*}$ = steady state passive sub-pool SOC given conditions in year y, tonnes C ha^{-1}

k_P = decay rate for passive SOC sub-pool, year^{-1}

$ACTIVE_{y^*}$ = steady state active sub-pool SOC stock given conditions in year y, tonnes C ha^{-1}

k_a = decay rate for active carbon sub-pool, year^{-1}

$SLOW_{y^*}$ = steady state slow sub-pool SOC stock given conditions in year y, tonnes C ha^{-1}

k_s = decay rate for slow carbon sub-pool, year^{-1}

k_{fac_p} = decay rate constant under optimal conditions for decomposition of the slow carbon sub-pool, year^{-1} (see Table 5.5a)

t_{fac} = temperature effect on decomposition, dimensionless (see Equation 5.0e)

w_{fac} = water effect on decomposition, dimensionless (see Equation 5.0f)

f_5 = fraction of active sub-pool decay products transferred to the slow sub-pool, proportion(see Table 5.5a)

f_6 = fraction of slow sub-pool decay products transferred to the passive sub-pool, proportion(see Table 5.5a)

NOTE: If the estimated k_p value is above 1, then set the value of k_p to 1 in the equation for calculating $PASSIVE_y$ in the first equation. The '1 year' designation in the equation is because the model is applied to estimate changes over a single year, which is needed so that units cancel appropriately in the calculation.

Calculate Temperature Effect on Decomposition

Calculate the temperature effect on soil organic matter decomposition using Equation 5.0e.

EQUATION 5.0E (NEW)
TEMPERATURE EFFECT ON DECOMPOSITION FOR MINERAL SOILS USING THE STEADY-STATE METHOD

$$t_{fac} = \frac{1}{12}\sum_{i=1}^{12} T_i$$

$$T_i = \left(\frac{t_{max} - temp_i}{t_{max} - t_{opt}}\right)^{0.2} \bullet exp\left\{0.076 \bullet \left[1 - \left(\frac{t_{max} - temp_i}{t_{max} - t_{opt}}\right)^{2.63}\right]\right\}$$

Where:

t_{fac} = annual average air temperature effect on decomposition, dimensionless

T_i = monthly average air temperature effect on decomposition, dimensionless (i = 1, 2, …, 12)

t_{max} = maximum monthly air temperature for decomposition, degrees C (see Table 5.5a)

$temp_i$ = monthly average air temperature (i = 1, 2, …, 12), degrees C

t_{opt} = optimum air temperature for decomposition, degrees C (see Table 5.5a)

NOTE: When the monthly average air temperature is greater than 45 °C (i.e., the maximum average air temperature) set T_i to 0.

Calculate Water Effect on Decomposition

Estimate the water effect on soil organic matter decomposition using Equation 5.0f

EQUATION 5.0F (NEW)
WATER EFFECT ON DECOMPOSITION FOR MINERAL SOILS USING THE STEADY-STATE METHOD

$$w_{fac} = 1.5 \bullet \left(\frac{1}{12}\sum_{i=1}^{12} w_i\right)$$

$$w_i = 0.2129 + \left(w_s \bullet mappet_i\right) - \left(0.2413 \bullet mappet_i^{\,2}\right)$$

$$mappet_i = \min\left(1.25, \frac{precip_i}{PET_i}\right)$$

Where:

w_{fac} = annual water effect on decomposition, dimensionless

w_i = monthly water effect on decomposition, dimensionless

w_s = modifier for $mappet_i$, dimensionless (see Table 5.5a)

$mappet_i$ = ratio of total precipitation to total potential evapotranspiration (dimensionless) for month i (i = 1, 2, …12)

$precip_i$ = total precipitation for month i, mm

PET_i = total potential evapotranspiration for month i, mm

NOTE: If the $mappet_i$ is >1.25, then set the value of $mappet_i$ for the month to 1.25 for non-irrigated system (i.e., $mappet_i$ does not exceed 1.25). Set w_i for months with irrigation to 0.775.

Calculate C Input to the Active Sub-pool

Calculate alpha value using Equation 5.0g, which is the C input to the active SOC sub-pool.

EQUATION 5.0G (NEW)
C INPUT TO THE ACTIVE SOIL C SUB-POOL FOR MINERAL SOILS USING THE STEADY-STATE METHOD

$$\alpha = \frac{[\beta \bullet f_1] + \left[\left(C_{input} \bullet (1 - LC) - \beta\right) \bullet f_2\right] + \left[\left(C_{input} \bullet LC\right) \bullet f_3 \bullet (f_7 + f_6 \bullet f_8)\right]}{1 - (f_4 \bullet f_7) - (f_5 \bullet f_8) - (f_4 \bullet f_6 \bullet f_8)}$$

$$\beta = C_{input} \bullet \left[0.85 - 0.018 \bullet \left(\frac{LC}{NC}\right)\right]$$

Where:

α = C input to the active soil carbon sub-pool, tonnes C ha^{-1}

β = C input to the metabolic dead organic matter C component, tonnes C ha^{-1} year^{-1}

C_{input} = total carbon input, tonnes C ha^{-1}year^{-1}

f_1 = fraction of metabolic dead organic matter decay products transferred to the active sub-pool, proportion (see Table 5.5a)

f_2 = fraction of structural dead organic matter decay products transferred to the active sub-pool, proportion (see Table 5.5a)

f_3 = fraction of structural dead organic matter decay products transferred to the slow sub-pool, proportion (see Table 5.5a)

f_4 = fraction of active sub-pool decay products transferred to the slow sub-pool, proportion, (see Equation 5.0c)

f_5 = fraction of active sub-pool decay products transferred to the passive sub-pool, proportion (see Table 5.5a)

f_6 = fraction of slow sub-pool decay products transferred to the passive sub-pool, proportion (see Table 5.5a)

f_7 = fraction of slow sub-pool decay products transferred to the active sub-pool, proportion (see Table 5.5a)

f_8 = fraction of passive sub-pool decay products transferred to the active sub-pool, proportion (see Table 5.5a)

LC = lignin content of carbon input, proportion (see Tables 5.5b and 5.5c for default values, otherwise compile country-specific values)

NC = nitrogen fraction of the carbon input, proportion (see Tables 5.5b and 5.5c) for default values, otherwise compile country-specific values)

Table 5.5A provides the default parameters, minimum and maximum values for parameters, and their associated standard deviation. The probability distribution functions for the parameters should be constructed as truncated normal distributions, in which parameter values lower than the minimum value are constrained the minimum value, and parameter values greater than the maximum values are constrained to the maximum value. Uncorrelated draws from the probability distribution functions of the parameters can be made using the data in this table, but more robust estimates of uncertainty can be made using a truncated joint probability distribution with the parameter covariance matrix found in Annex 2A.3

Step-by-Step procedure for implementing the Tier2 steady-state method for Mineral Soils

Steps 1 to 8 are conducted for each grid cell or region, depending on the spatial unit of the inventory. Step 9 sums the changes across the entire spatial domain[6].

Step 1. Calculate the Initial Stocks of the Active, Slow and Passive SOC sub-pools

The initial stocks are calculated based on the climatic, soil texture, management and carbon input data for a run-in period[7] of 5 to 20 years (more years may be used if data are available).

Step 1.1: Calculate the average annual values of t_{fac} (Equation 5.0e) and w_{fac} (Equation 5.0f) for the run-in period.

Step 1.2: Calculate the C input to the active sub-pool (α) for the run-in period (Equation 5.0g) using the following data:

a. the average annual carbon input (C_{input}) for the run-in period, which may be estimated with Equation 5.0h if country-specific methods are not available,
b. the appropriate values for *LC* and *NC* for the crop and/or grass in place during the run-in period can be found in the Tier2 steady-state method section for cropland (see Section 5.2.3.2 for cropland default values, otherwise compile country-specific values),
c. the value of f_2 from Table 5.5a, and
d. the sand content of the 0-30 cm soil layer ($sand$).

Step 1.3: Calculate the values of k_a (Equation 5.0b), k_s (Equation 5.0c) and k_p (Equation 5.0d) using:

a. the average values of t_{fac} and w_{fac} calculated in Step 1.1,
b. the values of k_{fac_a} , k_{fac_s} , k_{fac_p} and the appropriate tillage factor ($till_{fac}$) from Table 5.5A, and
c. the sand content of the 0-30 cm soil layer ($sand$).

Step 1.4: Calculate the values for $ACTIVE_{y*}$ (Equation 5.0b), $SLOW_{y*}$ (Equation 5.0c) and $PASSIVE_{y*}$ (Equation 5.0d) for the run-in period, which become the initial SOC stocks for the ACTIVE, SLOW and PASSIVE SOC sub-pools at the commencement of the inventory period.

Step 2. Calculate C Input to the Active Sub-pool for each year of the inventory period

Calculate value of α (the C input to the active SOC sub-pool) for each year in the inventory period using Equation 5.0g.

Step 2.1: Calculate the C input to the metabolic dead organic matter component (β).

Step 2.2: Calculate the C input to the active soil carbon sub-pool (α).

Step 2.3: Repeat Steps 2.1 to 2.2 for all other years in the inventory period to derive annual values for β and α .

Step 3. Calculate Water Effect on Decomposition

Estimate the water effect on soil organic matter decomposition using Equation 5.0f.

Step 3.1: For each month in a year, calculate the ratio of total precipitation to total potential evapotranspiration.

a. If the ratio is ≤1.25 then set the value of $mappet_i$ for the month to the estimated ratio.
b. If the ratio is >1.25 then set the value of $mappet_i$ for the month to 1.25.
c. Set w_i for months with irrigation to 0.775.

Step 3.2: Calculate water effect on decomposition for each month (w_i) in a year. For land area under irrigation management, set the water effect on decomposition for the month (w_i) to 0.775.

Step 3.3: Calculate the annual water effect on decomposition (w_{fac}).

[6]An example of the Tier 2 steady state method is provided in a supplementary file, V4_Ch5_Tier2_Steady_State_Method.xlsx

[7] Compilers can use longer run-in periods than 20 years to establish the initial soil organic C stocks for the inventory, but 5 years is considered a minimum period of time for this method. Initial values of the active, slow and passive pools can lead to biases in results if the run-in period is not long enough to capture the trajectory of the stocks based on legacy effects associated with historical land use and management.

Step 3.4: Repeat steps 3.1 to 3.3 to calculate the water effect (w_{fac}) on decomposition for all years in the inventory period.

Step 4. Calculate Temperature Effect on Decomposition

Calculate the temperature effect on soil organic matter decomposition using Equation 5.0e.

Step 4.1: For each month in a year, calculate temperature effect on decomposition (T_i) using the values for maximum monthly temperature for decomposition (t_{max}), optimum temperature for decomposition (t_{opt}) and the monthly average temperature ($temp_i$).

a. If the monthly average temperature is ≤45 °C, use the calculated value of T_i .

b. If the monthly average temperature is >45 °C, set T_i equal to 0.

Step 4.2: Calculate annual temperature effect on decomposition (t_{fac}).

Step 4.3: Repeat steps 4.1 and 4.2 to calculate the annual temperature effect on decomposition for all years in the inventory.

Step 5. Calculate the size of the Passive C Sub-pool

Calculate the size of the passive sub-pool using Equation 5.0d.

Step 5.1: Calculate decay rate for the PASSIVE SOC sub-pool in the soil *(* k_p).

Step 5.2: Calculate the steady state stock for the PASSIVE sub-pool SOC stock ($PASSIVE_{y^*}$).

Step 5.3: Calculate the PASSIVE sub-pool SOC stock by determining the additional increase or decrease in SOC from the previous year in the inventory ($PASSIVE_y$). Note that the initial size of the PASSIVE SOC sub-pool used at the start of the inventory period is calculated as defined in step 1. Note also that if the estimated k_p value is above 1, then set the value of k_p to 1 in the equation for calculating $PASSIVE_y$.

Step 5.4: Repeat steps 5.1 to 5.3 to calculate the PASSIVE SOC stocks for all years in the inventory.

Step 6. Calculate the size of the SLOW SOC Sub-pool

Calculate the size of the slow sub-pool using Equation 5.0c.

Step 6.1: Calculate decay rate for SLOW SOC sub-pool in the soil (k_s).

Step 6.2: Calculate the steady state stock for the SLOW SOC sub-pool ($SLOW_{y^*}$).

Step 6.3: Calculate the SLOW SOC stock by determining the additional increase or decrease in SOC from the previous year in the inventory ($SLOW_y$ **).** Note that the initial size of the SLOW SOC sub-pool used at the start of the inventory period is calculated as defined in step 1. Note also that if the estimated k_s value is above 1, then set the value of k_s to 1 in the equation for calculating $SLOW_y$ **).**

Step 6.4: Repeat steps 6.1 to 6.3 to calculate the SLOW SOC sub-pool stocks for all years in the inventory.

Step 7. Calculate the size of the ACTIVE SOC Sub-pool

Calculate the size of the active sub-pool using Equation 5.0b.

Step 7.1: Calculate decay rate for the ACTIVE SOC sub-pool in the soil (k_a).

Step 7.2: Calculate the steady state stock for the ACTIVE SOC sub-pool ($ACTIVE_{y^*}$).

Step 7.3: Calculate the ACTIVE SOC stock by determining the additional increase or decrease in SOC from the previous year in the inventory ($ACTIVE_y$). Note that the initial size of the ACTIVE SOC sub-pool used at the start of the inventory period is calculated as defined in step 1. Also note that if the estimated k_a value is above 1, then set the value of k_a to 1 in the equation for calculating ($ACTIVE_y$).

Step 7.4: Repeat Steps 7.1 to 7.3 to calculate the ACTIVE SOC sub-pool stocks for all years in the inventory.

Step 8. Calculate the total annual SOC stock change

Step 8.1: Calculate the SOC stock (SOC_y) for each grid cell or region by summing the SOC in the ACTIVE, SLOW and PASSIVE sub-pools ($ACTIVE_y$, $SLOW_y$ and $PASSIVE_y$, respectively) using Equation 5.0a.

Step 8.2: Calculate the stock change factor (F_{SOC_i}) for each grid cell or region using Equation 5.0a.

Step 8.3: Calculate the total change in SOC stock ($\Delta C_{Mineral}$) using Equation 5.0a by multiplying the stock change factor (F_{SOC_i}) by the area of the grid cell or region i (A), and summing the changes across all land included in the Tier 2 steady-state method.

Tier 3

Tier 3 approaches may use dynamic models and/or detailed soil C inventory measurements as the basis for estimating annual stock changes. Estimates from models are computed using coupled equations that estimate the net change of soil C. A variety of models exist (e.g., see reviews by McGill *et al.* 1996; and Smith *et al.* 1997). Key criteria in selecting an appropriate model include its capability of representing all of the relevant management practices/systems for croplands; model inputs (i.e., driving variables) are compatible with the availability of country-wide input data; and verification against experimental data.

A Tier 3 approach may also be developed using a measurement-based approach in which a monitoring network is sampled periodically to estimate soil organic C stock changes. A much higher density of benchmark sites will likely be needed than with models to represent adequately the combination of land-use and management systems, climate, and soil types. Additional guidance is provided in Section 2.3.3.1 of Chapter 2.

For biochar C amendments to soils, Tier 3 methods can be used to address GHG sources and sinks not captured in Tiers 1 or 2, such as priming effects, changes to N_2O or CH_4 fluxes from soils, and changes to net primary production. More information on Tier 3 methods is provided in Section 2.3.3.1 of Chapter 2, Volume IV.

Organic soils

No refinement.

The *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* provides additional guidance that updates the *2006 IPCC Guidelines for national Greenhouse Gas Inventories*. See section 2.2 of the *2013 Wetlands Supplement covers Tier 1, 2, and 3 approaches for drained organic soils in cropland.*

5.2.3.2 CHOICE OF STOCK CHANGE AND EMISSION FACTORS

Mineral soils

Tier 1

Table 5.5 provides Tier 1 approach default stock change factors for land use (F_{LU}), input (F_I) and management (F_{MG}). The method and studies that were used to derive the default stock change factors are provided in Annex 5A.1 and References. The default time period for stock changes (D) is 20 years and management practice is assumed to influence stocks to a depth of 30 cm, which is also the depth for the reference soil C stocks in Table 2.3 (Chapter 2).

Tier 2

Developing Country-Specific Factors for the Default Equations

A Tier 2 approach entails the estimation of country-specific stock change factors. Derivation of input (F_I) and management factors (F_{MG}) are based on comparisons to medium input and intensive tillage, respectively, because they are considered the nominal practices in the IPCC default management classification (see Choice of Activity Data). It is *good practice* to derive values for a higher resolution classification of management, climate and soil types if there are significant differences in the stock change factors among more disaggregated categories based on an empirical analysis and/or well tested model. Additional guidance is provided in Chapter 2, Section 2.3.3.1.

TABLE 5.5 (UPDATED)
RELATIVE CARBON STOCK CHANGE FACTORS (F_{LU}, F_{MG}, AND F_I) (OVER 20 YEARS) FOR MANAGEMENT ACTIVITIES ON CROPLAND

Factor value type	Level	Temperature regime	Moisture regime[1]	IPCC defaults	Error [2,3]	Description
Land use[5] (F_{LU})	Long-term cultivated	Cool Temperate/ Boreal	Dry	0.77	±14%	Represents area that has been converted from native conditions and continuously managed for predominantly annual crops over 50 yrs. Land-use factor has been estimated under a baseline condition of full tillage and nominal ('medium") carbon input levels. Input and tillage factors are also applied to estimate carbon stock changes, which includes changes from full tillage and medium input.
			Moist	0.70	±12%	
		Warm Temperate	Dry	0.76	±12%	
			Moist	0.69	±16%	
		Tropical	Dry	0.92	±13%	
			Moist/Wet	0.83	±11%	
Land use[6] (F_{LU})	Paddy rice	All	Dry and Moist/Wet	1.35	±4%	Long-term (> 20 year) annual cropping of wetlands (paddy rice). Can include double-cropping with non-flooded crops. For paddy rice, tillage and input factors are not used.
Land use[5] (F_{LU})	Perennial/ Tree Crop	Temperate/ Boreal	Dry and Moist	0.72	±22%	Long-term perennial tree crops such as fruit and nut trees, coffee and cacao.
		Tropical	Dry and Moist/Wet	1.01	±25%	
Land use (F_{LU})	Set aside (< 20 yrs)	Temperate/ Boreal and Tropical	Dry	0.93	±11%	Represents temporary set aside of annually cropland (e.g., conservation reserves) or other idle cropland that has been revegetated with perennial grasses.
			Moist/Wet	0.82	±17%	
		Tropical montane[44]	n/a	0.88	±50%	
Tillage (F_{MG})	Full	All	Dry and Moist/Wet	1.00	n/a	Substantial soil disturbance with full inversion and/or frequent (within year) tillage operations. At planting time, little (e.g., <30%) of the surface is covered by residues.
Tillage[7] (F_{MG})	Re-duced	Cool Temperate/ Boreal	Dry	0.98	±5%	Primary and/or secondary tillage but with reduced soil disturbance (usually shallow and without full soil inversion). Normally leaves surface with >30% coverage by residues at planting.
			Moist	1.04	±4%	
		Warm Temperate	Dry	0.99	±3%	
			Moist	1.05	±4%	
		Tropical	Dry	0.99	±7%	
			Moist/Wet	1.04	±7%	
Tillage[7] (F_{MG})	No-till	Cool Temperate/ Boreal	Dry	1.03	±4%	Direct seeding without primary tillage, with only minimal soil disturbance in the seeding zone. Herbicides are typically used for weed control.
			Moist	1.09	±4%	
		Warm Temperate	Dry	1.04	±3%	
			Moist	1.10	±4%	
		Tropical	Dry	1.04	±7%	
			Moist/Wet	1.10	±5%	

TABLE 5.5 (UPDATED) (CONTINUED)
RELATIVE CARBON STOCK CHANGE FACTORS (F_{LU}, F_{MG}, AND F_I) (OVER 20 YEARS) FOR MANAGEMENT ACTIVITIES ON CROPLAND

Factor value type	Level	Temper-ature regime	Moisture regime[1]	IPCC defaults	Error [2,3]	Description
Input (F_I)	Low	Temperate/ Boreal	Dry	0.95	±13%	Low residue return occurs when there is removal of residues (via collection or burning), frequent bare-fallowing, production of crops yielding low residues (e.g., vegetables, tobacco, cotton), no mineral fertilization or N-fixing crops.
			Moist	0.92	±14%	
		Tropical	Dry	0.95	±13%	
			Moist/ Wet	0.92	±14%	
		Tropical montane[4]	n/a	0.94	±50%	
Input (F_I)	Mediu m	All	Dry and Moist/ Wet	1.00	n/a	Representative for annual cropping with cereals where all crop residues are returned to the field. If residues are removed then supplemental organic matter (e.g., manure) is added. Also requires mineral fertilization or N-fixing crop in rotation.
Input (F_I)	High without manure	Temperate/ Boreal and Tropical	Dry	1.04	±13%	Represents significantly greater crop residue inputs over medium C input cropping systems due to additional practices, such as production of high residue yielding crops, use of green manures, cover crops, improved vegetated fallows, irrigation, frequent use of perennial grasses in annual crop rotations, but without manure applied (see row below).
			Moist/ Wet	1.11	±10%	
		Tropical montane[4]	n/a	1.08	±50%	
Input (F_I)	High – with manure	Temperate/ Boreal and Tropical	Dry	1.37	±12%	Represents significantly higher C input over medium C input cropping systems due to an additional practice of regular addition of animal manure.
			Moist/ Wet	1.44	±13%	
		Tropical montane[4]	n/a	1.41	±50%	

Notes: Long-term cultivation, perennial crops paddy rice and tillage management factors were derived using methods provided in Annex 5A1.

[1]Where data were sufficient, separate values were determined for temperate and tropical temperature regimes; and dry, moist, and wet moisture regimes. Temperate and tropical zones correspond to those defined in Chapter 3; wet moisture regime corresponds to the combined moist and wet zones in the tropics and moist zone in temperate regions.

[2]± two standard deviations, expressed as a percent of the mean; where sufficient studies were not available for a statistical analysis to derive a default, uncertainty was assumed to be ± 50% based on expert opinion. NA denotes 'Not Applicable', where factor values constitute defined reference values, and the uncertainties are reflected in the reference C stocks and stock change factors for land use.

[3] This error range does not include potential systematic error due to small sample sizes that may not be representative of the true impact for all regions of the world.

[4]There were not enough studies to estimate some of the stock change factors for mineral soils in the tropical montane climate region. As an approximation, the average stock change between the temperate and tropical regions was used to approximate the stock change for the tropical montane climate.

Sources:

[5] The following references used for land-use factors (other than paddy rice): Aborisade and Aweto 1990; Adachi *et al.* 2006; Agbenin and Goladi 1997; Aina 1979; Alcantara *et al.* 2004; Allen 1985; An *et al.* 2003; Ashagrie *et al.* 2005; Assad *et al.* 2013; Aweto 1981; Aweto and Ayuba 1988; Aweto and Ayuba 1993; Aweto and Ishola 1994; Ayanaba *et al.* 1976; Banaticla and Lasco 2006; Bashkin and Binkley 1998; Batlle-Bayer *et al.* 2010; Bautista-Cruz and del Castillo 2005; Berhongaray *et al.* 2013; Bernardi *et al.* 2007; Bernhardreversat 1988; Berthrong *et al.* 2012; Bertol and Santos 1995; Beyer 1994; Binkley *et al.* 2004; Binkley and Resh 1999; Bonde *et al.* 1992; Bowman and Anderson 2002; Brand and Pfund 1998; Brown and Lugo 1990; Bruun *et al.* 2006; Burke *et al.* 1995; Burke *et al.* 1995; Buschbacher *et al.* 1988; Buschiazzo *et al.* 1998; Buyanovksy *et al.* 1987; Cadisch *et al.* 1996; Cai *et al.* 2008; Cambardella and Elliott 1994; Cambardella and Elliott 1992; Campos *et al.* 2007; Cao *et al.* 2004; Carvalho *et al.* 2009; Carvalho *et al.* 2009; Cerri *et al.* 1991; Cerri *et al.* 2003; Cerri *et al.* 2007; Chan 1997; Chandran *et al.* 2009; Chen *et al.* 2007; Chen 2006; Chia *et al.* 2017; Chidumayo and Kwibisa 2003; Chiti *et al.* 2014; Chone *et al.* 1991; Cleveland *et al.* 2003; Collins *et al.* 1999; Conant *et al.* 2001; Conti *et al.* 2014; Cook *et al.* 2014; Corazza *et al.* 1999; D'Annunzio *et al.* 2008; da Silva-Junior *et al.* 2009; Dai *et al.* 2008a; Dai *et al.* 2008b; Dalal *et al.* 2005; Dalal and Mayer 1986; Dawoe *et al.* 2014; de Blecourt *et al.* 2013; de Camargo *et al.* 1999; de Freitas *et al.* 2000; de Koning *et al.* 2003; de Moraes *et al.* 2002; de Moraes *et al.* 1996; de Neergaard *et al.* 2008; Dechert *et al.* 2004; Delelegn *et al.* 2017; Denef *et al.* 2007; Desjardins *et al.* 1994; Desjardins *et al.* 2004; Detwiler 1986; Eaton and Lawrence 2009; Eclesia *et al.* 2012; Eden *et al.* 1990; Ekanade 1991; Elliott *et al.* 1991; Elmore and Asner 2006; England *et al.* 2016; Epron *et al.* 2009; Erickson *et al.* 2001; Fabrizzi *et al.* 2009; Farley *et al.* 2004; Feldpausch *et al.* 2004; Feller *et al.* 2001; Fernandes *et al.* 2002; Fernandez *et al.* 2012; Fisher *et al.* 1994; Follett *et al.* 1997; Freibauer 1996; Freixo *et al.* 2002; Fu *et al.* 2000; Fu *et al.* 2001; Han *et al.* 2004; Han *et al.* 2005; Harden *et al.* 1999; Hölscher *et al.* 1997; Hou *et al.* 2008;

TABLE 5.5 (UPDATED) (CONTINUED) **RELATIVE CARBON STOCK CHANGE FACTORS (F_{LU}, F_{MG}, AND F_I) (OVER 20 YEARS) FOR MANAGEMENT ACTIVITIES ON CROPLAN**
Hsieh 1996; Hu *et al.* 2007; Huang *et al.* 2007; Hughes *et al.* 2000; Hughes *et al.* 2002; Hughes *et al.* 2000; Ihori *et al.* 1995; Ishizuka *et al.* 2005; Islam and Weil 2000; Jakelaitis *et al.* 2008; Janssen and Wienk 1990; Jaramillo *et al.* 2003; Jia *et al.* 2004; Jia *et al.* 2007; Jimenez *et al.* 2007; Jun and Liqing 2007; Juo *et al.* 1995; Juo and Lal 1977; Juo and Lal 1979; Kainer *et al.* 1998; Karhu *et al.* 2011; Kawanabe *et al.* 2000; Keith *et al.* 2015; King and Campbell 1994; Kotto-Same *et al.* 1997; Koutika *et al.* 1997; Krishnaswamy and Richter 2002; Lal 1998; Lemenih *et al.* 2005; Lemenih *et al.* 2005; Lemma *et al.* 2006; Lepsch *et al.* 1994; Li *et al.* 2005; Li *et al.* 2007; Li *et al.* 2007; Li *et al.* 2007; Lilienfein *et al.* 2003; Lima *et al.* 2006; Lisboa *et al.* 2009; Lugo and Sanchez 1986; Luizao *et al.* 1992; Ma *et al.* 2006; Macedo *et al.* 2008; Maia *et al.* 2009; Makumba *et al.* 2007; Manlay *et al.* 2002; Manlay *et al.* 2002; Maquere *et al.* 2008; Marin-Spiotta *et al.* 2009; Markewitz *et al.* 2004; Martins *et al.* 2009; Masto *et al.* 2008; Materechera and Mkhabela 2001; McGrath *et al.* 2001; Mendham *et al.* 2003; Mikhailova *et al.* 2000; Morris 1984; Motavalli *et al.* 2000; Motavalli and McConnell 1998; Muller *et al.* 2001; Mutuo *et al.* 2005; Nadal-Romero *et al.* 2016; Navarrete *et al.*, 2016; Navarrete and Tsutsuki, 2008; Neill *et al.*, 1997; Neill *et al.*, 1997; Neufeldt *et al.*, 2002; Ogunkunle and Eghaghara 1992; Ohta 1990; Osher *et al.* 2003; Parfitt *et al.* 1997; Paul *et al.* 2008; Pennock and van Kessel 1997; Perrin *et al.* 2014; Piccolo *et al.* 2008; Potter *et al.* 1999; Potvin *et al.* 2004; Powers 2004; Powers and Veldkamp 2005; Rangel *et al.* 2007; Rasiah *et al.* 2004; Reeder *et al.* 1998; Reiners *et al.* 1994; Resh *et al.* 2002; Rhoades *et al.* 2000; Richards *et al.* 2007; Riezebos and Loerts 1998; Rojas *et al.* 2016; Roscoe and Buurman 2003; Rossi *et al.* 2009; Russell *et al.* 2007; Sa *et al.* 2001; Saggar *et al.* 2001; Saha *et al.* 2009; Saha *et al.* 2010; Salimon *et al.* 2004; Sanchez *et al.* 1983; Saynes *et al.* 2005; Schedlbauer and Kavanagh 2008; Schiffman and Johnson 1989; Schwendenmann and Pendall 2006; Shang and Tiessen 1997; Sheng *et al.* 2004; Siband 1974; Silva *et al.* 2009; Silver *et al.* 2004; Sitompul *et al.* 2000; Six *et al.* 1998; Six *et al.* 2000; Slobodian *et al.* 2002; Smiley and Kroschel 2008; Smith *et al.* 2002; Sohng *et al.* 2017; Solomon *et al.* 2002; Solomon *et al.* 2007; Solomon *et al.* 2000; Sommer *et al.* 2000; Sparling *et al.* 2000; Srivastava and Singh 1991; Su 2007; Su *et al.* 2006; Su *et al.* 2004; Su *et al.* 2002; Su *et al.* 2004; Szott and Palm 1996; Templer *et al.* 2005; Tian *et al.* 2001; Tian *et al.* 2008; Tiessen *et al.* 1992; Tiessen *et al.* 1982; Tornquist *et al.* 1999; Townsend *et al.* 1995; Trouve *et al.* 1994; Trumbore *et al.* 1995; Uhl and Jordan 1984; Unger 2001; Vagen *et al.* 2006; van Dam *et al.* 1997; van Noordwijk *et al.* 1997; van Straaten *et al.* 2015; Veldkamp 1994; Veldkamp *et al.* 2003; Villarino *et al.* 2014; Voroney *et al.* 1981; Wadsworth *et al.* 1988; Wairu and Lal 2003; Walker and Desanker 2004; Wang *et al.* 2004; Wang and Zhang 2009; Wang *et al.* 2011; Wang *et al.* 2005; Wang *et al.* 2006; Wang *et al.* 2007; Wang *et al.* 2006; Wang *et al.* 2008; Weaver *et al.* 1987; Wick *et al.* 2000; Wick *et al.* 2005; Wu and Tiessen 2002; Wu *et al.* 2006; Xu *et al.* 2013; Yan *et al.* 2008; Yang *et al.* 2004; Yang *et al.* 2016; Yemefack *et al.* 2006; Yin *et al.* 2008; Yonekura *et al.* 2010; Yu *et al.* 2007; Yue *et al.* 2007; Zhan *et al.* 2005; Zhang *et al.* 1988; Zhao *et al.* 2005; Zhou *et al.* 2007; Zingore *et al.* 2005; Zinn *et al.* 2005; Zinn *et al.* 2002; Zou and Bashkin 1998 [6] The following references were used for paddy rice land-use factor: Andreetta *et al.* 2016; Bi *et al.* 2009; Gami *et al.* 2001; Hao *et al.* 2008; Huang *et al.* 2015; Kölbl *et al.* 2014; Liu *et al.* 2003; Majumder *et al.* 2008; Mandal *et al.* 2007; Nayaka *et al.* 2012; Nayaka *et al.* 2009; Pampolino *et al.* 2008; Pan *et al.* 2009; Shen *et al.* 2007; Shirato *et al.* 2011; Shirato and Yokozawa 2005; Wang *et al.* 2011; Wu *et al.* 2000; Xu *et al.* 2007; Zhang *et al.* 2006 [7] The following references were used for tillage management factors: Ahl *et al.* 1998; Al-Kaisi *et al.* 2005; Al-Kaisi *et al.* 2005; Alvarez *et al.* 2014; Alvarez *et al.* 1998; Alvarez *et al.* 1995; Alvarez *et al.* 1998; Alvarez *et al.* 1995; Alvarez *et al.* 1995; Alvarez *et al.* 1995; Alvaro-Fuentes *et al.* 2009; Alvaro-Fuentes *et al.* 2008; Alvaro-Fuentes *et al.* 2014; Angers *et al.* 1997; Angers *et al.* 1995; Anken *et al.* 2004; Balesdent *et al.* 1990; Barber *et al.* 1996; Bayer *et al.* 2006; Bayer *et al.* 2000; Bayer *et al.* 2002; Beare *et al.* 1994; Bhattacharyya *et al.* 2008; Bhattacharyya *et al.* 2013; Bhattacharyya *et al.* 2009; Black and Tanaka 1997; Blanco-Canqui *et al.* 2004; Blanco-Canqui *et al.* 2011; Boddey *et al.* 2010; Bordovsky *et al.* 1999; Borin *et al.* 1997; Borresen and Njos 1993; Bowman and Anderson 2002; Bowman and Anderson 2002; Burch *et al.* 1986; Buschiazzo *et al.* 1998; Buyanovsky and Wagner 1998; Calegari *et al.* 2008; Campbell *et al.* 1999; Campbell *et al.* 1996; Carter 1991; Carter *et al.* 1988; Carter *et al.* 1994; Carter *et al.* 2002; Cavanagh *et al.* 1991; Chagas *et al.* 1995; Chan *et al.* 2002; Chan *et al.* 2003; Chan and Mead 1988; Chaney *et al.* 1985; Chen *et al.* 2009; Chen *et al.* 2009; Chen *et al.* 2015; Cheng-Fang *et al.* 2012; Choudhary *et al.* 2013; Clapp *et al.* 2000; Corazza *et al.* 1999; Costantini *et al.* 1996; Dalal 1989; Dalal *et al.* 1991; Denef *et al.* 2007; Devine *et al.* 2014; Diaz-Zorita 1999; Díaz-Zorita *et al.* 2004; Dick and Durkalski 1997; Dikgwatlhe *et al.* 2014; Dimassi *et al.* 2014; Dolan *et al.* 2006; Dominguez *et al.* 2016; Doran *et al.* 1998; Dou *et al.* 2008; Du *et al.* 2010; Du *et al.* 2015; Duiker and Lal 1999; Edwards *et al.* 1992; Eghball *et al.* 1994; Fabrizzi *et al.* 2003; Fabrizzi *et al.* 2009; Fan *et al.* 2014; Feiziene *et al.* 2011; Ferreras *et al.* 2000; Fettell and Gill 1985; Fleige and Baeumer 1974; Follett and Peterson 1988; Franzleubbers *et al.* 1995; Franzluebbers and Arshad 1996; Franzluebbers *et al.* 1999; Franzluebbers and Stuedemann 2002; Freitas *et al.* 2000; Freixo *et al.* 2002; Gál *et al.* 2007; Galantini *et al.* 2006; Garcia-Prechac *et al.* 2004; Ghimire *et al.* 2012; Ghuman and Sur 2001; Grabski *et al.* 1997; Green *et al.* 2007; Gwenzi *et al.* 2009; Halvorson *et al.* 1997; Halvorson *et al.* 2002; Hansmeyer *et al.* 1997; Hao *et al.* 2001; Havlin and Kissel 1997; Heenan *et al.* 1995; Heinze *et al.* 2010; Hendrix 1997; Hermle *et al.* 2008; Hernanz *et al.* 2002; Hernanz *et al.* 2009; Hertnanz *et al.* 2009; Higashi *et al.* 2014; Hou *et al.* 2011; Huggins *et al.* 2007; Hulugalle 2000; Hussain *et al.* 1999; Ismail *et al.* 1994; Jagadamma and Lal 2010; Jarecki and Lal 2010; Jarvis 1996; Jemai *et al.* 2012; Jemai *et al.* 2013; Karlen *et al.* 1998; Karlen *et al.* 1994; Kruger 1996; Kumar *et al.* 2012; Kumar *et al.* 2014; Kushwaha *et al.* 2000; Küstermann *et al.* 2013; Lal 1998; Lal *et al.* 1994; Lammerding *et al.* 2010; Larney *et al.* 1997; Laudicina *et al.* 2014; Lavado *et al.* 1999; Liang *et al.* 2011; Liang *et al.* 2007; Lilienfein *et al.* 2000; Liu *et al.* 2014; Lopez-Bellido *et al.* 2009; Lopez-Bellido *et al.* 2017; Lopez-Fando *et al.* 2007; Lopez-Fando and Pardo 2009; Lou *et al.* 2012; Martin-Lammerding *et al.* 2013; Martin-Rueda *et al.* 2007; Martinez *et al.* 2013; McCarty *et al.* 1998; McLeod *et al.* 2013; Melero *et al.* 2011; Mielke *et al.* 1986; Mikha *et al.* 2010; Mikha *et al.* 2013; Mrabet *et al.* 2001; Munoz-Romero *et al.* 2017; Murage *et al.* 2006; Nyamadzawo *et al.* 2008; Nyborg *et al.* 1995; Olson *et al.* 2005; Packer *et al.* 1992; Page *et al.* 2013; Pierce and Fortin 1997; Plaza-Bonilla *et al.* 2011; Powlson and Jenkinson 1982; Prasad *et al.* 2016; Presley *et al.* 2011; Puget and Lal 2005; Quincke *et al.* 2006; Rasmussen and Albrecht 1997; Rhoton *et al.* 1993; Robertson *et al.* 2015; Ross and Hughes 1985; Sa *et al.* 2014; Saffigna *et al.* 1989; Sainju *et al.* 2009; Sainju *et al.* 2005; Sainju *et al.* 2011; Sainju *et al.* 2005; Sainju *et al.* 2008; Sainju *et al.* 2002; Salinas-Garcia *et al.* 1997; Salinas-Garcia *et al.* 2002; Salvo *et al.* 2010; Schomberg and Jones 1998; Sheehy *et al.* 2013; Shi *et al.* 2011; Shrestha *et al.* 2015; Shukla *et al.* 2006; Singh *et al.* 2015; Six *et al.* 2000; Sombrero and de Benito 2010; Steinbach and Alvarez 2006; Studdert *et al.* 2017; Studdert *et al.* 1997; Sun *et al.* 2011; Taboada *et al.* 1998; Thomas *et al.* 2007; Tian *et al.* 2013; Tivet *et al.* 2013; Ussiri and Lal 2009; van Groenigen *et al.* 2011; VandenBygaart *et al.* 2002; Varvel and Wilhelm 2011; Venterea *et al.* 2006; Viaud *et al.* 2010; Wander *et al.* 1998; Wang and Dalal 2006; Wanniarachchi *et al.* 1999; Wright and Hons 2004; Xu *et al.* 2013; Yang and Kay 2001; Yang and Wander 1999; Zhang *et al.* 2007; Zhang *et al.* 2017

Reference C stocks can be derived from country-specific data in a Tier 2 approach. Reference values in Tier 1 correspond to non-degraded, unimproved lands under native vegetation, but other reference conditions can also be chosen for Tier 2. In addition, the depth for evaluating soil C stock changes can be different with the Tier 2 method. The effect of tillage on soil carbon stocks can be markedly different for depths above the tillage depth compared to below the tillage depth (Angers *et al*. 1997; Angers and Eriksen-Hamel, 2008; Gal *et al*. 2017), and including soil C stock data below the depth of tillage is necessary to provide an accurate estimate of tillage system effect on C stocks. However, the depth of the reference C stocks (SOC_{REF}) and stock change factors need to the same for all land uses (i.e., F_{LU}, F_I, and F_{MG}) to ensure consistent application of methods for determining the impact of land use change on soil C stocks..

The carbon stock estimates may be improved when deriving country-specific factors for F_{LU} and F_{MG}, by expressing carbon stocks on a soil-mass equivalent basis rather than a soil-volume equivalent (i.e. fixed depth) basis. This is because the soil mass in a certain soil depth changes with the various operations associated with land use that affect the density of the soil, such as uprooting, land levelling, tillage, and rain compaction due to the disappearance of the cover of tree canopy. However, it is important to realize that all soil C stocks used to derive stock change factors across all land uses must be on an equivalent mass basis if this method is applied. This will require necessary soils data to do comprehensively for all land uses. See Box 2.2b in Chapter 2, Section 2.3.3.1 for more information.

Biochar C Amendments

The parameter F_{perm_p} can be based on H/Corg or O/Corg measured directly from representative samples of biochar, or from published data for biochar produced using similar process conditions as the biochar that is applied to soils in the country. Tier 2 emission factors may be disaggregated based on variation in environmental conditions, such as the climate and soil types, in addition to variation associated with the biochar production methods that generate production types defined by the specific feedstock type and conversion process. See Section 2.3.3.1, Chapter 2, Volume IV for more information.

Steady-State Method

Default parameters are provided for the three-pool steady-state C pool equations (Table 5.5a). The average lignin and nitrogen contents of the C input is also required to estimate the size of the three C pools (See Tables 5.5b and 5.5c).

Tier 3

Constant stock change rate factors *per se* are less likely to be estimated in favor of variable rates that more accurately capture land-use and management effects. Tier 3 methods for biochar C amendments to soils are country-specific and may involve empirical or process-based models to account for a broader set of impacts of biochar amendments. More information on Tier 3 methods is provided in Section 2.3.3.1, Chapter 2, Volume IV.

TABLE 5.5A (NEW)
GLOBALLY CALIBRATED MODEL PARAMETERS TO BE USED TO ESTIMATE SOC CHANGES FOR MINERAL SOILS WITH THE TIER 2 STEADY-STATE METHOD

Parameter	Practice	Value (min, max)	Standard Deviation	Description
$till_{fac}$	Full-till	3.036 (1.4, 4.0)	0.579	Tillage disturbance modifier for decay rates
	Reduced-till	2.075 (1.0, 3.0)	0.569	
	No-till	1		
w_s	All	1.331 (0.8, 2.0)	0.386	slope parameter for $mappet_i$ term to estimate w_{fac}
k_{fac_a}	All	7.4	n/a	Decay rate constant under optimal conditions for decomposition of the active sub-pool
k_{fac_s}	All	0.209 (0.058, 0.3)	0.566	Decay rate constant under optimal conditions for decomposition of the slow sub-pool
k_{fac_p}	All	0.00689 (0.005, 0.01)	0.00125	Decay rate constant under optimal conditions for decomposition of the passive sub-pool
f_1	All	0.378 (0.01, 0.8)	0.0719	Fraction of metabolic dead organic matter decay products transferred to the active sub-pool
f_2	Full-till	0.368 (0.007, 0.5)	0.0998	Fraction of structural dead organic matter decay products transferred the active sub-pool
f_3	All	0.455 (0.1, 0.8)	0.201	Fraction of structural dead organic matter decay products transferred to the slow sub-pool
f_5	All	0.0855 (0.037, 0.1)	0.0122	Fraction of active sub-pool decay products transferred to the passive sub-pool
f_6	All	0.0504 (0.02, 0.19)	0.0280	Fraction of slow sub-pool decay products transferred to the passive sub-pool
f_7	All	0.42	n/a	Fraction of slow sub-pool decay products transferred to the active sub-pool
f_8	All	0.45	n/a	Fraction of passive sub-pool decay products transferred to the active sub-pool
t_{opt}	All	33.69 (30.7, 35.34)	0.66	Optimum temperature to estimate temperature modifier on decomposition
t_{max}	All	45	n/a	Maximum monthly average temperature for decomposition.

Methods used in the Bayesian calibration process are described in Annex 5A.3.

Source: Campbell *et al*. 1997; Collins *et al*. 2000; Dick et al. 1997; Diaz-Zorita *et al*. 1999; Dimassi *et al*. 2014; e-RA 2013; Gregorich *et al*. 1996; Halvorson *et al*. 1997; Huggins and Fuchs 1997; Janzen *et al*. 1997; Jenkinson 1990; Jenkinson and Johnston 1977; KBS LTER 2017; Küstermann and Hülsbergen 2013; Maillard *et al*. 2018; Marchado 2013; Marchado *et al*. 2008, 2011; Pierce and Fortin 1997; Rasmussen and Smiley 1997; Schultz 1995; Skjemstad *et al*. 2004; Vanotti *et al*. 1997; See Annex 5A.3 for more information.

TABLE 5.5B (NEW)
DEFAULT VALUES FOR NITROGEN AND LIGNIN CONTENTS IN CROPS FOR THE STEADY-STATE METHOD

Crops	N content of residues[1]	Lignin content of residues[2]
Generic value for crops not indicated below	0.0083	0.073
Generic Grains	0.0068	0.074
Winter Wheat	0.0069	0.053
Spring Wheat	0.0070	0.053
Barley	0.0090	0.046
Oats	0.0073	0.047
Maize	0.0063	0.11
Rye[3]	0.008	0.05
Rice[4]	0.007	0.125
Millet[4]	0.007	0.062
Sorghum[3]	0.0065	0.06
Beans and Pulses	0.008	0.075
Soybeans	0.008	0.085
Potatoes and Tubers	0.0169	0.073
Peanuts[4]	0.016	0.086
N-fixing forages	0.0250	0.072
Alfalfa	0.0238	0.072
Non-N-fixing forages	0.0134	0.049
Perennial Grasses	0.0126	0.049
Grass-Clover Mixtures[4]	0.0178	0.061
Non-legume hay	0.0134	0.057

[1] The estimates are in units of g N (g residue)$^{-1}$ on dry weight basis from a biomass-weighted average of aboveground and belowground for each crop based on data in Table 11.1a in Volume IV, Chapter 11 of this report.

[2] Winter wheat, spring wheat, barley, oats, millet, beans and pulses, soybeans, peanuts, values from Equi-Analytical Laboratories (2018); maize, rice, and sorghum from Cornell University (2017); and potatoes and tubers from Zereu *et al*. (2014).

[3] Simple average of nitrogent content of aboveground and belowground. [4] Nitrogen content of aboveground assumed to represent all residue.

[4] value is an average of N fixing and non-N fixing grasses.

Notes: Uncertainty is assumed to be ±75% for the N content estimates and ±50% for the lignin content estimates, expressed as a 95% confidence intervals.

TABLE 5.5C (NEW) DEFAULT VALUES FOR CARBON TO NITROGEN RATIOS, NITROGEN, AND LIGNIN CONTENTS IN LIVESTOCK MANURE FOR THE STEADY-STATE METHOD			
Livestock Manure Type	**C to N ratio of manure**	**N content of manure (% dry basis)**	**Lignin content of manure (% dry basis)**
Dairy Cattle	16	2.9	13
Beef Cattle	19[1]	2.3[1]	9[1]
Poultry	10[2]	5.1[2]	5[2]
Swine	11[3]	4.1[3]	5[3]
Horses/Mules/Asses	20	1.3	13[4]
Sheep	11	3.3	13[4]

Sources: Chen *et al*. 2003 for Dairy Cattle, Beef Cattle, Poultry and Swine.
ASAE 2005 for Horses/Mules/Asses.
MWPS 2004; Hébert *et al*. 1991; Sørensen and Jensen, 1995; Rees and Castle, 2002 for Sheep
[1]Average of Beef and Cattle- Feedlot categories.
[2]Average across four development categories.
[3]Average of Nursery, Grower and Finisher categories.
[4]Average of Beef and Dairy from Chen *et al*. 2003.
Notes: Uncertainty is assumed to be ± 50% for all of these estimates, expressed as a 95% confidence interval.

Organic soils

No refinement.

The *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* provides additional guidance that updates the *2006 IPCC Guidelines for national Greenhouse Gas Inventories*. See section 2.2 of the *2013 Wetlands Supplement* covers Tier 1, 2, and 3 approaches for drained organic soils in cropland.

5.2.3.3 CHOICE OF ACTIVITY DATA

Mineral soils

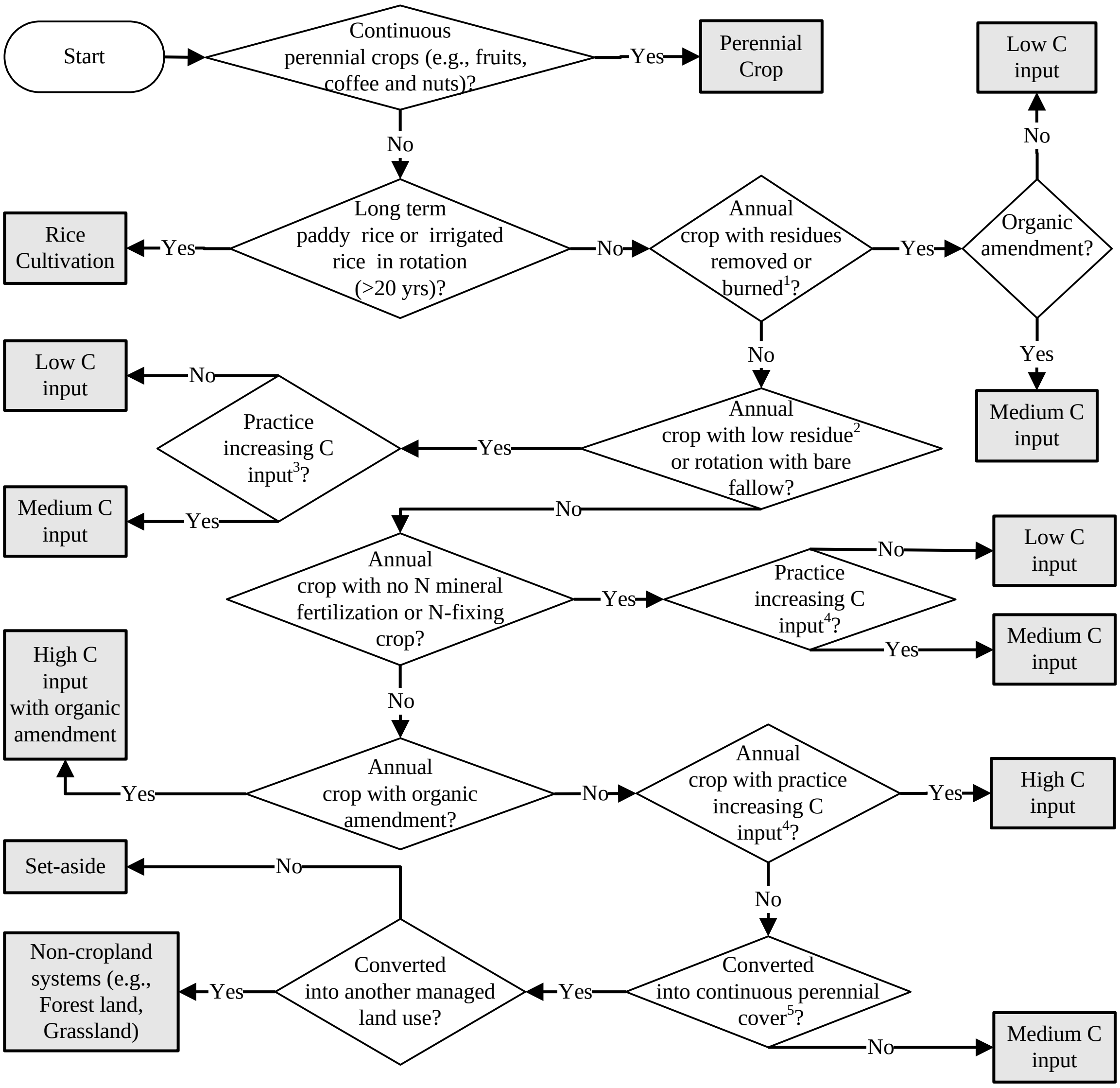
Tier 1

Cropland systems are classified by practices that influence soil C storage. The default management classification system is provided in Figure 5.1. Inventory compilers should use this classification to categorize management systems in a manner consistent with the default Tier 1 stock change factors. This classification may be further developed for Tiers 2 and 3 approaches. In general, practices that are known to increase C storage, such as irrigation, mineral fertilization, organic amendments, cover crops and high residue yielding crops, have higher inputs, while practices that decrease C storage, such as residue burning/removal, bare fallow, and low residue crop varieties, have lower inputs. These practices are used to categorize management systems and then estimate the change in soil organic C stocks. Practices should not be considered that are used in less than 1/3 of a given cropping sequence (i.e., crop rotation), which is consistent with the classification of experimental data used to estimate the default stock change factors. Rice production, perennial croplands, and set-aside lands (i.e., lands removed from production) are considered unique management systems (see below).

Each of the annual cropping systems (low input, medium input, high input, and high input w/organic amendment) are further subdivided based on tillage management. Tillage practices are divided into no-till (direct seeding without primary tillage and only minimal soil disturbance in the seeding zone; herbicides are typically used for weed control), reduced tillage (primary and/or secondary tillage but with reduced soil disturbance that is usually shallow and without full soil inversion; normally leaves surface with >30percent coverage by residues at planting) and full tillage (substantial soil disturbance with full inversion and/or frequent, within year tillage operations, while leaving <30percent of the surface covered by residues at the time of planting). It is *good practice* only to consider reduced and no-till if they are used continuously (every year) because even an occasional pass with a full tillage implement will significantly reduce the soil organic C storage expected under the reduced or no-till regimes (Pierce *et al*. 1994; Smith *et al*. 1998). Assessing the impact of rotational tillage systems (i.e., mixing reduced, no-till and/or full tillage practices) on soil C stocks will require a Tier 2 method.

Figure 5.1 Classification scheme for cropping systems

In order to classify cropland management systems, the inventory compiler should start at the top and proceed through the diagram answering questions (move across branches if answer is yes) until reaching a terminal point on the diagram. The classification Diagram is consistent with default stock change factors in Table 5.5.C input classes (i.e., low, medium, high and high with organic amendment) are further subdivided by tillage practice.



Note:
1: Does not typically include grazing of residues in the field.
2: e.g. cotton, vegetables and tobacco.
3: Practices that increase C input above the amount typically generated by the low residues yielding varieties such as using organic amendments, cover crops/green manures, and mixed crop/grass systems.
4: Practices that increase C input by enhancing residue production, such as using irrigation, cover crops/green manures, vegetated fallows, high residue yielding crops, and mixed crop/grass systems.
5 Perennial cover without frequent harvest.
Note: Only consider practices, such as irrigation, residue burning/removal, mineral fertilizers, N-fixing crops, organic amendment, cover crops/green manures, low residue crop, or fallow, if used in at least 1/3 of cropping rotation sequence.

The main types of land-use activity data are: i) aggregate statistics (Approach 1), ii) data with explicit information on land-use conversions but without specific geo-referencing (Approach 2), or iii) data with explicit information on land-use conversions and geo-referencing (Approach 3), such as land-use and management inventories making up a statistically-based sample of a country's land area (see Chapter 3 for discussion of approaches). At a minimum, globally available land-use and crop production statistics, such as FAO databases (http://www.fao.org/faostat), provide annual compilations of total land area by major land-uses, select management data (e.g., irrigated vs. non-irrigated cropland), land area in 'perennial' crops (i.e., vineyards, perennial herbaceous crops, and tree-based crops such as orchards) and annual crops (e.g., wheat, rice, maize, sorghum, etc.). FAO databases would be an example of aggregate data (Approach 1).

Management activity data supplement the land-use data, providing information to classify management systems, such as crop types and rotations, tillage practices, irrigation, manure application, residue management, etc. These data can also be aggregate statistics (Approach 1) or information on explicit management changes (Approach 2 or 3). Where possible, it is *good practice* to determine the specific management practices for land areas associated with cropping systems (e.g., rotations and tillage practice), rather than only area by crop. Remote sensing data are a valuable resource for land-use and management activity data, and potentially, expert knowledge is another source of information for cropping practices. It is *good practice* to elicit expert knowledge using methods provided in Volume 1, Chapter 2 (eliciting expert knowledge).

National land-use and resource inventories, based on repeated surveys of the same locations, constitute activity data gathered using Approach 2 or 3, and have some advantages over aggregated land-use and cropland management data (Approach 1). Time series data can be more readily associated with a particular cropping system (i.e., combination of crop type and management over a series of years), and the soil type can be determined by sampling or by referencing the location to a suitable soil map. Inventory points that are selected based on an appropriate statistical design also enable estimates of the variability associated with activity data, which can be used as part of a formal uncertainty analysis. An example of a survey using Approach 3 is the National Resource Inventory in the U.S. (Nusser and Goebel, 1997).

Activity data require additional in-country information to stratify areas by climate and soil types. If such information has not already been compiled, an initial approach would be to overlay available land cover/land-use maps (of national origin or from global datasets such as IGBP_DIS) with soil and climate maps of national origin or global sources, such as the FAO Soils Map of the World and climate data from the United Nations Environmental Program. A detailed description of the default climate and soil classification schemes is provided in Chapter 3, Annex 3A.5. The soil classification is based on soil taxonomic description and textural data, while climate regions are based on mean annual temperatures and precipitation, elevation, occurrence of frost, and potential evapotranspiration.

Tier 2

Developing Country-Specific Factors for the Default Equations

Tier 2 approaches are likely to involve a more detailed stratification of management systems than in Tier 1 (see Figure 5.1) if sufficient data are available. This can include further within country subdivisions of annual cropping input categories (i.e., low, medium, high, and high with amendment), rice cultivation, perennial cropping systems, and set-asides. It is *good practice* to further subdivide default classes based on empirical data that demonstrates significant differences in soil organic C storage among the proposed categories. In addition, Tier 2 approaches can involve a finer stratification of climate regions and soil types.

For Tier 2, the specific definitions of management and input factors are typically made to match available activity data on how an activity affects C stocks. For example, if a country has management factors related to specific tillage practices that involve a mix of intensities over time, then the country will also need activity data on those specific tillage practices to apply the country-specific factors.

Biochar C Amendments

For biochar C amendments, the activity data required for the Tier 2 method includes the total quantities of biochar distributed as amendment to mineral soils. These data must be disaggregated by production type, where production type is defined as a process utilizing a specific feedstock type, and a specific conversion process. Changes in soil C associated with biochar amendments are considered to occur where it is incorporated into soil. However, due to the distributed nature of the land sector in which this can take place, inventory compilers may not have access to data on when or where biochar C amendments occur. Inventory compilers may be able to compile data on the total amount of biochar applied to cropland mineral soils from biochar producers, exporters, importers, distributors and/or from those applying biochar to cropland in the country. Note that exported biochar is not included in the total amount of biochar amended to soils in the country.

Additionally, activity data on the amount of biochar amendments may be disaggregated by climate zones and/or soil types if country-specific factors are disaggregated by these environmental variables. The additional climate and soil activity data may be obtained with a survey of biochar distributors and land managers.

Steady-State Method

This method requires soil C input data based on the amount of biomass that is converted to dead organic matter annually. This rate will vary depending on the crop production, management activity, and other environmental variables. Removals or reductions in dead organic matter are subtracted from the C input amount, which could occur with livestock grazing, grassland burning, or harvesting of grass for feed or bioenergy. Additions of C, particularly organic amendments such as manure, are included in the estimate of C input.

It is *good practice* to estimate C input using country-specific factors in order to produce more accurate estimates. If country-specific factors are not available, Equation 5.0h can be used to estimate C inputs with global factors provided in Table 11.1a, Chapter 11, Volume 4 or alternatively, the amount can be calculated using the method and data in Table 11.2, Chapter 11.

EQUATION 5.0H (NEW)
CROPLAND C- INPUT TO SOIL FOR THE STEADY-STATE METHOD

$$C_{input} = \sum_T \left(AGR_{(T)} \bullet C_{AG(T)}\right) + \left(BGR_{(T)} \bullet C_{BG(T)}\right) + \left(F_{AM(T)} \bullet CN_{AM(T)}\right) + \left(F_{OON(T)} \bullet CN_{OON(T)}\right)$$

$$AGR_{(T)} = AG_{DM(T)} \bullet Area_{(T)} \bullet \left(1 - Frac_{Removal(T)} - \left(Frac_{Burnt(T)} \bullet C_f\right)\right)$$

$$BGR_{(T)} = \left(Crop_{(T)} + AG_{DM(T)}\right) \bullet RS_{(T)} \bullet Area_{(T)} \bullet Frac_{Renew(T)}$$

$$AG_{DM(T)} = Crop_{(T)} \bullet R_{AG(T)}$$

Where:

C_{input} = annual amount of C input from residues to the soil (above and below ground), kg C yr^{-1}

$AGR_{(T)}$ = annual total amount of above-ground crop residue for crop T, kg d.m. yr^{-1}.

$C_{AG(T)}$ = C content of above-ground residues for crop T, kg C (kg d.m.) $^{-1}$ (Default: 0.42 kg C (kg d.m.) $^{-1}$)

$Frac_{Remove(T)}$ = fraction of above-ground residues of crop T removed annually for purposes such as feed, bedding and construction, dimensionless. Survey of experts in country is required to obtain data. If data for $Frac_{Remove}$ are not available, assume no removal

$Frac_{Burnt(T)}$ = fraction of annual harvested area of crop T burnt, dimensionless

C_f = combustion factor (dimensionless) (refer to Chapter 2, Table 2.6)

$BGR_{(T)}$ = annual total amount of belowground crop residue for crop T, kg d.m. yr^{-1}

$C_{BG(T)}$ = C content of below-ground residues for crop T, kg C (kg d.m.)$^{-1}$, (Default: 0.42 kg C (kg d.m.) $^{-1}$)

$F_{AM(T)}$ = N in animal manures applied to crop T, kg N yr^{-1} (Equation 10.34 in Section 10.5.4, Chapter 10)

$CN_{AM(T)}$ = C to N ratio of animal manures applied to crop T, kg C (kg N)$^{-1}$ (Table 5.5c)

$F_{OON(T)}$ = N in other organic amendments applied to crop T, kg N yr^{-1} (Equation 11.3 in Section 11.2.1.3, Chapter 11; with the exclusion of FAM)

$CN_{OON(T)}$ = C to N ratio of other organic amendments applied to crop T, kg C (kg N)$^{-1}$. It is generally comprised between 10 and 20

$AG_{DM(T)}$ =Above-ground residue dry matter for crop T, kg d.m. ha^{-1}

(Use factors for $R_{AG(T)}$ in Table 11.1a, Chapter 11, or alternatively, the above-ground residue dry matter may be estimated using the method and data in Table 11.2, Chapter 11). It is good practice to ensure consistency in the method applied to estimate AGDM(T) in equations 5.0h (New) and 11.6 (Updated)

$Crop_{(T)}$ = harvested annual dry matter yield for crop T, kg d.m. ha^{-1} (Use Equation 11.7, Chapter 11)

$R_{AG(T)}$ = ratio of above-ground residues dry matter ($AG_{DM(T)}$) to harvested yield for crop T ($Crop_{(T)}$), kg d.m. ha^{-1}(kg d.m. ha^{-1})$^{-1}$, (Table 11.1a)

$Area_{(T)}$ = total annual area harvested of crop T, ha yr^{-1}

$Frac_{Renew(T)}$ = fraction of total area under crop T that is renewed annually [8], dimensionless. For countries where forages are renewed on average every X years, $Frac_{Renew(T)}$ = 1/X. For annual crops $Frac_{Renew(T)}$ = 1

$RS_{(T)}$ = ratio of below-ground root biomass to above-ground shoot biomass for crop T, kg d.m. ha^{-1} (kg d.m. $ha^{-1})^{-1}$, (Table 11.1a)

T = crop or forage type

Data on crop yield statistics (yields and area harvested, by crop) may be obtained from national sources. If such data are not available, FAO publishes data on crop production: (http://faostat.fao.org/). Tillage management data are also required (proportion of full tillage, reduced tillage and no-till), and irrigation data for any lands that are provided supplement water (proportion of land). Monthly average temperature, precipitation and potential evapotranspiration is needed for each grid cell or region. This information is available from global datasets, such as the CRU climate dataset (https://crudata.uea.ac.uk/cru/data/hrg/), if country-specific data are not available. The average sand content is needed for each grid cell or region, which is available from Harmonized World Soil Database (http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/).

Tier 3

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

For biochar C amendments, the additional activity data required to support a Tier 3 method will depend on which processes are represented and which environmental variables that are required as input to the model. Priming effects, soil GHG emissions, and plant production responses to biochar all vary with biochar type, climate, and soil type. Furthermore, soil GHG emissions and plant production responses also vary with crop type and management. Therefore, Tier 3 methods may require environmental data on climate zones, soil types, crop types and crop management systems (such as nitrogen fertilizer application rates, and whether soils are flooded for paddy rice production), in addition to the amount of biochar amendments in each of the individual combinations of strata for the environmental variables. More detailed activity data specifying the process conditions for biochar production or the physical and chemical characteristics of the biochar may also be required (such as surface area, cation exchange capacity, pH, and ash content).

Organic soils

No refinement.

The *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* provides additional guidance that updates the *2006 IPCC Guidelines for national Greenhouse Gas Inventories*. See section 2.2 of the *2013 Wetlands Supplement covers Tier 1, 2, and 3 approaches for drained organic soils in cropland.*

5.2.3.4 CALCULATION STEPS FOR TIER 1

Mineral soils

The steps for estimating SOC_0 and $SOC_{(0-T)}$ and net soil C stock change per ha for *Cropland Remaining Cropland* on mineral soils are as follows:

Step 1: Organize data into inventory time periods based on the years in which activity data were collected (e.g., 1990 to 1995, 1995 to 2000, etc.)

Step 2: Determine the amount *Cropland Remaining Cropland* by mineral soil types and climate regions in the country at the beginning of the first inventory time period. The first year of the inventory time period will depend on the time step of the activity data (0-T; e.g., 5, 10 or 20 years ago).

Step 3: Classify each Cropland into the appropriate management system using Figure 5.1.

[8] This term is included in the equation to account for N release and the subsequent increases in N_2O emissions (e.g., van der Weerden *et al.*, 1999; Davies *et al.*, 2001), from renewal/cultivation of grazed grass or grass/clover pasture and other forage crops.

Step 4: Assign a native reference C stock values (SOC_{REF}) from Table 2.3 based on climate and soil type.

Step 5: Assign a land-use factor (F_{LU}), management factor (F_{MG}) and C input levels (F_I) to each Cropland based on the management classification (Step 2). Values for F_{LU}, F_{MG} and F_I are given in Table 5.6.

Step 6: Multiply the factors (F_{LU}, F_{MG}, F_I) by the reference soil C stock (SOC_{REF}) to estimate an 'initial' soil organic C stock ($SOC_{(0-T)}$) for the inventory time period.

Step 7: Estimate the final soil organic C stock (SOC_0) by repeating Steps 1 to 5 using the same native reference C stock (SOC_{REF}), but with land-use, management and input factors that represent conditions for each cropland in the last (year 0) inventory year.

Step 8: Estimate the average annual change in soil organic C stocks for *Cropland Remaining Cropland* ($\Delta C_{Mineral}$) by subtracting the 'initial' soil organic C stock ($SOC_{(0-T)}$) from the final soil organic C stock (SOC_0), and then dividing by the time dependence of the stock change factors (i.e., 20 years using the default factors). If an inventory time period is greater than 20 years, then divide by the difference in the initial and final year of the time period.

Step 9: Repeat steps 2 to 8 if there are additional inventory time periods (e.g., 1990 to 2000, 2001 to 2010, etc.).

A numerical example is given below for *Cropland Remaining Cropland* on mineral soils, using Equation 2.25 and default reference C stocks (Table 2.3) and stock change factors (Table 5.6).

Example: The following example shows calculations for aggregate areas of cropland soil carbon stock change. In a warm temperate wet climate on high activity clay soils there are 1Mha of permanent annual cropland. The native reference carbon stock (SOC_{REF}) for the region is 64 tonnes C ha^{-1}. At the beginning of the inventory calculation period (in this example, 10 yrs earlier in 1990), the distribution of cropland systems were 400,000 ha of annual cropland with low carbon input levels and full tillage and 600,000 ha of annual cropland with medium input levels and full tillage. Thus, initial soil carbon stocks for the area were:

400,000 ha ● (64 tonnes C ha^{-1} ● 0.75 ● 1 ● 0.92) + 600,000 ha ● (64 tonnes C ha^{-1} ● 0.75 ● 1 ● 1) = 46.46 million tonnes C.

In the last year of the inventory time period (in this example, the last year is 2000), there are: 200,000 ha of annual cropping with full tillage and low C input, 700,000 ha of annual cropping with reduced tillage and medium C input, and 100,000 ha of annual cropping with no-till and medium C input. Thus, total soil carbon stocks based on the inventory year are:

200,000 ha ● (64 tonnes C ha^{-1} ● 0.75 ● 1 ● 0.92) + 700,000 ha ● (64 tonnes C ha^{-1} ● 0.75 ● 1.01 ● 1) + 100,000 ha ● (64 tonnes C ha^{-1} ● 0.75 ● 1.11 ● 1) = 49.06 million tonnes C.

Thus, the average annual stock change over the period for the entire area is: 49;06 – 46.46 = 2.60 million tonnes/20 yr = 130000 tonnes C per year soil C stock increase (Note: 20 years is the time dependence of the stock change factor, i.e., factor represents annual rate of change over 20 years).

Organic soils

No refinement.

The *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* provides additional guidance that updates the *2006 IPCC Guidelines for national Greenhouse Gas Inventories*. See section 2.2 of the *2013 Wetlands Supplement covers Tier 1, 2, and 3 approaches for drained organic soils in cropland.*

5.2.3.5 UNCERTAINTY ASSESSMENT

No refinement.

5.2.4 Non-CO_2 greenhouse gas emissions from biomass burning

No refinement.

5.3 LAND CONVERTED TO CROPLAND

No refinement in the Introduction.

5.3.1 Biomass

5.3.1.1 CHOICE OF METHOD

This section provides guidance on methods for calculating carbon stock change in biomass due to the conversion of land from natural conditions and other uses to Cropland, including deforestation and conversion of pasture and grazing lands to Cropland. The methods require estimates of carbon in biomass stocks prior to and following conversion, based on estimates of the areas of lands converted during the period between land-use surveys. As a result of conversion to Cropland, it is assumed (in Tier 1) that the dominant vegetation is removed entirely leading to emissions, resulting in near zero amounts of carbon remaining in biomass. Some type of cropping system is planted soon thereafter increasing the amount of carbon stored in biomass. The difference between initial and final biomass carbon pools is used to calculate carbon stock change from land-use conversion; and in subsequent years accumulations and losses in perennial woody biomass in Cropland are counted using methods in Section 5.2.1 (Cropland Remaining Cr*opland*).

It is *good practice* to consider all carbon pools (i.e., above ground and below ground biomass, dead organic matter, and soils) in estimating changes in carbon stocks in *Land Converted to Cropland*. Currently, there is insufficient information to provide a default approach with default parameters to estimate carbon stock change in dead organic matter (DOM) pools[9]. DOM is unlikely to be important except in the year of conversion. It is assumed that there will be no DOM in Cropland. In addition, the methodology below considers only carbon stock change in above-ground biomass since limited data are available on below-ground carbon stocks in perennial Cropland.

The *IPCC Guidelines* describe increasingly sophisticated alternatives that incorporate greater detail on the areas of land converted, carbon stocks on lands, and loss of carbon resulting from land conversions. It is g*ood practice* to adopt the appropriate tier depending on key source analysis, data availability and national circumstances. All countries should strive for improving inventory and reporting approaches by advancing to the highest tier possible given national circumstances. It is *good practice* for countries to use a Tier 2 or Tier 3 approach if carbon emissions and removals in *Land Converted to Cropland* is a *key category* and if the sub-category of biomass is considered significant based on principles outlined in Volume 1, Chapter 4. Countries should use the decision tree in Figure 1.3 to help with the choice of method. *Land Converted to Cropland* is likely to be a *key category* for many countries and further biomass is likely to be a key source.

Tier 1

The Tier 1 method follows the approach in Chapter 4 (Forest Land) where the amount of biomass that is cleared for cropland is estimated by multiplying the area converted in one year by the average carbon stock in biomass in the Forest Land or Grassland prior to conversion. It is *good practice* to account completely for all land conversions to Cropland. Thus, this section elaborates on the method such that it includes different initial uses, including but not limited to forests.

Equation 2.15 in Chapter 2 summarises the major elements of a first-order estimation of carbon stock change from land-use conversion to Cropland. Average carbon stock change on a per hectare basis is estimated for each type of conversion. The average carbon stock change is equal to the carbon stock change due to the removal of biomass from the initial land use (i.e., carbon in biomass immediately after conversion minus the carbon in biomass prior to conversion), plus carbon stocks from one year of growth in Cropland following conversion. It is necessary to account only for any woody vegetation that replaces the vegetation that was cleared during land-use conversion. The *GPG-LULUCF* combines carbon in biomass after conversion and carbon in biomass that grows on the land following conversion into a single term. In this method, they are separated into two terms, B_{AFTER} and ΔC_G to increase transparency.

As described in section 5.3.1.1., at Tier 1, carbon stocks in biomass immediately after conversion (B_{AFTER}) are assumed to be zero, since the land is cleared of all vegetation before planting crops. Average carbon stock change per hectare for a given land-use conversion is multiplied by the estimated area of lands undergoing such a conversion in a given year. In subsequent years, change in biomass of annual crops is considered zero because carbon gains in biomass from annual growth are offset by losses from harvesting. Changes in biomass of perennial woody crops are counted following the methodology in Section 2.3.1.1 (Change in carbon stocks in biomass in

[9] Any litter and dead wood pools (estimated using the methods described in Chapter 2, Section 2.3.2) should be assumed oxidized following land conversion.

land remaining in a land-use category) and Section 5.2.1 (Change in carbon stocks in biomass in cropland remaining cropland). Thus, carbon gain of an annual crop is estimated only for the first year following a conversion, whereas, carbon gains and losses of perennial woody crop may also occur in subsequent years up to 20 years (at maximum).

The default assumption for Tier 1 is that all carbon in biomass removed is lost to the atmosphere through burning or decay processes either on-site or off-site. Tier 1 calculations do not differentiate immediate emissions from burning and other conversion related losses.

Tier 2

The Tier 2 calculations are structurally similar to Tier 1, with the following distinctions. First, Tier 2 relies largely on country-specific estimates of the carbon stocks in initial and final land uses rather than the default data. Area estimates for *Land Converted to Cropland* are disaggregated according to original vegetation (e.g., from Forest Land or Grassland) at finer spatial scales to capture regional and crop systems variations in country-specific carbon stocks values.

Second, Tier 2 may modify the assumption that carbon stocks immediately following conversion are zero. This enables countries to take into account land-use transitions where some, but not all, vegetation from the original land use is removed.

Third, under Tier 2, it is *good practice* to apportion carbon losses to burning and decay processes if applicable. Emissions of carbon dioxide occur as a result of burning and decay in land-use conversions. Further, non-CO_2 trace gas emissions occur as a result of burning. By partitioning losses to burning and decay, countries can also calculate non-CO_2 trace gas emissions from burning (Section 5.3.4).

The immediate impacts of land conversion activities on the five carbon stocks can be summarized in a disturbance matrix, which describes the retention, transfers and releases of carbon in the pools in the original ecosystem following conversion to Cropland. A disturbance matrix defines for each pool the proportion that remains in that pool and the proportion that is transferred to other pools. A small number of transfers are possible and are outlined in a disturbance matrix in Table 5.7. The disturbance matrix ensures consistency of the accounting of all carbon pools.

TABLE 5.7
EXAMPLE OF A SIMPLE DISTURBANCE MATRIX (TIER 2) FOR THE IMPACTS OF LAND CONVERSION ACTIVITIES ON CARBON POOLS

From \ To	Above-ground biomass	Below-ground biomass	Dead wood	Litter	Soil organic matter	Harvested wood products	Atmosphere	Sum of row (must equal 1)
Above-ground biomass								
Below-ground biomass								
Dead wood								
Litter								
Soil organic matter								

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

Impossible transitions are blacked out.

Biomass transfers to dead wood and litter can be estimated using Equation 2.20.

Tier 3

The Tier 3 method is similar to Tier 2, with the following distinctions: i) rather than relying on average annual rates of conversion, countries can use direct estimates of spatially disaggregated areas converted annually for each initial and final land use; ii) carbon densities and soil carbon stock change are based on locally specific information, which makes possible a dynamic link between biomass and soil; and iii) biomass volumes are based on actual inventories. The transfer of biomass, to dead wood and litter following land-use conversion can be estimated using Equation 2.20.

5.3.1.2 CHOICE OF EMISSION FACTORS

The emission/removal factors needed for the default method are: carbon stocks before conversion in the initial land use and after conversion to Cropland; and growth in biomass carbon stock from one year of cropland growth.

Tier 1

Default biomass carbon stock in initial land-use categories (B_{BEFORE}) mainly Forest Land and Grassland are provided in Updated Table 5.8. Initial land-use based carbon stocks should be obtained for different Forest Land or Grassland categories based on biome type, climate, soil management systems, etc. It is assumed that all biomass is cleared when preparing a site for cropland use, thus, the default for B_{AFTER} is 0 tonne C ha^{-1}.

In addition, a value is needed for carbon stocks after one year of growth in crops planted after conversion (ΔC_G). Updated Table 5.9 provides general defaults for annual and perennial crop for ΔC_G while updated Table 5.3 provides defaults for specific perennial crops. Separate defaults are provided for annual non-woody crops and perennial woody crops. For lands planted in annual crops, the default value of ΔC_G is 4.7 tonnes of C per hectare, based on the original *IPCC Guidelines* recommendation of 10 tonnes of dry biomass per hectare (dry biomass has been converted to tonnes carbon in Table 5.9). The total accumulation of carbon in perennial woody biomass will, over time, exceed that of the default carbon stock for annual cropland. However, default values provided in this section are for one year of growth immediately following conversion, which usually give lower carbon stocks for perennial woody crops compared to annual crops.

TABLE 5.8 (UPDATED[1]).
DEFAULT BIOMASS CARBON STOCKS REMOVED DUE TO LAND CONVERSION TO CROPLAND

Land-use category	Carbon stock in biomass* before conversion (B_{Before}) (tonnes C ha^{-1})	Error range #
Forest Land	See Chapter 4 Tables 4.7 to 4.12 for carbon stocks in a range of forest types by climate regions. Stocks are in terms of dry matter. Multiply values by a carbon fraction (CF) in Table 4.3 consistent with what used in forest land estimation to convert dry matter to carbon.	See Section 4.3 (Land Converted to Forest Land)
Grassland	See Chapter 6 Table 6.4 for carbon stocks in a range of grassland types by climate regions. Multiply default carbon fraction (CF) 0.47 (for herbaceous biomass for Grassland, see page 6.29, Chapter 6 of the *2006 IPCC Guidelines* to convert dry matter to carbon.	± 75%

1 Updates Table 5.8 from the IPCC *2006 IPCC Guidelines*.

* Note that the condition of forests that are converted to grassland or cropland is not likely to be typical of the forest type in general, i.e. the carbon stocks are probably lower than average (Carter *et al*. 2017; Puhlick *et al*. 2017). Specific values for disturbed forest may be appropriate.

Represents a nominal estimate of error, equivalent to two times standard deviation, as a percentage of the mean.

TABLE 5.9 (UPDATED[1])
DEFAULT BIOMASS CARBON STOCKS PRESENT ON LAND CONVERTED TO CROPLAND IN THE YEAR FOLLOWING CONVERSION

Crop type by climate region	Ecological zone	Continent	Cropping system	Carbon stock in biomass after one year (ΔC_G) (tonnes C ha^{-1})	Error range#
Annual cropland	All	All	Annual cropland	4.7	± 75%
Perennial cropland	All	All	Agroforestry	See G in Tables 5.1 and 5.2	
	All	All	Monocultures	See G in Table 5.3	

[1] Update to Table 5.9 in the *2006 IPCC Guidelines*

Represents a nominal estimate of error, equivalent to two times standard deviation, as a percentage of the mean.

Tier 2

Tier 2 methods should include some country-specific estimates for biomass stocks and removals due to land conversion, and also include estimates of on-site and off-site losses due to burning and decay following land conversion to Cropland. These improvements can take the form of systematic studies of carbon content and emissions and removals associated with land uses and land-use conversions within the country and a re-examination of default assumptions in light of country-specific conditions. In general, the condition of forests that are converted to grassland or cropland is not likely to be typical of the forest type, i.e. the carbon stocks are probably lower than average. It is *good practice* for countries to evaluate country specific values for disturbed forest under Tier 2.

Default parameters for emissions from burning and decay are provided. However, countries are encouraged to develop country-specific coefficients to improve the accuracy of estimates. The *IPCC Guidelines* use a general default of 0.5 for the proportion of biomass burnt on-site for both Forest Land and Grassland conversions. Research studies suggest that the fraction is highly variable and could be as low as 0.2 (Fearnside, 2000; Barbosa and Fearnside, 1996; and Fearnside, 1990). Updated default proportions of biomass burnt on-site are provided in Chapter 4 (Forest Land) for a range of forest vegetation classes. These defaults should be used for transitions from Forest Land to Cropland. For non-forest initial land uses, the default proportion of biomass left on-site and burnt is 0.35. This default takes into consideration research, which suggests the fraction should fall within the range 0.2 to 0.5 (e.g., Fearnside, 2000; Barbosa and Fearnside, 1996; and Fearnside, 1990). It is *good practice* for countries to use 0.35 or another value within this range, provided that the rationale for the choice is documented. There is no default value for the amount of biomass taken off-site and burnt; countries will need to develop a proportion based on national data sources. In Chapter 4 (Forest Land), the default proportion of biomass oxidized as a result of burning is 0.9, as originally stated in the *GPG-LULUCF*.

The method for estimating emissions from decay assumes that all biomass decays over a period of 10 years. For reporting purposes countries have two options: 1) report all emissions from decay in one year, recognizing that in reality they occur over a 10 year period, and 2) report all emission from decay on an annual basis, estimating the rate as one tenth of the totals. If countries choose the latter option, they should add a multiplication factor of 0.10 to the equation.

Tier 3

Under Tier 3, all parameters should be country-defined using measurements and monitoring for more accurate values rather than the defaults. Process based models and decay functions can also be used.

5.3.1.3 CHOICE OF ACTIVITY DATA

All tiers require estimates of land areas converted to Cropland. The same area estimates should be used for both biomass and soil C calculations on *Land Converted to Cropland*. Higher tiers require greater specificity of areas. At a minimum, the area of Forest Land and natural Grassland converted to Cropland should be identified separately for all tiers. This implies at least some knowledge of the land uses prior to conversion. This may also require expert judgment if Approach 1 in Chapter 3 of these guidelines is used for land area identification.

Tier 1

Separate estimates are required of areas converted to Cropland from initial land uses (i.e., Forest Land, Grassland, Settlements, etc.) to final crop land type (i.e., annual or perennial) (A_{TO_OTHERS}). For example, countries should estimate separately the area of tropical moist forest converted to annual cropland, tropical moist forest converted to perennial cropland, tropical moist Grassland converted to perennial cropland, etc. Although, to allow other pools to equilibrate and for consistency with land area estimation overall, land areas should remain in the conversion category for 20 years (or other period reflecting national circumstances) following conversion. The methodology assumes that area estimates are based on a one-year time frame, which is likely to require estimation on the basis of average rates on land-use conversion, determined by measurements estimates made at longer intervals. If countries do not have these data, partial samples may be extrapolated to the entire land base or historic estimates of conversions may be extrapolated over time based on the judgement of country experts. Under Tier 1 calculations, international statistics such as FAO databases, *GPG-LULUCF* and other sources, supplemented with sound assumptions, can be used to estimate the area of *Land Converted to Cropland* from each initial land use. For higher tier calculations, country-specific data sources are used to estimate all possible transitions from initial land use to final crop type. For perennial woody cropland, the total area of planted perennial woody crops for the age classes within the maturing/harvesting cycle (up to 20 years) is required to estimate all biomass carbon change (ΔC_G). See section 5.2.1.3 for details.

Tier 2

It is *good practice* for countries to use actual area estimates for all possible transitions from initial land use to final crop type. Full coverage of land areas can be accomplished either through analysis of periodic remotely sensed images of land-use and land cover patterns, through periodic ground-based sampling of land-use patterns, or hybrid inventory systems. If finer resolution country-specific data are partially available, countries are encouraged to use sound assumptions from best available knowledge to extrapolate to the entire land base. Historic estimates of conversions may be extrapolated over time based on the judgment of country experts.

Tier 3

Activity data used in Tier 3 calculations should be a full accounting of all land-use transitions to Cropland and be disaggregated to account for different conditions within a country. Disaggregation can occur along political (county, province, etc.), biome, climate, or on a combination of such parameters. In many cases, countries may have information on multi-year trends in land conversion (from periodic sample-based or remotely sensed inventories of land use and land cover). Periodic land-use change matrix need to be developed giving the initial and final land-use areas at disaggregated level based on remote sensing and field surveys.

5.3.1.4 CALCULATION STEPS FOR TIER 1 AND TIER 2

No refinement.

5.3.1.5 UNCERTAINTY ASSESSMENT

No refinement.

5.3.2 Dead organic matter

No refinement.

5.3.3 Soil carbon

Land is typically converted to Cropland from native lands, managed Forest Land and Grassland, but occasionally conversions can occur from Wetlands and seldom Settlements. Regardless of soil type (i.e., mineral or organic), the conversion of land to Cropland will, in most cases, result in a loss of soil C for some years following conversion (Mann, 1986; Armentano and Menges, 1986; Davidson and Ackerman, 1993). Possible exceptions are irrigation of formerly arid lands and conversion of degraded lands to Cropland.

General information and guidance for estimating changes in soil C stocks are provided in Section 2.3.3 of Chapter 2 (including equations), and that section needs to be read before proceeding with a consideration of specific guidelines dealing with cropland soil C stocks. The total change in soil C stocks for *Land Converted to Cropland* is estimated using Equation 2.24 (Chapter 2), which combines the change in soil organic C stocks (SOC stocks) for mineral soils and organic soils; and stock changes associated with soil inorganic C pools (Tier 3 only). This section provides specific guidance for estimating soil organic C stock changes; see Section 2.3.3.1 for discussion on soil inorganic C (no additional guidance is provided in the Cropland section below).

To account for changes in soil C stocks associated with *Land Converted to Cropland*, countries need to have, at a minimum, estimates of the areas of *Land Converted to Cropland* during the inventory time period. If land-use and management data are limited, aggregate data, such as FAO statistics, can be used as a starting point, along with knowledge of country experts of the approximate distribution of land-use types being converted and their associated management. If the previous land uses and conversions are unknown, SOC stocks changes can still be computed using the methods provided in *Cropland Remaining Cropland*, but the land base area will likely be different for croplands in the current year relative to the initial year in the inventory. It is critical, however, that the total land area across all land-use sectors be equal over the inventory time period (e.g., 7 million ha may be converted from Forest Land and Grassland to Cropland during the inventory time period, meaning that croplands will have an additional 7 Million ha in the last year of the inventory, while grasslands and forests will have a corresponding loss of 7 Million ha in the last year). *Land Converted to Cropland* is stratified according to climate regions and major soil types, which could either be based on default or country-specific classifications. This can be accomplished with overlays of climate and soil maps, coupled with spatially-explicit data on the location of land conversions.

5.3.3.1 CHOICE OF METHOD

Inventories can be developed using a Tier 1, 2 or 3 approach with each successive tier requiring more detail and resources than the previous one. It is also possible that countries will use different tiers to prepare estimates for the separate subcategories of soil C (i.e., soil organic C stocks changes in mineral soils and organic soils; and stock changes associated with soil inorganic C pools). Decision trees are provided for mineral soils (Figure 2.5) and organic soils (Figure 2.6) in Section 2.3.3.1 (Chapter 2) to assist inventory compilers with selection of the appropriate tier for their soil C inventory.

Mineral soils

Tier 1

Soil organic C stock changes for mineral soils can be estimated for land-use conversion to Cropland using Equation 2.25 in Chapter 2. For Tier 1, the initial (pre-conversion) soil organic C stock ($SOC_{(0-T)}$) and C stock in the last year of the inventory time period (SOC_0) are computed from the default reference soil organic C stocks (SOC_{REF}) and default stock change factors (F_{LU}, F_{MG}, F_I). Annual rates of stock changes are estimated as the difference in stocks (over time) divided by the time dependence (D) of the Cropland stock change factors (default is 20 years).

Tier 2

The Tier 2 method for mineral soils also uses Equation 2.25, but involves country-specific or region-specific reference C stocks and/or stock change factors and may include disaggregated land-use activity and environmental data. Tier 2 methods for biochar C amendments utilize a top-down approach in which the total amount of biochar generated and added to mineral soil is used to estimate the change in soil organic C stocks with country-specific factors. See Section 2.3.3.1, Chapter 2, Volume IV for more information.

Tier 3

Tier 3 methods will involve more detailed and country-specific models and/or measurement-based approaches along with highly disaggregated land-use and management data. Tier 3 approaches estimate soil C change from land-use conversions to Cropland, and may employ models, data sets and/or monitoring networks. If possible, it is recommended that Tier 3 methods be integrated with estimates of biomass removal and the post-clearance treatment of plant residues (including woody debris and litter), as variation in the removal and treatment of residues (e.g., burning, site preparation) will affect C inputs to soil organic matter formation and C losses through decomposition and combustion. It is important that models be evaluated with independent observations from country-specific or region-specific field locations that are representative of the interactions of climate, soil and cropland management on post-conversion change in soil C stocks.

Tier 3 methods for biochar C amendments can be used to address GHG sources and sinks not captured in Tiers 1 or 2, such as priming effects, changes to N_2O or CH_4 fluxes from soils, and changes to net primary production. More information on Tier 3 methods is provided in Section 2.3.3.1 of Chapter 2, Volume IV.

Organic soils

No refinement.

The *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* provides additional guidance that updates the *2006 IPCC Guidelines for national Greenhouse Gas Inventories*. See section 2.2 of the *2013 Wetlands Supplement* covers Tier 1, 2, and 3 approaches for drained organic soils in cropland.

5.3.3.2 CHOICE OF STOCK CHANGE AND EMISSION FACTORS

Mineral soils

Tier 1

For native unmanaged land, as well as for managed forest lands, settlements and nominally managed grasslands with low disturbance regimes, soil C stocks are assumed equal to the reference values (i.e., land-use, disturbance (forests only), management and input factors equal 1), while it will be necessary to apply the appropriate stock change factors to represent previous land-use systems that are not the reference condition, such as improved and degraded grasslands. It will also be necessary to apply the appropriate stock change factor to represent input and management effects on soil C storage in the new cropland system. Default reference C stocks are found in Table 2.3 (Chapter 2). See the appropriate land-use chapter for default stock change factors.

In the case of transient land-use conversions to Cropland, the stock change factors are given in Table 5.10, and depend on the length of the fallow (vegetation recovery) cycle in a shifting cultivation system, representing an average soil C stock over the crop-fallow cycle. Mature fallow denotes situations where the non-cropland vegetation (e.g., forests) recovers to a mature or near mature state prior to being cleared again for cropland use, whereas in shortened fallow, vegetation recovery is not attained prior to re-clearing. If land already in shifting-cultivation is converted to permanent Cropland (or other land uses), the stock change factors representing shifting cultivation would provide the ‘initial’ C stocks ($SOC_{(0-T)}$) in the calculations using Equation 2.25 (Chapter 2).

TABLE 5.10
SOIL STOCK CHANGE FACTORS (F_{LU}, F_{MG}, F_I) FOR LAND-USE CONVERSIONS TO CROPLAND

Factor value type	Level	Climate regime	IPCC default	Error #	Definition

Land use	Native forest or grassland (non-degraded)	All	1	NA	Represents native or long-term, non-degraded and sustainably managed forest and grasslands.
		Tropical	1	NA	
Land use	Shifting cultivation – Shortened fallow	Tropical	0.64	$\pm$ 50%	Permanent shifting cultivation, where tropical forest or woodland is cleared for planting of annual crops for a short time (e.g., 3-5 yr) period and then abandoned to regrowth.
	Shifting cultivation – Mature fallow	Tropical	0.8	$\pm$ 50%	
Land-use, Management, & Input	Managed forest	(default value is 1)			
Land-use, Management, & Input	Managed grassland	(See default values in Table 6.2)			
Land-use, Management, & Input	Cropland	(See default values in Table 5.5)			

[#] Represents a nominal estimate of error, equivalent to two times standard deviation, as a percentage of the mean. NA denotes 'Not Applicable', where factor values constitute defined reference values.

Tier 2

Estimation of country-specific stock change factors is probably the most important development associated with the Tier 2 approach. Differences in soil organic C stocks among land uses are computed relative to a reference condition, using land-use factors (F_{LU}). Input factors (F_I) and management factors (F_{MG}) are then used to further refine the C stocks of the new cropland system. Additional guidance on how to derive these stock change factors is given in *Croplands Remaining Croplands*, Section 5.2.3.2. See the appropriate chapter for specific information regarding the derivation of stock change factors for other land-use categories (Forest Land in Section 4.2.3.2, Grassland in 6.2.3.2, Settlements in 8.2.3.2, and Other Land in 9.3.3.2).

Reference C stocks can be derived from country-specific data in a Tier 2 approach. Reference values in Tier 1 correspond to non-degraded, unimproved lands under native vegetation, but other reference conditions can also be chosen for Tier 2. In addition, the depth for evaluating soil C stock changes can be different with the Tier 2 method (see also section 6.2.3.1). However, the depth of the reference C stocks (SOC_{REF}) and stock change factors needs to be the same for all land uses (i.e., F_{LU}, F_I, and F_{MG}) to ensure consistency in the application of methods for estimating the impact of land use change on soil C stocks.

The Tier 1 method may over- or under-estimate soil C stock changes on an annual basis, particularly with land use change (e.g., Villarino *et al*. 2014). Therefore, land use change, such as *Cropland converted to Grassland*, may include development of factors that estimate changes over longer periods of time than the default 20 years, and may better match the period of time over which carbon accumulates or is lost from soils due to land use change. When C stock changes extend over periods of many decades, activity data for historical land-use change are needed to estimate the soil C stock changes that are still occurring in the current inventory year.

The carbon stock estimates may be improved when deriving country-specific factors for F_{LU} and F_{MG}, by expressing carbon stocks on a soil-mass equivalent basis rather than a soil-volume equivalent (i.e. fixed depth) basis. This is because the soil mass in a certain soil depth changes with the various operations associated with land use that affect the density of the soil, such as uprooting, land levelling, tillage, and rain compaction due to the disappearance of the cover of tree canopy. However, it is important to realize that all data used to derive stock change factors across all land uses must be on an equivalent mass basis if this method is applied. This will be challenging to do comprehensively for all land uses. See Box 2.2b in Chapter 2, Section 2.3.3.1 for more information.

For biochar C amendments, the parameter F_{perm_p} can be based on H/Corg or O/Corg measured directly from representative samples of biochar, or from published data for biochar produced using similar process conditions as the biochar that is applied to soils in the country. Tier 2 emission factors may be disaggregated based on variation in environmental conditions, such as the climate and soil types, in addition to variation associated with the biochar production methods that generate production types defined by the feedstock type and conversion process. See Section 2.3.3.1, Chapter 2, Volume IV for more information.

Country-specific emission factors (i.e., permanence factors) for biochar C for croplands may be different from the past land use for *Land Converted to Cropland*, and these differences need to be addressed in the calculations. This requires estimating the biochar carbon stocks from past biochar carbon additions that remain in *Land Converted to Cropland* after conversion. The biochar C stocks are then subject to the conditions for cropland, which may lead some additional loss of biochar C.

Tier 3

Constant stock change rate factors *per se* are less likely to be estimated in favor of variable rates that more accurately capture land-use and management effects.

Tier 3 methods for biochar C amendments are country-specific and may involve empirical or process-based models to account for a broader set of impacts of biochar amendments. These methods will likely estimate biochar C stocks and associated changes over time so the biochar C stocks in Land Converted to Cropland will need to be tracked through the land use change process.

More information on Tier 3 methods is provided in Section 2.3.3.1, Chapter 2, Volume IV.

Organic soils

No refinement.

The *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* provides additional guidance that updates the *2006 IPCC Guidelines for national Greenhouse Gas Inventories*. See section 2.2 of the *2013 Wetlands Supplement* covers Tier 1, 2, and 3 approaches for drained organic soils in cropland.

5.3.3.3 CHOICE OF ACTIVITY DATA

Mineral soils

Tier 1 and Tier 2 - Default Equations

For purposes of estimating soil carbon stock change, area estimates of *Land Converted to Cropland* should be stratified according to major climate regions and soil types. This can be based on overlays with suitable climate and soil maps and spatially-explicit data of the location of land conversions. Detailed descriptions of the default climate and soil classification schemes are provided in Chapter 3, Annex 3A.5. Specific information is provided in the each of the land-use chapters regarding treatment of land-use/management activity data (Forest Land in Section 4.2.3.3, Cropland in 5.2.3.3, Grassland in 6.2.3.3, Settlements in 8.2.3.3, and Other Land in 9.3.3.3).

One critical issue in evaluating the impact of *Land Converted to Cropland* on soil organic C stocks is the type of land-use and management activity data. Activity data gathered using Approach 2 or 3 (see Chapter 3 for discussion about approaches) provide the underlying basis for determining the previous land use for *Land Converted to Cropland*. In contrast, aggregate data (Approach 1, Chapter 3) only provide the total amount of area in each land at the beginning and end of the inventory period (e.g., 1985 and 2005). Approach 1 data are not sufficient to determine specific transitions. In this case all Cropland will be reported in the *Cropland Remaining Cropland* category and in effect transitions become step changes across the landscape. This makes it particularly important to achieve coordination among all land sectors to ensure that the total land base is remaining constant over time, given that some land area will be lost and gained within individual sectors during each inventory year due to land-use change.

For biochar C amendments, the activity data for the Tier 2 method includes the total quantities of biochar distributed as amendment to mineral soils. These data must be disaggregated by production type, where production type is defined as a process utilizing a specific feedstock type, and a specific conversion process. Changes in soil C associated with biochar amendments are considered to occur where it is incorporated into soil. However, due to the distributed nature of the land sector in which this can take place, inventory compilers may not have access to data on when or where biochar C amendments occur. Inventory compilers may be able to compile data on the total amount of biochar applied to cropland mineral soils from biochar producers, distributors and/or from those applying biochar to cropland in the country. Note that exported biochar is not included in the total amount of biochar amended to soils in the country.

Additionally, activity data on the amount of biochar amendments may be disaggregated by climate zones and/or soil types if country-specific factors are disaggregated by these environmental variables. The additional climate and soil activity data may be obtained with a survey of biochar distributors and land managers.

Tier 3

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

For biochar C, the additional activity data required to support a Tier 3 method will depend on which processes are represented and environmental variables that are required as input to the model. Priming effects, soil GHG emissions, and plant production responses to biochar all vary with biochar type, climate, and soil type. Furthermore, soil GHG emissions and plant production responses also vary with crop type and management. Therefore, Tier 3 methods may require environmental data on climate zones, soil types, crop types and crop management systems (such as nitrogen fertilizer application rates, and whether soils are flooded for paddy rice production), in addition to the amount of biochar amendments in each of the individual combinations of strata for the environmental variables. More detailed activity data specifying the process conditions for biochar production or the physical and chemical characteristics of the biochar may also be required (such as surface area, cation exchange capacity, pH, and ash content).

Organic soils

No Refinement.

The *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* provides additional guidance that updates the *2006 IPCC Guidelines for national Greenhouse Gas Inventories*. See section 2.2 of the *2013 Wetlands Supplement* covers Tier 1, 2, and 3 approaches for drained organic soils in cropland.

5.3.3.4 CALCULATION STEPS FOR TIER 1

Mineral soils

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

Step 1: Organize data into inventory time periods based on the years in which activity data were collected (e.g., 1990 to 1995, 1995 to 2000, etc.)

Step 2: Determine the amount of *Land Converted to Cropland* by mineral soil types and climate regions in the country at the beginning of the first inventory time period. The first year of the inventory time period will depend on the time step of the activity data (0-T; e.g., 5, 10 or 20 years ago).

Step 3: For Grassland converted to Cropland, classify previous grasslands into the appropriate management system using Figure 6.1. No classification is needed for other land uses at the Tier 1 level.

Step 4: Assign native reference C stock values (SOC_{REF}) from Table 2.3 based on climate and soil type.

Step 5: Assign a land-use factor (F_{LU}), management factor (F_{MG}) and C input levels (F_I) to each grassland based on the management classification (Step 2). Values for F_{LU}, F_{MG} and F_I are given in Table 6.2 for grasslands. Values are assumed to be 1 for all other land uses.

Step 6: Multiply the factors (F_{LU}, F_{MG}, F_I) by the reference soil C stock to estimate an 'initial' soil organic C stock ($SOC_{(0-T)}$) for the inventory time period.

Step 7: Estimate the final soil organic C stock (SOC_0) by repeating Steps 1 to 5 using the same native reference C stock (SOC_{REF}), but with land-use, management and input factors that represent conditions for the cropland in the last (year 0) inventory year.

Step 8: Estimate the average annual change in soil organic C stocks for land converted to Cropland ($\Delta C_{Mineral}$) by subtracting the 'initial' soil organic C stock ($SOC_{(0-T)}$) from the final soil organic C stock (SOC_0), and then dividing by the time dependence of the stock change factors (i.e., 20 years using the default factors). Note: if an inventory time period is greater than 20 years, then divide by the difference in the initial and final year of the time period.

Step 9: Repeat Steps 2 to 8 if there are additional inventory time periods (e.g., 1990 to 2000, 2001 to 2010, etc.). Note that *Land Converted to Cropland* will retain that designation for 20 years. Therefore, inventory time periods that are less than 20 years may need to refer to the previous inventory time period to evaluate if a parcel of land is considered *Land Converted to Cropland* or *Cropland Remaining Cropland*.

A numerical example is given below for Forest Land converted to Cropland on mineral soils, using Equation 2.25 and default reference C stocks (Table 2.3) and stock change factors (Table 5.6).

Example: For a forest on volcanic soil in a tropical moist environment: SOC_{Ref} = 70 tonnes C ha^{-1}. For all forest soils (and for native grasslands) default values for stock change factors (F_{LU}, F_{MG}, F_I) are all 1; thus $SOC_{(0-T)}$ is 70 tonnes C ha^{-1}. If the land is converted into annual cropland, with intensive tillage and low residue C inputs then:

SOC_0 = 70 tonnes C ha^{-1} ● 0.90 ● 1 ● 0.92 = 58.0 tonnes C ha^{-1}.

Thus the average annual change in soil C stock for the area over the inventory time period is calculated as:

(58 tonnes C ha^{-1} – 70 tonnes C ha^{-1}) / 20 yrs = -0.6 tonnes C ha^{-1} yr^{-1}.

Organic soils

No refinement.

The *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* provides additional guidance that updates the *2006 IPCC Guidelines for national Greenhouse Gas Inventories*. See section 2.2 of the *2013 Wetlands Supplement* covers Tier 1, 2, and 3 approaches for drained organic soils in cropland.

5.3.3.5 UNCERTAINTY ASSESSMENT

No refinement.

5.3.4 Non-CO_2 greenhouse gas emissions from biomass burning

No refinement.

5.4 COMPLETENESS, TIME SERIES, QA/QC, AND REPORTING

No refinement.

5.5 METHANE EMISSIONS FROM RICE CULTIVATION

No refinement in the Introduction.

5.5.1 Choice of method

The basic equation to estimate CH_4 emissions from rice cultivation is shown in Equation 5.2. CH_4 emissions are estimated by multiplying daily emission factors by cultivation period[10] of rice and annual harvested areas[11]. In its most simple form, this equation is implemented using national activity data (i.e., national average cultivation period of rice and area harvested) and a single emission factor. However, the natural conditions and agricultural management of rice production may be highly variable within a country. It is *good practice* to account for this variability by disaggregating national total harvested area into sub-units (e.g., harvested areas under different water regimes). Harvested area for each sub-unit is multiplied by the respective cultivation period and emission factor that is representative of the conditions that define the sub-unit (Sass, 2002). With this disaggregated approach, total annual emissions are equal to the sum of emissions from each sub-unit of harvested area.

EQUATION 5.1
CH_4 EMISSIONS FROM RICE CULTIVATION

$$CH_{4\ Rice} = \sum_{i,j,k} (EF_{i,j,k} \bullet t_{i,j,k} \bullet A_{i,j,k} \bullet 10^{-6})$$

Where:

$CH_{4\ Rice}$ = annual methane emissions from rice cultivation, Gg CH_4 yr^{-1}

$EF_{i,j,k}$ = a daily emission factor for i, j, and k conditions, kg CH_4 ha^{-1} day^{-1}

$t_{i,j,k}$ = cultivation period of rice for i, j, and k conditions, day

$A_{i,j,k}$ = annual harvested area of rice for i, j, and k conditions, ha yr^{-1}

i, *j*, and *k* = represent different ecosystems, water regimes, type and amount of organic amendments, and other conditions under which CH_4 emissions from rice may vary

The different conditions that should be considered include rice ecosystem types, flooding pattern before and during cultivation period, and type and amount of organic amendments. Other conditions such as soil type, and rice cultivar can be considered for the disaggregation if country-specific information about the relationship between these conditions and CH_4 emissions are available. The rice ecosystem types and water regimes during cultivation period are listed in Table 5.12. If the national rice production can be sub-divided into agro-climatic zones with different production systems (e.g., flooding patterns), Equation 5.2 should be applied to each region separately. The same applies if rice statistics or expert judgments are available to distinguish management practices or other factors along administrative units (district or province). In addition, if more than one crop is harvested during a given year, emissions should be estimated for each cropping season taking into account possible differences in cultivation practices (e.g., use of organic amendments, flooding pattern before and during the cultivation period).

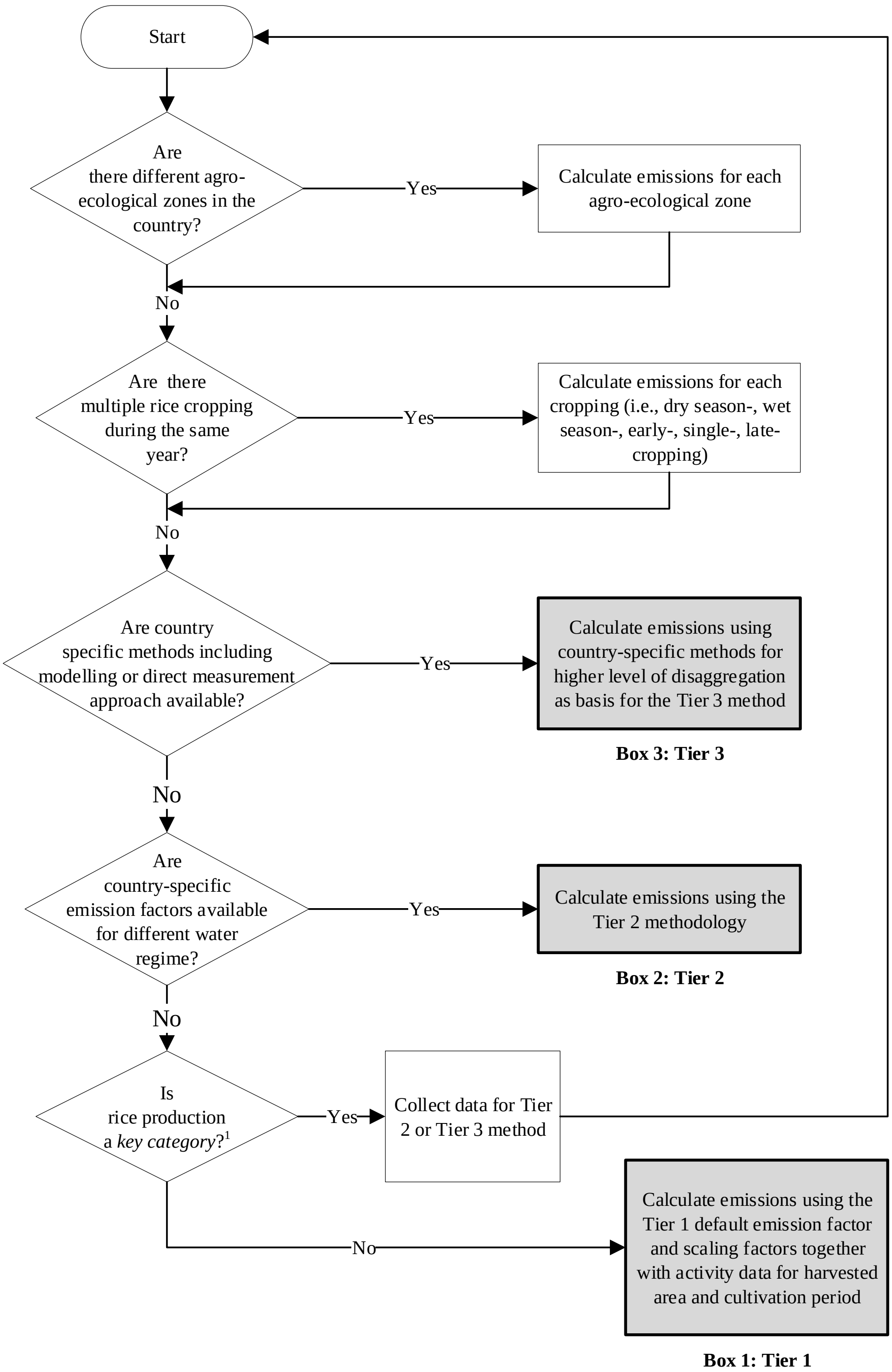
The decision tree in Figure 5.2 guides inventory agencies through the process of applying the *good practice* IPCC approach. Implicit in this decision tree is a hierarchy of disaggregation in implementing the IPCC method. Within this hierarchy, the level of disaggregation utilised by an inventory agency will depend upon the availability of activity and emission factor data, as well as the importance of rice as a contributor to its national greenhouse gas

[10] In the case of a ratoon crop, 'cultivation period' should be extended by the respective number of days.

[11] In case of multiple cropping during the same year, 'harvested area' is equal to the sum of the area cultivated for each cropping.

emissions. The specific steps and variables in this decision tree, and the logic behind it, are discussed in the text that follows the decision tree.

Figure 5.2 Decision tree for CH_4 emissions from rice production



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

Tier 1

Tier 1 applies to countries in which either CH_4 emissions from rice cultivation are not a *key category* or country-specific emission factors do not exist. The disaggregation of the annual harvest area of rice needs to be done for at least three baseline water regimes including irrigated, rainfed, and upland. It is encouraged to incorporate as many of the conditions (*i*, *j*, *k*, etc.) that influence CH_4 emissions (summarized in Box 5.2) as possible. Emissions for each sub-unit are adjusted by multiplying a baseline default emission factor (for field with no pre-season flooding for less than 180 days prior to rice cultivation and continuously flooded fields without organic amendments, EF_c) by various scaling factors as shown in Equation 5.2. The calculations are carried out for each water regime and organic amendment separately as shown in Equation 5.3.

EQUATION 5.2 (UPDATED)
ADJUSTED DAILY EMISSION FACTOR (TIER 1)

$$EF_i = EF_c \bullet SF_w \bullet SF_p \bullet SF_o$$

Where:

EF_i = adjusted daily emission factor for a particular harvested area

EF_c = baseline emission factor for continuously flooded fields without organic amendments

SF_w = scaling factor to account for the differences in water regime during the cultivation period (from Table 5.12)

SF_p = scaling factor to account for the differences in water regime in the pre-season before the cultivation period (from Table 5.13)

SF_o = scaling factor should vary for both type and amount of organic amendment applied (from Equation 5.3 and Table 5.14)

Tier 2

Tier 2 applies the same methodological approach as Tier 1, but country-specific emission factors and/or scaling factors should be used. These country-specific factors are needed to reflect the local impact of the conditions (*i*, *j*, *k*, etc.) that influence CH_4 emissions, preferably being developed through collection of field data (e.g. effects of soil type and rice cultivar). As for Tier 1 approach, it is encouraged to implement the method at the most disaggregated level and to incorporate the multitude of conditions (*i*, *j*, *k*, etc.) that influence CH_4 emissions.

EQUATION 5.2A (NEW)
ADJUSTED DAILY EMISSION FACTOR (TIER 2)

$$EF_i = EF_c \bullet SF_w \bullet SF_p \bullet SF_o \bullet SF_s \bullet SF_r$$

Where:

SF_s = scaling factor for soil type

SF_r = scaling factor for rice cultivar

Tier 3

Tier 3 includes models and monitoring networks tailored to address national circumstances of rice cultivation, repeated over time, driven by high-resolution activity data (e.g. satellite-based and in-situ measurement) and disaggregated at sub-national level. Models can be empirical or mechanistic, but in either case need to be validated with independent observations from country or region-specific studies (Cai *et al.* 2003b; Li *et al.* 2004; Huang *et al.* 2004; and Pathak *et al.* 2005). Tier 3 methodologies may also take into account inter-annual variability triggered by typhoon, flooding, drought, etc. A few countries have used Tier 3 method in their national communications to

UNFCCC[12] [e.g. China and Japan used CH_4MOD (Huang *et al.* 2004) and DNDC-Rice models (Katayanagi *et al.* 2017), and USA used DayCent (Cheng *et al.* 2013)].

BOX 5.2 (UPDATED)
CONDITIONS INFLUENCING CH_4 EMISSIONS FROM RICE CULTIVATION

The following rice cultivation characteristics should be considered in calculating CH_4 emissions as well as in developing emission factors:

Regional differences in rice cropping practices: If the country is large and has distinct agricultural regions with different climate and/or production systems (e.g., flooding patterns), a separate set of calculations should be performed for each region.

Multiple crops: If more than one rice crop is harvested on a given area of land during the year, and the growing conditions vary among cropping seasons, calculations should be performed for each season.

Water regime: In the context of this chapter, water regime is defined as a combination of (i) ecosystem type and (ii) flooding pattern.

Ecosystem type: At a minimum, separate calculations should be undertaken for each rice ecosystem (i.e., irrigated, rainfed, and deep-water rice production).

Flooding pattern: Flooding pattern of rice fields has a significant effect on CH_4 emissions (Sass *et al.* 1992; Yagi *et al.* 1996; Wassmann *et al.* 2000; Pathak and Wassmann 2007; Pathak *et al*. 2003). Rice ecosystems can further be distinguished into continuously and intermittently flooded (irrigated rice), and regular rainfed, drought prone, and deep water (rainfed), according to the flooding patterns during the cultivation period. Also, flooding pattern before cultivation period should be considered (Yagi *et al.* 1998; Cai *et al.* 2000; 2003a; Fitzgerald *et al.* 2000).

Organic amendments to soils: Organic material incorporated into rice soils increases CH_4 emissions (Schütz *et al.* 1989; Yagi and Minami 1990; Sass *et al.* 1991; Pathak and Wassmann 2007; Pathak *et al*. 2003). The impact of organic amendments on CH_4 emissions depends on type and amount of the applied material which can be described by a dose response curve (Denier van der Gon and Neue 1995; Yan *et al.* 2005). Organic material incorporated into the soil can either be of endogenous (straw, green manure, etc.) or exogenous origin (compost, farmyard manure, etc.). Calculations of emissions should consider the effect of organic amendments.

Other conditions: It is known that other factors, such as soil type (Sass *et al.* 1994; Wassmann *et al.* 1998; Huang *et al.* 2002), rice cultivar (Watanabe and Kimura 1998; Wassmann and Aulakh 2000), sulphate containing amendments (Lindau *et al.* 1993; Denier van der Gon and Neue 2002), etc., can significantly influence CH_4 emissions. Inventory agencies are encouraged to make every effort to consider these conditions if country-specific information about the relationship between these conditions and CH_4 emissions is available.

5.5.2 Choice of emission and scaling factors

Tier 1

Scaling factors are used to adjust the baseline emission factor (EF_c), as provided in Table 5.11, to account for the various conditions discussed in Box 5.2, which result in adjusted daily emission factors (EF_i) for a particular sub-unit of disaggregated harvested area according to Equation 5.3. Default cultivation period is provided in Table 5.11A which can be used for Equation 5.1.

The most important scaling factors, namely water regime during and before cultivation period and organic amendments, are represented in Tables 5.12, 5.13 and 5.14, respectively, through default values. Country-specific

[12] https://unfccc.int/

scaling factors should only be used if they are based on well-researched and documented measurement data. It is encouraged to consider soil type, rice cultivar, and other factors, if available.

TABLE 5.11 (UPDATED)
DEFAULT CH_4 BASELINE EMISSION FACTOR ASSUMING NO FLOODING FOR LESS THAN 180 DAYS PRIOR TO RICE CULTIVATION, AND CONTINUOUSLY FLOODED DURING RICE CULTIVATION WITHOUT ORGANIC AMENDMENTS

World		Regional		
Emission factor (kg CH_4 ha^{-1} d^{-1})	**Error range (kg CH_4 ha^{-1} d^{-1})**	**Region**	**Emission factor (kg CH_4 ha^{-1} d^{-1})**	**Error range (kg CH_4 ha^{-1} d^{-1})**
1.19	0.80 – 1.76	Africa [1]	1.19	0.80 – 1.76
		East Asia	1.32	0.89 – 1.96
		Southeast Asia	1.22	0.83 – 1.81
		South Asia	0.85	0.58 – 1.26
		Europe	1.56	1.06 – 2.31
		North America	0.65	0.44 – 0.96
		South America	1.27	0.86 – 1.88

Note: Emission factors and error ranges were estimated based on 95% confidence interval, using statistical model with updated database; See Annex 5A.2 for more information.

[1] For Africa, the global estimate is used due to lack of data.

TABLE 5.11A (NEW)
DEFAULT CULTIVATION PERIOD OF RICE

World		Regional		
Cultivation Period (day)	**Error range (day)**	**Region**	**Cultivation Period (day)**	**Error Range (day)**
113	74– 152	Africa [1]	113	74 – 152
		East Asia	112	73 – 147
		Southeast Asia	102	78 – 150
		South Asia	112	90 – 140
		Europe	123	111 – 153
		North America	139	110 – 165
		South America	124	110 – 146

Note: Cultivation period was calculated from updated database, and the error range or uncertainty was based on the 2.5th percentile to 97.5th percentile of the distribution of ratios; See Annex 5A.2 for more information.

[1] For Africa, the global estimate is used due to lack of data.

Water regime during the cultivation period (SFw): Table 5.12 provides default scaling factors and error ranges reflecting different water regimes. The aggregated case refers to a situation when activity data are only available for rice ecosystem types, but not for flooding patterns (see Box 5.2). In the disaggregated case, flooding patterns can be distinguished in the form of three subcategories as shown in Table 5.12. It is *good practice* to collect more disaggregated activity data and apply disaggregated case SF_w whenever possible.

TABLE 5.12 (UPDATED)
DEFAULT CH_4 EMISSION SCALING FACTORS FOR WATER REGIMES DURING THE CULTIVATION PERIOD RELATIVE TO CONTINUOUSLY FLOODED FIELDS

Water regime		Aggregated case		Disaggregated case	
		Scaling factor (SFw)	Error range	Scaling factor (SFw)	Error range
Upland [a]		0	-	0	-
Irrigated [b]	Continuously flooded	0.60	0.44 – 0.78	1.00	0.73 – 1.27
	Single drainage period			0.71	0.53 – 0.94
	Multiple drainage periods			0.55	0.41 – 0.72
Rainfed and deep water [c]	Regular rainfed	0.45	0.32 – 0.62	0.54	0.39 – 0.74
	Drought prone			0.16	0.11 – 0.24
	Deep water	0.06	0.03 – 0.12	0.06	0.03 – 0.12

Source: Scaling factors and error ranges (based on 95% confidential interval) were determined using statistical model and updated database; see Annex 5A.2 for more information.

Notes:

[a] Fields are never flooded for a significant period of time.

[b] Fields are flooded for a significant period of time and the water regime is fully controlled.

• Continuously flooded: Fields have standing water throughout the rice growing season and may only dry out for harvest (end-season drainage).

• Single drainage period: Fields have a single drainage event and period during the cropping season at any growth stage, in addition to the end of season drainage.

• Multiple drainage periods: Fields have more than one drainage event and period of time without flooded conditions during the cropping season, in addition to an end of season drainage, including alternate wetting and drying (AWD).

[c] Fields are flooded for a significant period of time with water regimes that depend solely on precipitation.

• Regular rainfed: The water level may rise up to 50 cm during the cropping season.

• Drought prone: Drought periods occur during every cropping season.

• Deep-water rice: Water level rises to more than 50 cm above the soil for a significant period of time during the cropping season.

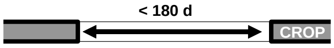
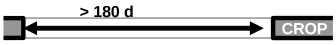
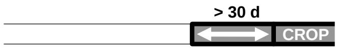
Other rice ecosystem categories, like swamps and inland, saline or tidal wetlands may be discriminated within each sub-category.

Water regime before the cultivation period (SF_p): Table 5.13 provides default scaling factors for water regime before the cultivation period, which can be used when country-specific data are unavailable. This table distinguishes four different water regimes prior to rice cultivation, namely:

1. Non-flooded pre-season < 180 days, which often occurs under double cropping of rice;
2. Non-flooded pre-season > 180 days, e.g., single rice crop following a dry fallow period;
3. Flooded pre-season in which the minimum flooding interval is set to 30 days; i.e., shorter flooding periods (usually done to prepare the soil for ploughing) will not be included in this category; and
4. Non-flooded pre-season in which the rice fields were not flooded for > 365 days such as upland crop–paddy rotation.

When activity data for the pre-season water status are not available, aggregated case factors can be used. It is *good practice* to collect more disaggregated activity data and apply disaggregated case of SF_p. Scaling factors for additional water regimes can be applied if country-specific data are available. Note that the scaling factor SF_p indicates the water management condition of a rice field before planting, which consequently affects the seasonal CH_4 emission. SF_p, however, is only used to estimate CH_4 emission during the rice growing period, and cannot be used to quantify CH_4 emissions that occurred before the cultivation period or after harvest (i.e. outside of rice growing season, such as CH_4 emission during winter flooding period).

TABLE 5.13 (UPDATED)
DEFAULT CH_4 EMISSION SCALING FACTORS FOR WATER REGIMES BEFORE THE CULTIVATION PERIOD

Water regime prior to rice cultivation (schematic presentation showing flooded periods as shaded)		Aggregated case		Disaggregated case	
		Scaling factor (SF_p)	Error range	Scaling factor (SF_p)	Error range
Non flooded pre-season <180 d		1.22	1.08 – 1.37	1.00	0.88 – 1.12
Non flooded pre-season >180 d				0.89	0.80 – 0.99
Flooded pre-season (>30 d)[a,b]				2.41	2.13 – 2.73
Non-flooded pre-season >365 d [c]				0.59	0.41 – 0.84

Source: Scaling factors and error ranges (based on 95% confidential interval) were determined using statistical model and updated database; see Annex 5A.2 for more information.

[a] Short pre-season flooding periods of less than 30 d are not considered in selection of SFp

[b] For calculation of pre-season emission see below (section on completeness)

[c] Refers to "upland crop - paddy rotation" or fallow without flooding in previous year.

Organic amendments (SF_o): It is *good practice* to develop scaling factors that incorporate information on the type and amount of organic amendment applied (compost, farmyard manure, green manure, and rice straw). On an equal mass basis, more CH_4 is emitted from amendments containing higher amounts of easily decomposable carbon and emissions also increase as more of each organic amendment is applied. Equation 5.3 and Table 5.14 present an approach to vary the scaling factor according to the amount of different types of amendment applied. Rice straw is often incorporated into the soil after harvest. In the case of a long fallow after rice straw incorporation, CH_4 emissions in the ensuing rice-growing season will be less than the case that rice straw is incorporated just before rice transplanting (Fitzgerald *et al.* 2000). Therefore, the timing of rice straw application was distinguished. An uncertainty range of 0.54-0.64 can be adopted for the exponent 0.59 in Equation 5.3.

EQUATION 5.3
ADJUSTED CH_4 EMISSION SCALING FACTORS FOR ORGANIC AMENDMENTS

$$SF_o = \left(1 + \sum_i ROA_i \bullet CFOA_i\right)^{0.59}$$

Where:

SF_o = scaling factor for both type and amount of organic amendment applied

ROA_i = application rate of organic amendment *i*, in dry weight for straw and fresh weight for others, tonne ha^{-1}

$CFOA_i$ = conversion factor for organic amendment *i* (in terms of its relative effect with respect to straw applied shortly before cultivation) as shown in Table 5.14.

TABLE 5.14 (UPDATED) DEFAULT CONVERSION FACTORS FOR DIFFERENT TYPES OF ORGANIC AMENDMENTS		
Organic amendment	**Conversion factor (CFOA)**	**Error range**
Straw incorporated shortly (<30 days) before cultivation[a]	1.00	0.85 – 1.17
Straw incorporated long (>30 days) before cultivation[a]	0.19	0.11 – 0.28
Compost	0.17	0.09 – 0.29
Farm yard manure	0.21	0.15 – 0.28
Green manure	0.45	0.36 – 0.57

Source: Conversion factors and error ranges (based on 95% confidential interval) were determined using statistical model and updated database; see Annex 5A.2 for more information.

[a] Straw application means that straws are incorporated into the soil. It does not include cases where straws are just placed on soil surface, and straws that were burnt on the field.

Tier 2

Inventory agencies can use country-specific emission factors from field measurements that cover the conditions of rice cultivation in their respective country. Box 5.2a provides information about measuring methane emissions for developing a baseline emission factor for rice cultivation. It is *good practice* to compile country-specific data bases on available field measurements which supplement the Emission Factor database [13] by other measurement programs (e.g., national) not yet included in this data base. However, certain standard QA/QC requirements apply to these field measurements (see Section 5.5.5).

In Tier 2, inventory agencies can define the baseline management according to the prevailing conditions found in their respective country and determine country-specific emission factors for such a baseline. Then, inventory agencies can also determine country-specific scaling factors for management practices other than the baseline. In case where country-specific scaling factors are not available, default scaling factors can be used. However, this may require some recalculation of the scaling factors given in Tables 5.12 to 5.14 if the condition is different from the baseline.

Soil type (SF_s) and rice cultivar (SF_r): In some countries, emission data for different soil types and rice cultivar are available and can be used to derive SFs and SFr, respectively, for Tier 2 method. Both experiments and mechanistic knowledge confirm the importance of these factors, but large variations within the available data do not allow one to define reasonably accurate default values for Tier 1 method.

Tier 3

Tier 3 approaches do not require choice of emission factors, but are instead based on a thorough understanding of drivers and parameters (see above).

[13] https://www.ipcc-nggip.iges.or.jp/EFDB/main.php

BOX 5.2A (NEW)
***GOOD PRACTICE* GUIDANCE FOR DEVELOPING BASELINE EMISSION FACTORS (EF) FOR CH_4 EMISSIONS FROM RICE CULTIVATION**

The following information provides *good practices* in performing manual measurement of methane emissions using the closed-chamber technique for continuously flooded rice fields with recommended fertilizer application and no organic amendment. The data can be used to develop country- and region-specific EFc.

Chamber Design: It is *good practice* to use lightweight material that is break resistant and inert to reactions with CH_4 (e.g., acrylic and PVC). It may be a rectangular or cylindrical chamber, covering at least two rice hills. The chamber height must be higher than the rice plant. If necessary, use a base with a grove that can be filled with water to ensure a gas-tight closure. The chamber is equipped with a small fan, a thermometer, a vent hole with a stopper, and a gas sampling port (e.g., a flexible tube connected to a valve).

Field Set up and Experimental Design: Select a field that is homogeneous with respect to soil properties. Use an appropriate experimental design with at least 3 replications.

Sampling Strategies: Sampling can be done 1 or 2 times per day between mid-morning and late morning period, and at least once a week for the whole growing period. More frequent measurements are needed during agricultural management events (e.g., irrigation, drainage, and N fertilization). All treatments would have to be measured at the same time. At each sampling time, it is *good practice* to obtain 3 to 4 gas samples within 30 minutes after closure of the chamber.

For gas sampling, the use of a syringe or a pump is recommended depending on the required sample volume. Plastic or glass containers can be used for collecting samples and should be transferred to a laboratory and analyzed within the allowable storage period.

Gas Analysis: Use gas chromatograph (GC) equipped with a flame ionization detector (FID) for analysis. Calibrate the GC before every analysis, using certified standard gases.

Data Processing: Use a linear regression of the gas concentration inside the chamber against time to calculate the hourly flux. Identify the reasons of non-linearity (if exists) for the validation and correction of calculated flux. Use trapezoidal integration to calculate cumulative gas emissions from the hourly flux data.

Deriving Emission Factor: Flux data from several sites, regions, or environmental conditions that conform to the requirements for a continuously flooded rice system with no organic amendments, can be used to derive region- or country-specific EFs based on a simple average and standard deviation. The compiler could also derive disaggregated EFs using regression models to predict the values for different regions and/or environmental conditions.

For more details refer to Minamikawa *et al*. (2015) and Sanders and Wassmann (2014).

5.5.3 Choice of activity data

In addition to the essential activity data requested above, it is *good practice* to match data on organic amendments and soil types to the same level of disaggregation as the activity data. It may be necessary to complete a survey of cropping practices to obtain data on the type and amount of organic amendments applied.

Activity data are primarily based on harvested area statistics, which should be available from a national statistics agency as well as complementary information on cultivation period and agronomic practices. The activity data should be broken down by regional differences in rice cropping practices or water regime (see Box 5.2). Harvested area estimates corresponding to different conditions may be obtained on a countrywide basis through accepted methods of reporting. The use of locally verified areas would be most valuable when they are correlated with available data for emission factors under differing conditions such as climate, agronomic practices, and soil properties. If these data are not available in-country, they can be obtained from international data sources: e.g., the World Rice Statistics on the website of International Rice Research Institute (IRRI[14]), which include harvest area of rice by ecosystem type for major rice producing counties, a rice crop calendar for each country, and other useful information, and the FAOSTAT on the website of FAO[15], where data of rice area harvested can be obtained. The use of locally verified areas would be most valuable when they are correlated with available data for emission

[14] http://www.irri.org/science/ricestat/

[15] www.fao.org/faostat/

factors under differing conditions such as climate, agronomic practices, and soil properties. It may be necessary to consult local experts for a survey of agronomic practices relevant to methane emissions (organic amendments, water management, etc.).

Most likely, activity data will be more reliable as compared to the accuracy of the emission factors. However, for various reasons the area statistics may be biased and a check of the harvested area statistics for (parts of) the country with remotely sensed data is encouraged.

In addition to the essential activity data requested above, it is *good practice*, particularly in Tiers 2 and 3 approaches, to match data on organic amendments and other conditions, e.g., soil types, to the same level of disaggregation as the activity data.

5.5.4 Example Calculation for Tier 1

An example is provided for estimating methane emission from rice cultivation, with the following background information.

A country in Southeast Asia has rice area of 3 million hectares, with 50percent of the area classified as irrigated, 30percent rainfed, 15percent upland, and 5percent deep water. Irrigated areas are planted for 2 growing seasons annually. Rice growing periods are 102 days, except for deep water rice which has 220 days. For irrigated areas, 50percent is continuously flooded and 50percent is managed with multiple drainage periods. All irrigated areas are not flooded for less than 180 days prior to cultivation, while rainfed and upland areas are not flooded for more than 180 days prior to cultivation. Deepwater rice areas are flooded for 30 days prior to cultivation. For irrigated areas, 2 tonnes/ha of straw residues are incorporated shortly before cultivation (less than 30 days).

Table 5.14a shows the calculation for total rice harvested area in a given year. Cropping season refers to the number of times rice is harvested per year. The calculation for adjusted daily emission factor is presented in Table 5.14b using Equation 5.2. The scaling factor for organic amendment (SF_O), for irrigated rice field, is computed using Equation 5.3 for rice straw application rate of 2 tonnes/ha and conversion factor (CFOA) of 1.0 as provided in Table 5.14. Based on Equation 5.1, the total methane emission is 410.47 Gg CH_4/yr, as shown in Table 5.14c.

TABLE 5.14A (NEW)
CALCULATION FOR TOTAL HARVESTED AREA

Rice Ecosystem	Rice Area (ha)	% of Total Area	Cropping Season (yr^{-1})	Harvested Area (ha yr^{-1})
	A	**B**	**C**	**D = (A x C)**
Irrigated				
- Irrigated, continuously flooded	750,000	25	2	1,500,000
- Irrigated, with multiple drainage periods	750,000	25	2	1,500,000
Rainfed	900,000	30	1	900,000
Upland	450,000	15	1	450,000
Deepwater	150,000	5	1	150,000
Total	**3,000,000**	**100**		**4,500,000**

TABLE 5.14B (NEW)
CALCULATION FOR ADJUSTED DAILY EMISSION FACTOR

Rice Ecosystem	Baseline Emission Factor (EFc) ($kg\ CH_4\ ha^{-1}\ d^{-1}$) [from Table 5.11 (Updated)]	Scaling Factor for Water Regime during Cultivation (SFw) [from Table 5.12 (Updated)]	Scaling Factor for Pre-season Water Regime (SFp) [from Table 5.13 (Updated)]	Scaling Factor for Organic Amendment (SFo) [using Equation 5.3 and Table 5.14 (Updated]	Adjusted Daily Emission Factor (EFi) [$kg\ CH_4\ ha^{-1}\ d^{-1}$]
	E	F	G	H	I= (E x F x G x H)
Irrigated					
- Irrigated, continuously flooded	1.22	1.00	1.00	1.21	1.48
- Irrigated, with multiple drainage periods	1.22	0.55	1.00	1.21	0.81
Rainfed	1.22	0.54	0.89	1.00	0.59
Upland	1.22	0	0.89	1.00	0.00
Deepwater	1.22	0.06	2.41	1.00	0.18

TABLE 5.14C (NEW)
CALCULATION FOR TOTAL METHANE EMISSIONS FROM RICE CULTIVATION

Rice Ecosystem	Harvested Area ($ha\ yr^{-1}$) [from Table 5.14a (New)]	Adjusted Daily Emission Factor (EFi) [$kg\ CH_4\ ha^{-1}\ d^{-1}$] [from Table 5.14b (New)]	Cultivation Period (days)	Methane Emissions ($Gg\ CH_4\ y^{-1}$)
	D	I	J	K= [(D x I x J)/10^6]
Irrigated				
- Irrigated, continuously flooded	1,500,000	1.48	102	226.44
- Irrigated, with multiple drainage periods	1,500,000	0.81	102	123.93
Rainfed	900,000	0.59	102	54.16
Upland	450,000	0.00	102	-
Deepwater	150,000	0.18	220	5.94
Total	**4,500,000**			**410.47**

5.5.5 Uncertainty assessment

The general principles of uncertainty assessment relevant for national emission inventories are elucidated in Volume 1, Chapter 3. The uncertainty of emission and scaling factors may be influenced by climatic, temporal, and spatial heterogeneity. Reducing the uncertainty depends on a better understanding of the spatial heterogeneity and correlation among these variables and the complexity of the mechanisms driving methane emission (Zhang *et al*. 2017).

For this source category, *good practice* should permit determination of uncertainties using standard statistical methods when enough experimental data are available. Studies to quantify some of this uncertainty are rare but available (e.g., for soil type induced variability). The variability found in such studies is assumed to be generally valid. For more detail, see Sass (2002).

Important activity data necessary to assign scaling factors (i.e., data on cultural practices and organic amendments) may not be available in current databases/statistics. Estimates of the fraction of rice farmers using a particular practice or amendment must then be based on expert judgement, and the uncertainty range in the estimated fraction should also be based on expert judgement. As a default value for the uncertainty in the fraction estimate as ± 0.2 (e.g., the fraction of farmers using organic amendment estimated at 0.4, the uncertainty range being 0.2 - 0.6). Volume 1, Chapter 3 provides advice on quantifying uncertainties in practice including combining expert judgements and empirical data into overall uncertainty estimates.

In the case of CH_4 emissions from rice cultivation, the uncertainty ranges of Tier 1 values (emission and scaling factors) can be adopted directly from Tables 5.11-5.14. Ranges are defined as the standard deviation about the mean, indicating the uncertainty associated with a given default value for this source category. The exponent in Equation 5.3 is provided with an uncertainty range of 0.54 - 0.64. Uncertainty assessment of Tier 2 and Tier 3 approaches will depend on the respective data-base and model used. Therefore, it is *good practice* to apply general principles of statistical analysis as outlined in Volume 1, Chapter 3 as well as model approaches as outlined in Volume 4, Chapter 3, Section 3.5.

5.5.6 Completeness, time series, QA/QC, and reporting

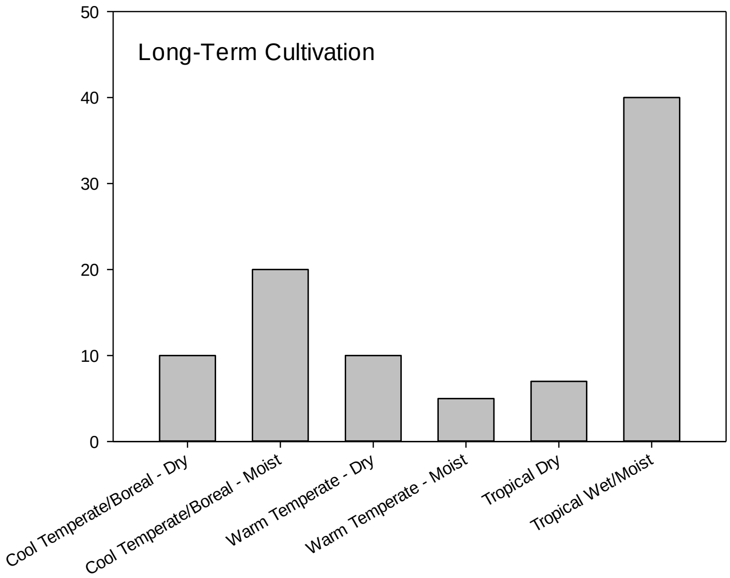
No Refinement.

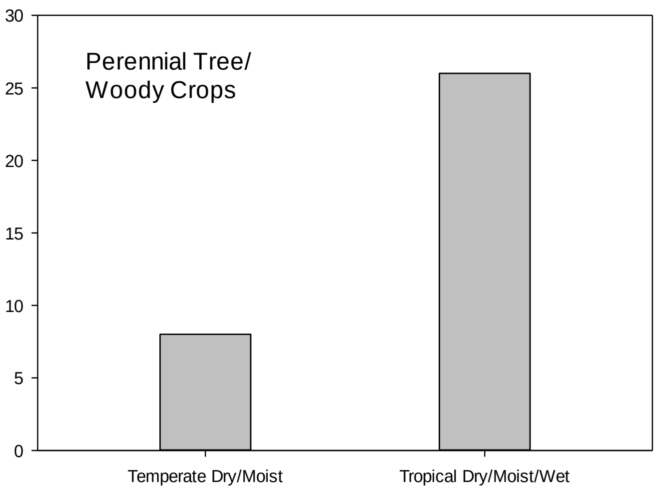
Annex 5A.1 Estimation of default stock change factors for mineral soil C emissions/removals for cropland

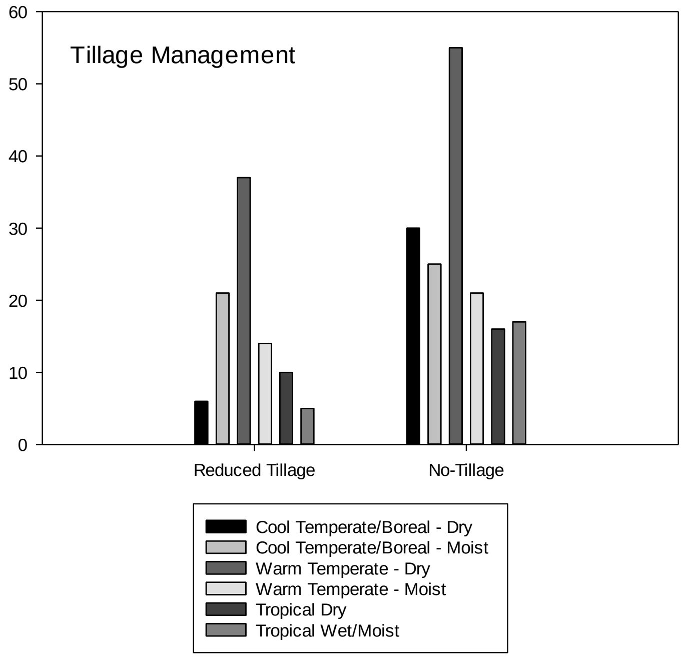
Long-Term Cultivation, Perennial Crops and Tillage Management Factors:

Default stock change factors have been updated in Table 5.5 based on an analysis of a global dataset of experimental results for tillage long-term cultivation, and perennial crops to a 30cm depth. The land-use factor for long-term cultivation and perennial crops represents the change in carbon that occurs after 20 or more years of continuous cultivation or perennial crop production, respectively. Tillage factors represent the effect on C stocks at 20 years following the management change. Data were compiled from published literature based on the following criteria: a) must be an experiment with a control and treatment; b) provide soil organic C stocks or the data needed to compute soil organic C stocks (bulk density, OC content, gravel content); c) provide depth of measurements; d) provide the number of years from the beginning of the experiment to C stock sample collection; and c) provide location information.

There were 303 published studies with 2383 observations for long-term cultivation and perennial tree/woody crops, and 212 published studies with 2046 observations for reduced tillage and no-tillage (References provided at bottom of Table 5.5). The histograms below provide summaries of the distribution of published studies for climate regions.







Semi-parametric mixed effect models were developed to estimate the new factors (Breidt *et al*. 2007). Several variables were tested including depth, number of years since the management change, climate, the type of management change (e.g., reduced tillage vs. no-till), and the first-order interactions among the variables. Variables and interactions terms were retained in the model if they met an alpha level of 0.05 and decreased the Akiake Information Criterion by two. For depth, data were not aggregated to a standardized set of depths but rather each of the original depth increments were used in the analysis (e.g., 0-5 cm, 5-10 cm, and 10-30 cm) as separate observations of stock changes. Similarly, time series data were not aggregated, even though those measurements are taken from the same plots. Consequently, random effects were included to account for the dependencies in times series data and among data points representing different depths from the same study.

Special consideration was given to representing depth increments in order to avoid aggregating data across increments from the original experiments. Data are collected by researchers at various depths that do not match among studies. We created a custom set of covariates, which are functions of the increment endpoints. These functions come from integrating the underlying quadratic function over the increments. This approach was needed in order to make statistically valid inferences with the semi-parametric mixed effect model techniques, and to avoid errors associated with aggregating data into a uniform set of depth increments.

Using this customized approach, we estimated land use and management factors to a 30 cm depth. Uncertainty was quantified based on the prediction error for the model, and represents a 95percent confidence interval for each of the factor values. The resulting confidence intervals can be used to construct probability distribution functions with a normal density for propagating error through the inventory calculations.

Paddy Rice Land-Use Factors:

Evidence from chronosequences with up to 2000 years of rice cultivation history show rice paddy production accumulates soil organic carbon at a fast rate during the first few decades, and then continues to accumulate carbon at a slower rate until a steady-state is reached at about 300 years (Huang *et al*. 2015; Kölbl *et al*. 2014). To update this land use factor for paddy rice, we conducted a literature review and collected the field experiment data of soil carbon stock changes in paddy rice fields that are available in peer-reviewed journals (References provided at bottom of Table 5.5). For each long-term experiment site, data were compiled for conventional management (e.g., normal levels for N, P, K chemical fertilizer applications, rice straw residue management and organic amendments). We calculated the ratio of soil organic carbon (tonne C ha^{-1} for 0-30 cm soil depth) between survey years for the paired comparisons between paddy rice and corresponding native vegetation. The length of time ranged from 15 to 25 years. The resulting estimates capture the large increase in carbon in the first few decades after rice cultivation, and therefore, are considered conservative because carbon can still increase at a slower rate for several more years (Huang *et al*. 2015; Kölbl *et al*. 2014). The land use factor for paddy rice is estimated as the average of these ratios, and uncertainty is based on the 2.5 percentile to 97.5 percentile of the distribution of ratios.

Annex 5A.2 Background for developing emission factors and scaling factors for methane emission from paddy field, using scientific literature

1. **Collection of data**

- Since 2004, there exists a large body of field measurements of CH_4 emission from rice fields across the world. The data set of Yan *et al.* 2005 (which is the data set used in developing the default emission factor and scaling factors in the IPCC *2006 IPCC Guidelines*) was updated with all studies conducted through 30 June 2017, expanding the dataset with observations of CH_4 emission from rice fields around the world.
- A comprehensive search was performed of published literature, which report field measurements of CH_4, as described previously in the paper by Yan *et al.* 2005. This included a keyword search for topics such as rice or paddy*; methane or CH_4 or greenhouse gas*; and flux* or emission*, in the ISI Web of Science (Thomson Reuters, New York, NY, USA) and Google Scholar (Google, Mountain View, CA, USA).
- From this comprehensive search, the following information was compiled: (i) the average CH_4 flux in the rice-growing season; (ii) integrated seasonal emission; (iii) water regime during and before the rice-growing season; (iv) the timing, type and amount of organic amendment; (v) soil properties (i.e., SOC and soil pH); (vi) location, agroecological zone, and year of experiment or studies; and (viii) duration and season of measurement.
- The following information describes the criteria for selecting data that were included in the data set:

  (i) As suggested previously by Yan *et al.* 2005, hourly or daily flux is used in the compilation because it has a better index of emission strength than the integrated seasonal emission. When the average daily CH_4 flux was not directly reported, the value is estimated using integrated seasonal emissions divided by the measurement period.

  (ii) Water regimes were categorized into following conditions: (i) continuous flooding; (ii) single drainage; (iii) multiple drainage; (iv) rainfed; and (v) deep water. The pre-season water regime was classified as: (i) non flooded pre-season for less than 180 days; (ii) non flooded pre-season for more than 180 days; (iii) flooded pre-season for more than 30 days; and (iv) non-flooded pre-season for more than 365 days. See Table 5.15 for the illustration of the water regimes before the cultivation period.

  (iii) For organic amendments, the data were classified as (i) straw incorporated shortly (i.e. less than 30 days) before cultivation; (ii) straw incorporated long (i.e. more than 30 days) before cultivation; (iii) compost; (iv) farmyard manure; and (v) green manure. Data for rice straw are expressed in dry weight, while for other organic materials data are expressed in fresh weight.

  (iv) To account for the spatial variability of CH_4 emissions at the global scale, experimental sites were classified into different zones based on their climatic conditions. Using IRRI's climatic classification (IRRI, 2002), Asian rice fields were categorized into six agro-ecological zone: (i) warm arid and semi-arid tropics; (ii) warm sub-humid tropics; (iii) warm humid tropics; (iv) warm arid and semi-arid sub-tropics with summer rainfall; (v) warm sub-humid sub-tropics with summer rainfall; and (vi) warm/cool humid sub-tropics with summer rainfall. Rice fields in the other region of the world were grouped into three regions, i.e., Latin America, Europe and United States.

  (v) For soil properties, because of the limited availability of information, only soil organic carbon (SOC) and soil pH (as continuous variables) were included in the data set. If soil organic matter content rather than SOC was reported, it was converted to SOC using a Bemmelen index value of 0.58. To meet the requirement of the statistical model, measurements without information for three continuous variables (i.e. SOC data, soil pH and the amount of organic amendment) were excluded. The final dataset used in the analysis included 1089 measurements, from 122 rice fields across the world. In this data set, measurements from Asian rice fields increased from 554 (Yan *et al.* 2005) to

942. In addition, 147 measurements from other regions of the world were added to the datasets (dataset provided in Wang *et al.* 2018).

2. **Processing and compilation of data**

Consistent with previous study by Yan *et al.* (2005), the following linear mixed model, suitable for analyzing unbalanced data (Speed *et al.* 2013), was used to determine the effect of controlling variables on CH_4 flux from rice fields:

EQUATION 5A.2.1 (NEW)
EFFECT OF CONTROLLING VARIABLES ON CH_4 FLUX FROM RICE FIELDS

$$\ln(flux) = \text{constant} + \text{a} \bullet \ln(SOC) + pH_h + PW_i + WR_j + CL_k + OM_l \bullet \ln(1 + AOM_l)$$

Where:

$\ln(flux)$ = natural logarithm of average CH_4 flux (mg CH_4 m^{-2} h^{-1}) during the rice-growing season

SOC = soil organic carbon content, %

constant = the intercept of the mixed linear model, dimensionless

"a" = represents the effect on soil organic carbon, dimensionless

pH_h = soil pH, dimensionless

PW_i = pre-season water regime (e.g. continuous flooding; single drainage; multiple drainage; rainfed; and deep water), dimensionless

WR_j = water regime in the rice-growing season (e.g. non flooded pre-season for less than 180 days; non flooded pre-season for more than 180 days; flooded pre-season for more than 30 days; and non-flooded pre-season for more than 365 days), dimensionless

CL_k = climate type expressed using IRRI's agro-ecological zone for Asia; other regions were categorized into Europe, Latin America and United States, dimensionless

OM_l = organic amendment (straw incorporated shortly (<30 days) before cultivation, straw incorporated long (>30 days) before cultivation, compost, farmyard manure, and green manure), dimensionless

AOM_l = amount of organic amendment, tonne ha^{-1}

In this model soil pH was treated as a categorical variable and grouped into the following "h" classes: <4.5, 4.5-5.0, 5.0-5.5, 5.5-6.0, 6.0-6.5, 6.5-7.0, 7.0-7.5, 7.5- 8.0 and >8.0. For other categorical variables, their corresponding sublevels (i, j, k, l) and descriptions are shown in Tables 5A.2-1.

The last part of Equation 5A.2-1 reflects the effect of the application of organic amendment on CH_4 flux. This effect is an interaction of the type and amount of organic material. In cases where the amount of organic amendment is zero, it is assumed that there is zero application rate for each type of organic material. Obviously, this assumption will result in more data points in the analysis than there are in real observations of organic amendments. To ameliorate this problem, the residuals of observations are weighted with organic amendment as 1 and those without as 0.2 (as the observational result was repeated five times for the five types of organic materials. All the variables were treated as fixed effect, and experimental site was treated as a random effect to address dependencies in data collected from the same experiment.

The effects of the controlling variables on CH_4 flux were computed by fitting Equation 5A.2.1 to field observations using the SPSS Mixed Model procedure (V24.0, SPSS Inc., Chicago, IL, USA).

3. **Developing of global and regional emission factors and scaling factors**

- The estimated effects of various variables were used to derive a default EF. In the model, the CH_4 emissions from rice fields are a combination of the effects of SOC and pH values, pre-season water status, water regime in the rice-growing season, organic amendment and climate. An assumption was made to provide a default EF, that is, all observations in the data set to have a water regime of continuous flooding, a preseason water status of non flooded pre-season <180 d and no organic amendments, while keeping other conditions constant, as stated in the original papers (Yan *et al.* 2005). Using Equation 5A.2.2, the default EF is derived for continuously flooded rice fields, with a pre-season water status of non flooded pre-season <180 days, and without organic amendment:

EQUATION 5A.2.2 (NEW)
DEFAULT EMISSION FACTOR FOR CONTINUOUSLY FLOODED RICE FIELDS

$$EF = e^{\text{constant}} \bullet \left(\frac{1}{n} \sum_{i=1}^{n} SOC_i^a \bullet e^{pH_i} \bullet e^{CL_i} \right) \bullet e^{PW_{short\_drainage}} \bullet e^{WR_{continuous\_flooding}}$$

Where:

EF = default emission factor derived for continuously flooded rice fields, with a pre-season water status of non-flooded pre-season <180 days, and without organic amendment, mg CH_4 m^{-2} h^{-1} (Note: EF was converted to "kg CH_4 ha^{-1} day^{-1}" in Table 5.11)

constant"a" 'constant' and 'a' = values estimated in Equation 5A.2.1

n = total number of observations in the data set

SOC_i = soil organic carbon content for the i[th] observation, %

pH_i = soil pH for the i[th] observation, dimensionless

CL_i = climate type for the i[th] observation, (expressed using IRRI's agro-ecological zone for Asia, other regions were categorized into Europe, Latin America and United States), dimensionless

$PW_{short\_drainage}$ = pre-season water regime (i.e. as 'non flooded pre-season <180 days), dimensionless

$WR_{continuous\_flooding}$ = water regime in the rice-growing season (i.e. as continuous flooding), dimensionless

The values of scaling factors from the aggregated and disaggregated cases are assumed to be referenced as global and regional scaling factors, respectively. The scaling factors of the disaggregated case for water regime during the rice season and preseason are estimated using the modelling results in Equation 5A.2.1. Firstly, the fluxes of CH_4 for 'continuously flooding' during the rice season and 'non flooded pre-season <180 d' in preseason were assumed to be 1. Then, the corresponding relative fluxes for different water regimes were calculated by the ratios of back-transformed estimates (i.e., exponential function) of different water regimes to back-transformed estimates (i.e., exponential function) of 'continuously flooding' during the rice season and 'non flooded pre-season <180 d' in pre-season. Given the different sizes of observations for various water regimes in the data set, the calculations of the scaling factors for the aggregated case were weighted accordingly. For organic amendment, the fluxes of CH_4 from various form of organic materials were calculated, first with an application amount of 6 t/ha. The CH_4 flux from straw applied shortly (<30 days) before cultivation (6 t/ha) is assumed to be 1, the relative fluxes for other organic materials are then calculated.

See Wang *et al*. (2018) for more information and datasets used for the analysis.

TABLE 5A.2.1 (NEW)
DESCRIPTION OF THE SELECTED VARIABLES THAT CONTROL CH_4 EMISSIONS FROM RICE FIELDS

Variables	Description
Preseason water status	
Flooded pre-season	Permanently flooded rice fields are assumed to have a preseason water regime of 'flooded pre-season'. Late rice (e.g., in China) is usually planted immediately after early rice on the same field and is therefore regarded as having a preseason water regime of 'flooded pre-season'.
Non flooded pre-season >180 d	If rice is planted once a year and the field is not flooded in the non-rice growing season, the preseason water regime is classified as 'non flooded pre-season >180 d'.
Non flooded pre-season <180 d	Rice is planted more than once a year, but there is more than one month of fallow time between the two seasons, 'non-flooded pre-season <180 d' usually implies preseason drainage.
Non-flooded pre-season >365 d	For measurements conducted on rice fields that are preceded by two upland crops or an upland crop and a drained fallow season, the preseason water regime of such experiments is classified as 'non-flooded pre-season >365 d'.
Water regime in the rice-growing season	
Continuous flooding	Rice is cultivated under continuously flooded condintion but sometimes an end-season drainage before rice harvest included.
Single drainage	One mid-season drainage and an end-season drainage are adopted over the entire rice-growing season.
Multiple drainage	Multiple drainge refers to the management water regime, also called 'intermittent irrigation', in which the number of drainage events was not clear, but there are more than one events during the growing season.
Rainfed, wet season (regular rainfed)	Rice cultivation that relies on rainfall for water, in this case the field is flood prone during the rice-growing season.
Rainfed, dry season (drought prone)	Rice cultivation that relies on rainfall for water, in this case the field is drought prone during the rice-growing season.
Deep water	Rice grown in flooded conditions with water depth more than 50 cm deep.
Organic amendment	
Straw incorporated shortly (<30 days) before cultivation	Straw applied just before rice transplanting as on-season; straw that is left on the soil surface in the fallow season and incorporated into the soil before the next rice transplanting is also categorized as 'straw incorporated shortly (<30 days) before cultivation'. The amount of straw return is expressed in dry weight (t ha^{-1}).
Straw incorporated long (>30 days) before cultivation	Straw incorporated into soils in the previous season (upland crop or fallow) is categorized as 'straw incorporated long (>30 days) before cultivation'. The amount of straw return is expressed in dry weight (t ha^{-1}).
Compost, farmyard manure, green manure	The amount of organic materials is expressed in fresh weight (t ha^{-1}).

Annex 5A.3 Parameterisation of the Tier 2 – Steady State Method for Mineral Soils

The Tier 2 steady state method was parameterised using Bayesian methods after evaluating the sensitivity of the model parameters. The studies that were used to evaluate model sensitivities and parameterise the model are given in Table 5A.3.1.

TABLE 5A.3.1 (NEW)
STUDIES THAT WERE USED TO EVALUATE THE MODEL SENSITIVITIES AND PARAMETERISE THE TIER 2 STEADY-STATE METHOD FOR MINERAL SOILS

References	Site Location	Length of Study (years)	Treatments
Halvorson *et al*. 1997	Akron, CO, USA	25	Till
Vanotti *et al*. 1997	Arlington, WI, USA	34	MN
Dimassi *et al*. 2013	Boigneville, France	41	Till
Juma *et al*. 1997	Breton, AB, Canada	62	MN, ON
e-RA 2013; Jenkinson 1990	Broadbalk, Rothamsted, UK	153	MN, ON
Pierce and Fortin 1997	East Lansing, MI, USA	12	Till, CC
e-RA 2013; Jenkinson and Johnston 1977	Hoosefield, Rothamsted, UK	146	MN, ON
Dick *et al*. 1997	Hoytville, OH, USA	42	CR, Till
Campbell *et al*. 1997	Indianhead, SK, Canada	35	MN, CR
KBS LTER 2017; Collins *et al*. 2000	Hickory Corners, MI, USA	7	Till
Díaz-Zorita *et al*. 2004	General Villegas, Argentina	25	Till
Huggins and Fuchs 1997	Lamberton, MN, USA	32	MN
Janzen *et al*. 1997	Lethbridge, AB, Canada	41	MN, CR
Janzen *et al*. 1997	Lethbridge, AB, Canada	80	CR
Machado et al. 2008; Marchado 2011; Rasmussen and Smiley 1997	Pendleton, OR, USA	64	MN, ON
Machado et al. 2008; Marchado 2011; Rasmussen and Smiley 1997	Pendleton, OR, USA	55	MN, Till
Dick *et al*. 1997	South Charleston, OH, USA	29	Till
Küstermann *et al*. 2013	Scheyern, Germany	12	Till
Maillard *et al*. 2018	Swift Current, SK, Canada	30	Till, CR
Skjemstad *et al*. 2004; Schultz 1995	Tarlee, Australia	20	CR
Gregorich *et al*. 1996	Woodslee, ON, Canada	36	MN
Dick *et al*. 1997	Wooster, OH, USA	31	CR, Till

MN = Mineral nitrogen additions; ON = organic nitrogen additions; Till = Tillage change; CR = Crop Rotations; CC = Cover Crops

The sensitivity analysis was based on a method developed by Sobol (2001). We evaluated all parameters except for the temperate effect on decomposition (Equation 5.0e) and moisture effects on decomposition (Equation 5.0F). The parameters in these functions were highly correlated so we only evaluated one parameter from each function (t_{opt} for Equation 5.0e and w_1 for Equation 5.0f). A bootstrap sampling method was used to evaluate the total global sensitivity index of the parameters given the log-likelihood value of the mismatch between the model output and the observed data. This information was used to determine if the sample size was sufficient for ranking the sensitivity of the parameters (i.e., minimising the variance enough on the index values to avoid Type 1 error). The sensitivity analysis was conducted in R using the Sensitivity Package (Pujol, Iooss, & Janon, 2017). The results are given in the Table 5A.3.2.

TABLE 5A.3.2 (NEW)
SENSITIVITY OF MODEL PARAMETERS, PARAMETER VALUES AND MINIMUM AND MAXIMUM VALUES FOR THE TIER 2 STEADY-STATE METHOD FOR MINERAL SOILS

Parameter	Practice	Sensitivity	Value (min, max)
$till_{fac}$	Full-till	0.001	3.036 (1.4, 4.0)
	Reduced-till	<0.001	2.075 (1.0, 3.0)
	No-till	n/a1	1
w_s	All	0.003	1.331 (0.8, 2.0)
k_{fac_a}	All	<0.001	7.4
k_{fac_s}	All	0.005	0.209 (0.058, 0.3)
k_{fac_p}	All	0.015	0.00689 (0.005, 0.01)
f_1	All	0.032	0.378 (0.01, 0.8)
f_2	All	0.016	0.368 (0.007, 0.5)
f_3	All	0.003	0.455 (0.1, 0.8)
f_5	All	0.020	0.0855 (0.037, 0.1)
f_6	All	0.040	0.0504 (0.02, 0.19)
f_7	All	<0.001	0.42
f_8	All	<0.001	0.45
t_{opt}	All	0.960	33.69 (30.7, 35.34)
$t_{\max}$	All	n/a2	45

[1] No-till cultivation factor is fixed at a value of 1 based on the model formulation.

[2] The maximum temperature for decomposition was not evaluated because it was highly correlated with the temperature optimum for decomposition.

Bayesian parameterisation techniques were used to determine the probability distributions of the most sensitive parameters, which included parameters with a sensitivity greater than 0.001 (Table 5A.3-2). However, the $till_{fac}$ parameter for reduced-till is included because the parameter for full-till was included. Sampling-importance resampling was used to generate a joint posterior distribution (Rubin, 1998). This approach includes two steps, a) drawing independent random samples from a known prior distribution, and b) resampling the initial draws from step (a) based on importance sampling weights for individual parameter sets. Samples are more likely to be maintained in the posterior distribution with higher likelihoods (Smith & Gelfand, 1992). Uniform priors were selected with an initial sample size $n = 1{,}000{,}000$ and a re-sample size $m = \sqrt{n}$, i.e., 1000, which allows for distributional convergence in the posterior distribution (Givens & Hoeting, 2005). The final posterior distribution was estimated as a truncated multivariate distribution under the assumption that parameter values should not exceed the minimum and maximum values in the posterior distribution. The resulting parameters are given in Table 5A.3-2 and the covariance matrix is given Table 5A.3-3.

TABLE 5A.3.3 **COVARIANCE MATRIX FOR THE THREE-POOL STEADY-STATE METHOD FOR MINERAL SOILS**											
	$till_{fac}-CT$	$till_{fac}-RT$	w_{par}	k_{fac_s}	k_{fac_p}	f_1	f_2	f_3	f_5	f_6	t_{opt}
$till_{fac}-CT$	0.3353436	-0.0007128	0.0124072	0.0077939	0.0000277	0.0007889	-0.0010958	-0.0024497	0.0001000	0.0015558	0.0387919
$till_{fac}-RT$	-0.0007128	0.3239992	-0.0167975	0.0008191	-0.0000013	0.0041484	0.0020256	0.0068887	0.0000775	-0.0017836	0.0047429
w_{par}	0.0124072	-0.0167975	0.1486482	-0.0005654	-0.0001156	0.0084023	0.0055629	-0.0033270	0.0004484	0.0011228	-0.0389749
k_{fac_s}	0.0077939	0.0008191	-0.0005654	0.0032024	0.0000244	0.0022843	0.0015645	0.0008130	-0.0001062	-0.0002235	0.0051276
k_{fac_p}	0.0000277	-0.0000013	-0.0001156	0.0000244	0.0000016	0.0000217	0.0000186	0.0000116	0.0000033	0.0000077	0.0002567
f_1	0.0007889	0.0041484	0.0084023	0.0022843	0.0000217	0.0051767	0.0021790	0.0023559	-0.0001210	-0.0004680	-0.0086628
f_2	-0.0010958	0.0020256	0.0055629	0.0015645	0.0000186	0.0021790	0.0099681	-0.0049865	0.0000755	-0.0005823	-0.0139913
f_3	-0.0024497	0.0068887	-0.0033270	0.0008130	0.0000116	0.0023559	-0.0049865	0.0405470	-0.0001415	0.0001638	-0.0274010
f_5	0.0001000	0.0000775	0.0004484	-0.0001062	0.0000033	-0.0001210	0.0000755	-0.0001415	0.0001479	-0.0000365	-0.0009000
f_6	0.0015558	-0.0017836	0.0011228	-0.0002235	0.0000077	-0.0004680	-0.0005823	0.0001638	-0.0000365	0.0007861	-0.0057748
t_{opt}	0.0387919	0.0047429	-0.0389749	0.0051276	0.0002567	-0.0086628	-0.0139913	-0.0274010	-0.0009000	-0.0057748	0.4347643

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CHAPTER 6

GRASSLAND

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No refinement.

6.2 GRASSLAND REMAINING GRASSLAND

No refinement.

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No refinement.

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No refinement.

6.2.3 Soil carbon

This section deals with the impacts of grassland management on soil organic C stocks, primarily by influencing C inputs to the soil, and thus soil C storage, by affecting net primary production, root turnover, and allocation of C between roots and shoots. Soil C stocks in grassland are influenced by fire, grazing intensity, fertilizer management, liming, irrigation, re-seeding with more or less productive grass species and mixed swards with N-fixing legumes (Conant *et al*., 2001; Follett *et al*., 2001; Ogle *et al*., 2004). In addition, drainage of organic soils for grassland management causes losses of soil organic C (Armentano and Menges, 1986).

General information and guidance for estimating changes in soil C stocks are provided in Chapter 2, Section 2.3.3 (including equations), and this section needs to be read before proceeding with a consideration of specific guidelines dealing with grassland soil C stocks. The total change in soil C stocks for grassland is estimated using Equation 2.24 (Chapter 2), which combines the change in soil organic C stocks for mineral soils and organic soils; and stock changes associated with soil inorganic C pools (if estimated at Tier 3). This section provides specific guidance for estimating soil organic C stocks. There is a general discussion in Section 2.3.3.1 on soil inorganic C and no additional information on this is provided here.

To account for changes in soil C stocks associated with *Grassland Remaining Grassland*, countries need to have, at a minimum, estimates of grassland areas at the beginning and end of the inventory time period. If land-use and management data are limited, aggregate data, such as Food and Agriculture Organization (FAO) statistics on grassland, can be used as a starting point, along with knowledge of country experts about the approximate distribution of land management systems (e.g., degraded, nominal and improved grassland/grazing systems). Grassland management classes must be stratified according to climate regions and major soil types, which could either be based on default or country-specific classifications. This can be accomplished with overlays of land use on suitable climate and soil maps.

6.2.3.1 CHOICE OF METHOD

Inventories can be developed using a Tier 1, 2 or 3 approach, with each successive Tier requiring more details and resources than the previous one. It is also possible that countries will use different tiers to prepare estimates for the separate sub-categories of soil C (i.e., soil organic C stocks changes in mineral and organic soils; and stock changes associated with soil inorganic C pools). Decision trees are provided for mineral (Figure 2.4) and organic soils (Figure 2.5) in Section 2.3.3.1 (Chapter 2) to assist inventory compilers with the selection of the appropriate tier for their soil C inventory.

Mineral soils

Tier 1

For mineral soils, the estimation method is based on changes in soil organic C stocks over a finite period following changes in management that impact soil organic C storage. After a finite transition period, one can assume a steady state for this stock. Equation 2.25 (Chapter 2) is used to estimate change in soil organic C stocks in mineral soils by subtracting the C stock in the last year of an inventory time period (SOC_0) from the C stock at the beginning of the inventory time period ($SOC_{(0-T)}$) and dividing by the time dependence of the stock change factors (D). Note that area of exposed bedrock in grasslands are not included in the soil C stock calculation (assume a stock of 0). In practice, country-specific data on grassland management activity should be obtained and classified into appropriate land management systems, and then stratified by IPCC climate regions and soil types (see Chapter 3). Soil organic C stocks (SOC) are estimated for each time period in the inventory using default reference carbon stocks (SOC_{ref}) and default stock change factors (F_{LU}, F_{MG}, F_I).

Tier 2

The Tier 2 method for mineral soils also uses Equation 2.25 (Chapter 2), but the inventory approach is further developed with country-specific information to better specify stock change factors, reference C stocks, climate regions, soil types, and/or the land management classification system. For biochar C amendments, Tier 2 methods utilize a top-down approach in which the total amount of biochar generated and added to mineral soil is used to estimate the change in soil organic C stocks with country-specific factors. See Section 2.3.3.1, Chapter 2, Volume IV for more information.

Tier 3

Tier 3 approaches do not employ simple stock change factor *per se*, but rather use dynamic models and/or detailed soil C inventory measurements as the basis for estimating annual stock changes.

Estimates of stock changes using model-based approaches are computed from the coupled equations that estimate the net change of soil carbon. A variety of models designed to simulate soil carbon dynamics exist (for example, see reviews by McGill *et al.*, 1996; Smith *et al.*, 1997). Key criteria in selecting an appropriate model include its capability of representing all of the relevant management practices/systems for grasslands; model inputs (i.e., driving variables) are compatible with the availability of country-wide input data; and the model sufficiently represents stock changes based on comparisons with experimental data.

A Tier 3 approach may also be developed using a measurement-based approach in which a monitoring network is sampled periodically to estimate soil organic C stock changes. In contrast to a network associated with model validation, a much higher density of benchmark sites will be needed to adequately represent the combination of land-use and management systems, climate and soil types. Additional guidance is provided in Section 2.3.3.1 (Chapter 2).

For biochar C amendments to soils, Tier 3 methods can be used to address GHG sources and sinks not captured in Tiers 1 or 2, such as priming effects, changes to N_2O or CH_4 fluxes from soils, and changes to net primary production. More information on Tier 3 methods is provided in Section 2.3.3.1 of Chapter 2, Volume IV.

Organic soils

No refinement.

The *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* provides additional guidance that updates the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. See section 2.2 of the *2013 Wetlands Supplement* for guidance on Tier 1, 2, and 3 approaches for drained organic soils.

6.2.3.2 CHOICE OF STOCK CHANGE AND EMISSION FACTOR

Mineral soils

Tier 1

For the Tier 1 approach, default stock change factors are provided in Table 6.2, which includes values for land use factor (F_{LU}), input factor (F_I), and management factor (F_{MG}). The method and studies that were used to derive the default stock change factors are provided in Annex 6A.1. The time dependence (D) is 20 years for default stock change factors in grasslands, and they represent the influence of management to a depth of 30cm. Default reference soil organic C stocks are found in Table 2.3 of Chapter 2. The reference stock estimates are for the top 30cm of the soil profile, to be consistent with the depth increment for default stock change factors.

TABLE 6.2 (UPDATED)
RELATIVE STOCK CHANGE FACTORS FOR GRASSLAND MANAGEMENT

Factor	Level	Climate regime	IPCC default	Error [1,2]	Definition
Land use (F_{LU})	All	All	1.0	NA	All native and/or permanent grassland in a nominal condition is assigned a land-use factor of 1.
Management (F_{MG})	Nominally managed (non – degraded)	All	1.0	NA	Represents low or medium intensity grazing regimes, in addition to periodic cutting and removal of above-ground vegetation, without significant management improvements.
Management (F_{MG})	High Intensity Grazing[3]	All	0.90	±8%	Represents high intensity grazing systems (or cutting and removal of vegetation) with shifts in vegetation composition and possibly productivity but is not severely degraded[4].
Management (F_{MG})	Severely degraded	All	0.7	±40%	Implies major long-term loss of productivity and vegetation cover, due to severe mechanical damage to the vegetation and/or severe soil erosion.
Management (F_{MG})	Improved grassland	Temperate/ Boreal	1.14	±11%	Represents grassland which is sustainably managed with light to moderate grazing pressure (or cutting and removal of vegetation) and that receive at least one improvement (e.g., fertilization, species improvement, irrigation).
		Tropical	1.17	±9%	
		Tropical Montane[5]	1.16	±40%	
Input (applied only to improved grassland) (F_I)	Medium	All	1.0	NA	Applies to improved grassland where no additional management inputs have been used.
Input (applied only to improved grassland) (F_I)	High	All	1.11	±7%	Applies to improved grassland where one or more additional management inputs/improvements have been used (beyond that required to be classified as improved grassland).

Management factors were derived using methods and studies provided in Annex 6A1. The basis for the other factors is described in the *2006 IPCC Guidelines*.

Source:

[3] The bibliography for the following references used for management factor can be found in Annex 6A.1:

Cao *et al.*, 2013; Ding *et al.*, 2014; Du *et al.*, 2017; Frank *et al.*, 1995; Franzluebbers and Stuedemann, 2009; Gao *et al.*, 2018; Gao *et al.*, 2007; Gillard, 1969; Han *et al.*, 2008; He *et al.*, 2008; Ingram *et al.*, 2008; Kioko *et al.*, 2012; Kölbl *et al.*, 2011; Li *et al.*, 2008; Liu *et al.*, 2012; Manley *et al.*, 1995; Martinsen *et al.*, 2011; Potter *et al.*, 2001; Qi *et al.*, 2010; Rutherford and Powrie, 2011; Schulz *et al.*, 2016; Schuman *et al.*, 1999; Segoli *et al.*, 2015; Smoliak *et al.*, 1972; Sun *et al.*, 2011; Talore *et al.*, 2016; Teague *et al.*, 2011; Wang *et al.*, 2017; Wei *et al.*, 2011; Xu *et al.*, 2014; Yanfen *et al.*, 1998; Zhang *et al.*, 2018; Zhou *et al.*, 2010; Zou *et al.*, 2015

Notes:

[1] ± two standard deviations, expressed as a percent of the mean; where sufficient studies were not available for a statistical analysis a default, based on expert judgement, of ± 40% is used as a measure of the error. NA denotes 'Not Applicable', for factor values that constitute reference values or nominal practices for the input or management classes.

[2] This error range does not include potential systematic error due to small sample sizes that may not be representative of the true impact for all regions of the world.

[4] High intensity grazing may be moderately degraded, but do not represent excessive grazing intensity that leads to severe grassland degradation.

[5] There were not enough studies to estimate stock change factors for mineral soils in the tropical montane climate region. As an approximation, the average stock change between the temperate and tropical regions was used to approximate the stock change for the tropical montane climate.

Tier 2

Estimation of country-specific stock change factors is an important advancement for improving an inventory that can be developed in the Tier 2 approach. Derivation of management factors (F_{MG}) and input factors (F_I) are based on experimental comparisons to nominally-managed grasslands with medium input, respectively, because these classes are considered the nominal practices in the IPCC default classification scheme for management systems (see Choice of Activity Data). It is considered *good practice* to derive values for more detailed classification schemes of management, climate and soil types, if there are significant differences in the stock change factors among finer categories based on an empirical analysis.

Reference C stocks can be derived from country-specific data in a Tier 2 approach. Reference values in Tier 1 correspond to non-degraded, unimproved lands under native vegetation, but other reference conditions can also be chosen for Tier 2. In addition, the depth for evaluating soil C stock changes can be different with the Tier 2 method. However, this will require consistency with the depth of the reference C stocks (SOC_{REF}) and stock change factors for all land uses (i.e., F_{LU}, F_{MG}, and F_I) to ensure consistent application of methods for determining the impact of land use change on soil C stocks.

The carbon stock estimates may be improved when deriving country-specific factors for F_{LU} and F_{MG}, by expressing carbon stocks on a soil-mass equivalent basis rather than a soil-volume equivalent (i.e. fixed depth) basis. This is because the soil mass in a certain soil depth changes with the various operations associated with land use that affect the density of the soil, such as uprooting, land levelling, tillage, and rain compaction due to the disappearance of the cover of tree canopy. However, it is important to realize that all data used to derive stock change factors across all land uses must be on an equivalent mass basis if this method is applied. This will be challenging to do comprehensively for all land uses. See Box 2.2C in Chapter2, Section 2.3.3.1 for more information.

For biochar C amendments to soils, the parameter F_{perm_p} can be based on H/Corg or O/Corg measured directly from representative samples of biochar, or from published data for biochar produced using similar process conditions as the biochar that is applied to soils in the country. Tier 2 emission factors may be disaggregated based on variation in environmental conditions, such as the climate and soil types, in addition to variation associated with the biochar production methods that generate production types defined by a specific feedstock type and conversion process. See Section 2.3.3.1, Chapter 2, Volume IV for more information.

Tier 3

Constant stock change rate factors *per se* are less likely to be estimated in favor of variable rates that more accurately capture land-use and management effects. See Section 2.3.3.1 (Chapter 2) for further discussion. Tier 3 methods for biochar C amendments to soils are country-specific and may involve empirical or process-based models to account for a broader set of impacts of biochar amendments. More information on Tier 3 methods is provided in Section 2.3.3.1, Chapter 2, Volume IV.

Organic soils

No refinement.

The *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* provides additional guidance that updates the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. See section 2.2 of the *2013 Wetlands Supplement* for guidance on Tier 1, 2, and 3 approaches for drained organic soils.

6.2.3.3 CHOICE OF ACTIVITY DATA

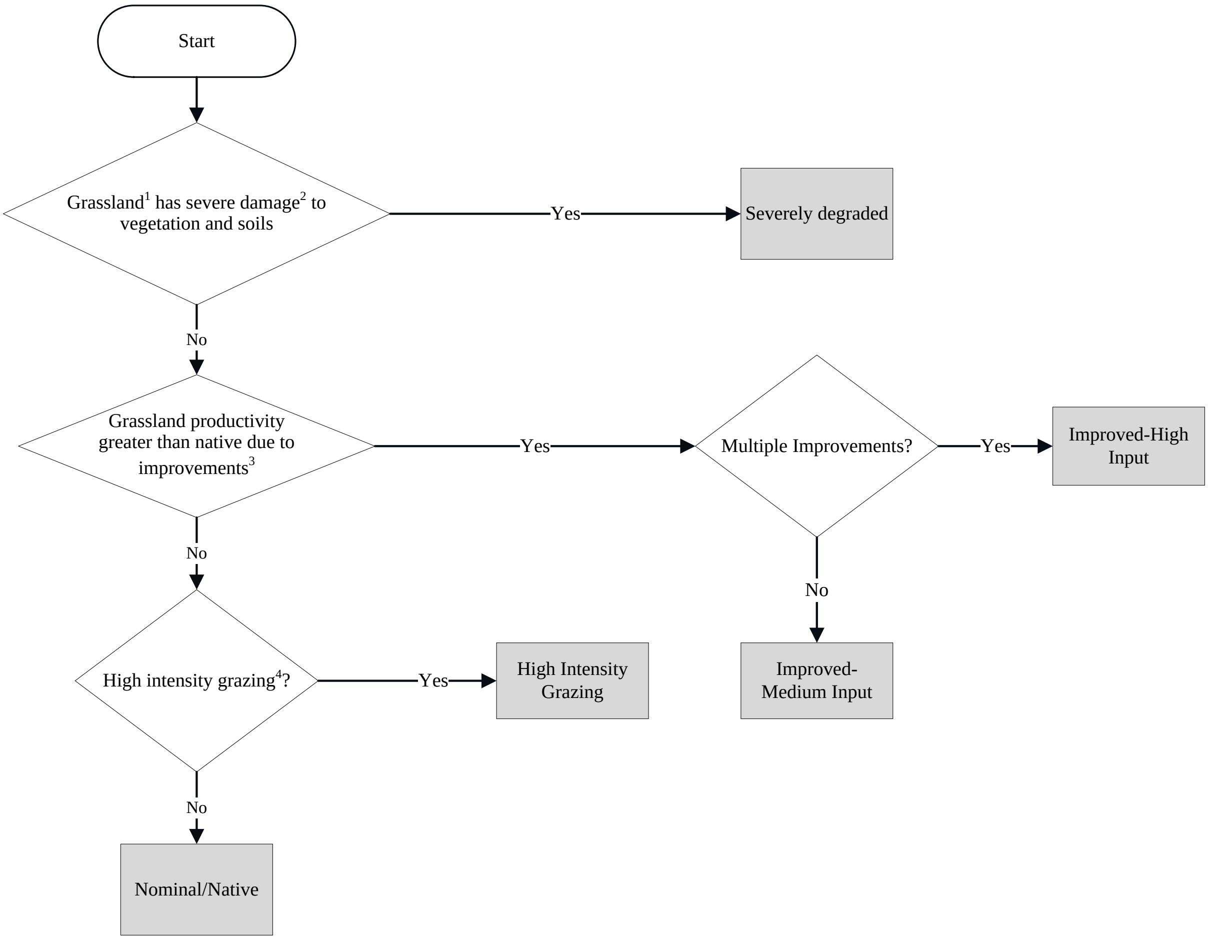
Mineral soils

Tier 1

Grassland systems are classified by practices that influence soil C storage. In general, practices that are known to increase C input to the soil and thus soil organic C stocks, such as irrigation, fertilization, liming, organic amendments, more productive grass varieties, are given an improved status, with medium or high inputs depending on the level of improvement. Practices that decrease C input and soil organic C storage, such as long-term heavy grazing, are given a degraded status relative to nominally-managed seeded pastures or native grassland that are neither improved nor degraded. These practices are used to categorize management systems and then estimate the change in soil organic C stocks. A classification system is provided in Figure 6.1, which forms the basis for a Tier 1 inventory. Inventory compilers should use this classification to categorize management systems in a manner consistent with the default Tier 1 stock change factors. This classification may be further developed for Tiers 2 and 3 approaches.

The main types of land-use activity data include: i) aggregate statistics (Approach 1), ii) data with explicit information on land-use conversions but without specific geo-referencing (Approach 2), or iii) data with information on land-use conversion and explicit geo-referencing (Approach 3), such as point-based land-use and management inventories making up a statistically-based sample of a country's land area. (See Chapter 3 for discussion of Approaches). At a minimum, globally available land-use statistics, such as FAO's databases (http://www.fao.org/faostat/en/#home), provide annual compilations of total land area by major land-use types. This would be an example of aggregate data (Approach 1).

Figure 6.1 Classification scheme for grassland/grazing systems. In order to classify grassland management systems, the inventory compiler should start at the top and proceed through the diagram answering questions (move across branches if answer is yes) until reaching a terminal point on the diagram. The classification diagram is consistent with default stock change factors in Table 6.2.



Notes:

1: Includes continuous pasture, hay lands and rangelands

2: Large loss in vegetation cover and productivity due to continual overgrazing and/or high rates of erosion.

3: Productivity refers explicitly to C input to soil (management improvements that increase input e.g., fertilization, organic amendment, irrigation, planting more productive varieties, liming, and seeding legumes).

4: High intensity grazing is defined as grazing that deteriorates the condition and/or long-term recovery capacity of the vegetation compared with the vegetation state under nominal to moderate grazing intensity. High intensity grazing does not refer to stocking rate and duration only, but to the stocking rate and duration in relation to grassland productivity and resilience. This may be called a moderately degraded condition but high intensity grazing does not lead to the severe degradation such as is caused by relentless overgrazing. High intensity grazing also includes land where vegetation is frequently cut and removed equivalent to high intensity grazing and without application of any animal manure.

Management activity data supplement the land-use data, providing information to classify management systems, such as stocking rates, fertilizer use, irrigation, etc. These data can also be aggregate statistics (Approach 1) or provide information on explicit management changes (Approach 2 or 3). It is *good practice* where possible for grassland areas to be assigned appropriate general management activities (i.e., degraded, native, or improved) or specific management activities (e.g., fertilization or grazing intensity). Soil degradation maps may be a useful source of information for stratifying grassland according to management (e.g., Conant and Paustian, 2002; McKeon *et al*., 2004). Expert knowledge is another source of information for management practices. It is *good practice* to elicit expert knowledge, where appropriate, using methods provided in Volume 1, Chapter 2 (Annex 2A.1, A protocol for expert elicitation).

National land-use and resource inventories based on repeated surveys of the same locations constitute activity data gathered using Approach 2 or 3 and have some advantages over aggregated pastoral and land-use statistics (Approach 1). Time series data can be more readily associated with a particular grassland management system and the soil type associated with the particular location can be determined by sampling or by referencing the location to a suitable soil map. Inventory points that are selected based on an appropriate statistical design also enable estimates of the variability associated with activity data, which can be used as part of a formal uncertainty analysis. An example of a survey using Approach 3 is the National Resource Inventory in the U.S. (Nusser and Goebel, 1997).

Activity data require additional in-country information to stratify areas by climate and soil types. If such information has not already been compiled, an initial approach would be to overlay available land cover/land-use maps (of national origin or from global datasets such as IGBP_DIS) with soil maps of national origin or global sources, such as the FAO Soils Map of the World and climate data from the United Nations Environmental Program. A detailed description of the default climate and soil classification schemes is provided in Chapter 3, Annex 3A.5. The soil classification is based on soil taxonomic description and textural data, while climate regions are based on mean annual temperatures and precipitation, elevation, occurrence of frost, and potential evapotranspiration.

Tier 2

Tier 2 approaches are likely to involve a more detailed stratification of management systems (Figure 6.1) than in Tier 1, if sufficient data are available. This could include further subdivisions of grassland systems (i.e., moderately degraded, severely degraded, nominal and improved), and the input classes (medium and high input). It is *good practice* to further subdivide default classes based on empirical data that demonstrates significant differences in soil organic C storage among the proposed categories. In addition, Tier 2 approaches could involve a finer stratification of climate regions and soil types. The resolution of activity data, such as that determined by intensity of survey data, often determines the finest feasible resolutions for spatial stratification.

For Tier 2, the specific definitions of management and input factors are typically made to match available activity data on how activities affects C stocks. For example, if a country has management factors related to levels of grazing intensity, then the country will also need activity data on grazing intensity to apply the country-specific factors.

For biochar C amendments, the activity data for the Tier 2 method includes the total quantities of biochar distributed for amendment to mineral soils. These data must be disaggregated by production type, where production type is defined as a process utilizing a specific feedstock type, and a specific conversion process). Changes in soil C associated with biochar amendments are considered to occur where it is incorporated into soil. However, due to the distributed nature of the land sector in which this can take place, inventory compilers may not have access to data on when or where biochar C amendments occur. Inventory compilers may be able to compile data on the total amount of biochar applied to grassland mineral soils from biochar producers, importers, exporters or distributors, and/or from those applying biochar to grassland in the country. Note that exported biochar is not included in the total amount of biochar amended to soils in the country. Additionally, activity data on the amount of biochar amendments may be disaggregated by climate zones and/or soil types if country-specific factors are disaggregated by these environmental variables. The additional climate and soil activity data may be obtained with a survey of biochar distributors and land managers.

Tier 3

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

For biochar C amendments, the additional activity data required to support a Tier 3 method will depend on which processes are represented and which environmental variables that are required as input to the model. Priming effects, soil GHG emissions, and plant production responses to biochar all vary with biochar type, climate, and soil type. Furthermore, soil GHG emissions and plant production responses also vary with vegetation type and management. Therefore, Tier 3 methods may require environmental data on climate zones, soil types, vegetation type and grazing management systems, in addition to the amount of biochar amendments in each of the individual combinations of strata for the environmental variables. More detailed activity data specifying the process conditions for biochar production or the physical and chemical characteristics of the biochar may also be required (such as surface area, cation exchange capacity, pH, and ash content).

Organic soils

No refinement.

The *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* provides additional guidance that updates the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. See section 2.2 of the *2013 Wetlands Supplement for guidance* on Tier 1, 2, and 3 approaches for drained organic soils.

6.2.3.4 CALCULATION STEPS FOR TIER 1

Mineral soils

The steps for estimating SOC_0 and $SOC_{(0\text{-}T)}$ and net soil C stock change from *Grassland Remaining Grassland* are as follows:

Step 1: Organize data into inventory time periods based on the years in which activity data were collected (e.g., 1990 and 1995, 1995 and 2000, etc.)

Step 2: Determine the land-use and management by mineral soil type and climate region for land at the beginning of the inventory period, which can vary depending on the time step of the activity data (0-T; e.g., 5, 10 or 20 years ago).

Step 3: Select the native reference C stock value (SOC_{REF}), based on climate and soil type from Table 2.3, for each area of land being inventoried. The reference C stocks are the same for all land-use categories to ensure that erroneous changes in the C stocks are not computed due to differences in reference stock values among sectors.

Step 4: Select the land-use factor (F_{LU}), management factor (F_{MG}) and C input levels (F_I) representing the land-use and management system present at the beginning of the inventory period. Values for F_{LU}, F_{MG} and F_I are provided in Table 6.2.

Step 5: Multiply these values by the reference soil C stock to estimate the 'initial' soil organic C stock ($SOC_{(0\text{-}T)}$) for the inventory time period.

Step 6: Estimate SOC_0 by repeating Step 1 to 4 using the same native reference C stock (SOC_{REF}), but with land-use, management and input factors that represent conditions in the last (year 0) inventory year.

Step 7: Estimate the average annual change in soil organic C stock for the area over the inventory time period ($\Delta C_{Mineral}$).

Step 8: Repeat Steps 1 to 6 if there are additional inventory time periods (e.g., 1995 to 2000, 2001 to 2005, etc.).

A case example is given below for computing a change in grassland soil organic C stocks using Equation 2.25 (Chapter 2), default stock change factors and reference C stocks.

Updated Example: The following example shows calculations for aggregate areas of grassland soil carbon stock change to a 30 cm depth. In a tropical moist climate on Ultisol soils, there are 1Mha of permanent grassland. The native reference carbon stock (SOC_{REF}) for the climate/soil type is 47 tonnes C ha^{-1}. At the beginning of the inventory time period (1990 in this example) the distribution of grassland systems was 500,000 ha of unmanaged native grassland; 400,000 ha of unimproved, moderately degraded grazing land; and 100,000 ha of heavily degraded grassland. Thus, initial soil carbon stocks for the area were:

500,000 ha ● (47 tonnes C ha^{-1} ● 1 ● 1 ● 1) + 400,000 ha ● (47 tonnes C ha^{-1} ● 1 ● 0.97 ● 1) + 100,000 ● (47 tonnes C ha^{-1} ● 1 ● 0.7 ● 1) = 45,026,000 tonnes C.

In the last year of inventory time period (2010 in this example), there are: 300,000 ha of unmanaged native grassland; 300,000 ha of unimproved, moderately degraded grazing land; 200,000 ha of heavily degraded grassland; 100,000 ha of improved pasture receiving fertilizer; and 100,000 of highly improved pasture receiving fertiliser together with irrigation. Thus, total soil carbon stocks in the inventory year are:

300,000 ha ● (47 tonnes C ha^{-1} ● 1 ● 1 ● 1) + 300,000 ha ● (47 tonnes C ha^{-1} ● 1 ● 0.97 ● 1) + 200,000 ● (47 tonnes C ha^{-1} 1 ● 0.7 ● 1) + 100,000 ● (47 tonnes C ha^{-1} 1 ● 1.17 ● 1) + 100,000 ● (47 tonnes C ha^{-1} ● 1 ● 1.17 ● 1.11) = 45,959,890 tonnes C.

The average annual stock change over the period for the entire area is: 45,959,890 – 45,026,000 = 933,890 tonnes/20 yr = 46,694.5 tonnes per year soil C stock increase. (Note: 20 years is the time dependence of the stock change factor, i.e., factor represents annual rate of change over 20 years).

Organic soils

No refinement.

The *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* provides additional guidance that updates the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. See section 2.2 of the *2013 Wetlands Supplement* for guidance on Tier 1, 2, and 3 approaches for drained organic soils.

6.2.3.5 UNCERTAINTY ASSESSMENT

No refinement.

6.2.4 Non-CO_2 greenhouse gas emissions from biomass burning

No refinement.

6.3 LAND CONVERTED TO GRASSLAND

No refinement.

6.3.1 Biomass

No refinement.

6.3.2 Dead organic matter

No refinement.

6.3.3 Soil carbon

Grassland management involving drainage will generate emissions from organic soil, regardless of the previous land use. However, the impact on mineral soils is less clear-cut for lands converted to Grassland. Literature on one of the dominant conversion types globally (from Forest Land to Grassland in the tropics) provides evidence for net gains as well as net losses in soil C, and it is known that the specific management of the grassland after conversion is critical (e.g., Veldkamp, 2001).

General information and guidance for estimating changes in soil C stocks are provided in Chapter 2, Section 2.3.3 (including equations), and this section needs to be read before proceeding with a consideration of specific guidelines dealing with grassland soil C stocks. The total change in soil C stocks for *Land Converted to Grassland* is estimated using Equation 2.24 for the change in soil organic C stocks for mineral soils and organic soils; and stock changes associated with soil inorganic C pools (if estimated at Tier 3). This section provides specific guidance for estimating soil organic C stock changes. There is a general discussion in Section 2.3.3 in Chapter 2 on soil inorganic C and no additional information is provided here.

To account for changes in soil C stocks associated with *Land Converted to Grassland*, countries need to have, at a minimum, estimates of the areas of *Land Converted to Grassland* during the inventory time period, stratified by climate region and soil type. If land-use and management data are limited, aggregate data, such as FAO statistics, can be used as a starting point, along with country expert knowledge of the approximate distribution of land-use types being converted and the management of those lands. If the previous land uses and conversions are unknown, SOC stocks changes can still be estimated using the methods provided in *Grassland Remaining Grassland*, but the land base area will likely be different for grasslands in the current year relative to the initial year in the inventory. It is critical, however, that the total land area accounted across all land-use sectors be equal over the inventory time period (e.g., if 3 Million ha of Forest Land and Cropland are converted to Grassland during the inventory time period, then Grassland will have an additional 3 Million ha in the last year of the inventory, while Cropland and Forest Land will have a corresponding loss of 3 Million ha in the last year). *Land Converted to Grassland* is stratified according to climate regions, management, and major soil types, which could either be based on default or country-specific classifications. This can be accomplished with overlays of suitable climate and soil maps, coupled with spatially-explicit data on the location of land conversions.

6.3.3.1 CHOICE OF METHOD

Inventories can be developed using a Tier 1, 2 or 3 method, with each successive Tier requiring more details and resources than the previous one. It is possible that countries will use different tiers to prepare estimates for the separate sub-categories of soil C (i.e., soil organic C stocks changes in mineral soils and organic soils; and stock changes associated with soil inorganic C pools). Decision trees are provided for mineral soils (Figure 2.4) and organic soils (Figure 2.5) in Section 2.3.3.1 Chapter 2 to assist inventory compilers with selection of the appropriate tier for their soil C inventory.

Mineral soils

Tier 1

Using Equation 2.25 (Chapter 2), the change in soil organic C stocks can be estimated for mineral soils accounting for the impact of land-use conversion to Grassland. The method is fundamentally the same as the one used for *Grassland Remaining Grassland*, except pre-conversion C stocks are dependent on stock change factors for another land use. Specifically, the initial (pre-conversion) soil organic C stock ($SOC_{(0-T)}$) and stock in the last year of inventory time period (SOC_0) are computed from the default reference soil organic C stocks (SOC_{REF}) stock change factors (F_{LU}, F_{MG}, F_I). Note that area of exposed bedrock in Forest Land or the previous land use are not included in the soil C stock calculation (assume a stock of 0). Annual rates of stock changes are estimated based on the difference in stocks (over time) for the first and last year in the inventory time period divided by the time dependence of the stock change factors (D, default is 20 years).

Tier 2

The Tier 2 method for mineral soils also uses Equation 2.25, but involves country-specific or region-specific reference C stocks and/or stock change factors and more disaggregated land-use activity and environmental data. For biochar C amendments, Tier 2 methods utilize a top-down approach in which the total amount of biochar generated and added to mineral soil is used to estimate the change in soil organic C stocks with country-specific factors. See Section 2.3.3.1, Chapter 2, Volume IV for more information.

Tier 3

Tier 3 methods will involve more detailed and country-specific models and/or measurement-based approaches along with highly disaggregated land-use and management data. It is *good practice* that Tier 3 approaches, estimating soil C change from land-use conversions to Grassland, employ models, data sets and/or monitoring networks that are capable of representing transitions over time from other land uses, including Forest Land, Cropland, and possibly Settlements or other lands. If possible, it is also recommended for Tier 3 methods to be integrated with estimates of biomass removal and the post-clearance treatment of plant residues (including woody debris and litter), as variation in the removal and treatment of residues (e.g., burning, site preparation) will affect C inputs to soil organic matter formation and C losses through decomposition and combustion. It is important that models be evaluated with independent observations from country-specific or region-specific field locations that are representative of the interactions of climate, soil, and grassland management on post-conversion change in soil C stocks.

Tier 3 methods for biochar C amendments can be used to address GHG sources and sinks not captured in Tiers 1 or 2, such as priming effects, changes to N_2O or CH_4 fluxes from soils, and changes to net primary production. More information on Tier 3 methods is provided in Section 2.3.3.1 of Chapter 2, Volume IV.

Organic soils

No refinement.

The *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* provides additional guidance that updates the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. See Section 2.3 of the *2013 Wetlands Supplement* for guidance on Tier 1, 2, and 3 approaches for land use conversions associated with drained organic soil.

6.3.3.2 CHOICE OF STOCK CHANGE AND EMISSION FACTORS

Mineral soils

Tier 1

For unmanaged land, as well as for managed Forest Land, Settlements and nominally managed Grassland with low disturbance regimes, soil C stocks are assumed equal to the reference values (i.e., land use, disturbance (forests only), management and input factors equal 1), while it will be necessary to apply the appropriate stock change factors to represent other systems such as improved and degraded grasslands, as well as all cropland systems. Default reference C stocks are given in Chapter 2, Table 2.3. See the *Choice of Stock Change and Emission Factors* in the appropriate land-use chapter for default stock change factors (Forest Land in Section 4.2.3.2, Cropland in 5.2.3.2, Grassland in 6.2.3.2, Settlements in 8.2.3.2, and Other land in 9.3.3.2).

Note that it is *good practice* to use the management factor (F_{LU}) for set-asides (Table 5.5) if dealing with cultivated annual Cropland converted into Grassland (i.e., until the land is re-classified as *Grassland Remaining Grassland*) because recently converted annual cropland systems will typically gain C at a rate similar to set-aside lands. Moreover, the Tier 1 set-aside factors were derived from empirical data to explicitly represent the expected gain during the first 20 years for lands removed from cultivation. If countries decide to assume a faster increase in C that raises levels to native conditions within 20 years, a justification should be provided in the documentation.

Tier 2

Estimation of country-specific stock change factors is probably the most important development for the Tier 2 approach. Differences in soil organic C stocks among land uses are computed relative to a reference condition, using land-use factor (F_{LU}). Input factor (F_I) and management factor (F_{MG}) are then used to further refine the C stocks of the new grassland system. Additional guidance on how to derive these stock change factors is given in *Grassland Remaining Grassland*, Section 6.2.3.2 as well as other general guidance in Section 2.3.3.1 (Chapter 2). See the appropriate section for specific information regarding the derivation of stock change factors for other land-use sectors (Forest Land in Section 4.2.3.2, Cropland in 5.2.3.2, Wetlands in 7.2.3.3, Settlements in 8.2.3.2, and Other Land in 9.3.3.2).

Reference C stocks can be derived from country-specific data in a Tier 2 approach. Reference values in Tier 1 correspond to non-degraded, unimproved lands under native vegetation, but other reference conditions can also be chosen for Tier 2. In general, reference C stocks should be consistent across the land uses (i.e., Forest Land, Cropland, Grassland, Settlements, Other Land) (see section 2.3.3.1). Therefore, the same reference stock should be used for each climate zone and soil type, regardless of the land use. The reference stock is then multiplied by land use, input and management factors to estimate the stock for each land use based on the set of management systems that are present in a country. In addition, the depth for evaluating soil C stock changes can be different with the Tier 2 method. However, this will require consistency with the depth of the reference C stocks (SOC_{REF}) and stock change factors for all land uses (i.e., F_{LU}, F_I, and F_{MG}) to ensure consistency in the application of methods for estimating the impact of land use change on soil carbon stocks.

The Tier 1 method may over- or under-estimate soil C stock changes on an annual basis, particularly with land use change (e.g., Villarino et al., 2014). Therefore, land use change, such as Croplands converted to Grasslands, may include development of factors that estimate changes over longer periods of time than the default of 20 years, and may better match the period of time over which carbon accumulates or is lost from soils due to land use change. When C stock changes extend over periods of many decades, activity data for historical land-use change are needed to estimate the soil C stock changes that are still occurring in the current inventory year.

The carbon stock estimates may be improved when deriving country-specific factors for F_{LU} and F_{MG}, by expressing carbon stocks on a soil-mass equivalent basis rather than a soil-volume equivalent (i.e. fixed depth) basis. This is because the soil mass in a certain soil depth changes with the various operations associated with land use that affect the density of the soil, such as uprooting, land levelling, tillage, and rain compaction due to the disappearance of the cover of tree canopy. However, it is important to realize that all data used to derive stock change factors across all land uses must be on an equivalent mass basis if this method is applied. This will be challenging to do comprehensively for all land uses. See Box 2.2C in Chapter2, Section 2.3.3.1 for more information.

For biochar C amendments, the parameter F_{perm_p} can be based on H/Corg or O/Corg measured directly from representative samples of biochar, or from published data for biochar produced using similar process conditions as the biochar that is applied to soils in the country. Tier 2 emission factors may be disaggregated based on variation in environmental conditions, such as the climate and soil types, in addition to variation associated with the biochar production methods that generates production types defined by the specific feedstock type and conversion process, where production type is defined as a process utilizing a specific feedstock type, and a specific conversion process. See Section 2.3.3.1, Chapter 2, Volume IV for more information.

Country-specific emission factors (i.e., permanence factors) for biochar C for grassland may be different from the past land use for *Land Converted to Grassland,* and these differences need to be addressed in the calculations. This requires estimating the biochar carbon stocks from past biochar carbon additions that remain in *Land Converted to Grassland* after conversion. The biochar C stocks are then subject to the conditions for grassland, which may lead some additional loss of biochar C.

Tier 3

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

Tier 3 methods for biochar C amendments are country-specific and may involve empirical or process-based models to account for a broader set of impacts of biochar amendments. These methods will likely estimate biochar C stocks and associated changes over time so the biochar C stocks in Land Converted to Grassland will need to be tracked through the land use change process.

Organic soils

No refinement.

The *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* provides additional guidance that updates the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. See Section 2.3 of the *2013 Wetlands Supplement* for guidance on Tier 1, 2, and 3 approaches for land use conversions associated with drained organic soil.

6.3.3.3 CHOICE OF ACTIVITY DATA

Mineral soils

Tier 1 and Tier 2 –Default Equations

For purposes of estimating soil carbon stock change, area estimates of *Land Converted to Grassland* should be stratified according to major climate regions and soil types. This can be based on overlays with suitable climate and soil maps and spatially-explicit data of the location of land conversions. A detailed description of the default climate and soil classification schemes is provided in Chapter 3. See corresponding sections dealing with each land-use category for sector-specific information regarding the representation of land-use/management activity data (Forest Land in Section 4.2.3.3, Cropland in 5.2.3.3, Grassland in 6.2.3.3, Wetlands in 7.2.3.3, Settlements in 8.2.3.3 and Other land in 9.3.3.3).

An important issue in evaluating the impact of *Land Converted to Grassland* on soil organic C stocks is the type of land-use and management activity data. Activity data gathered using Approach 2 or 3 (see Chapter 3 for discussion about Approaches) provide the underlying basis for determining the previous land use for land categorized as *Land Converted to Grassland*. In contrast, aggregate data (Approach 1) only provide the total amount of area in each land use at the beginning and end of the inventory period (e.g., 1985 and 2005). Thus, unless supplementary information can be gathered to infer the pattern of land-use change (as suggested in Chapter 3) Approach 1 data are insufficient to determine specific transitions between land-use categories. Therefore, the previous land use before conversion to grasslands will be unknown. Fortunately, this is not problematic using a Tier 1 or 2 method because the calculation is not dynamic and assumes a step change from one equilibrium state to another. Therefore, with aggregated data (Approach 1), changes in soil organic C stocks may be computed separately for each land-use category and then combined to obtain the total stock change for all land uses combined. The soil C stock change estimate will be equivalent to results using Approach 2 (or 3) activity data (i.e., a full land-use change matrix), but evaluation of C stock trends will only be relevant after combining the stock estimates for all land uses (i.e., stocks will increase or decrease with the changes in land area within individual land uses, but this will offset by gains or losses in other land uses, and thus not an actual stock change in the soil pool for a country. Thus, with aggregate (Approach 1 data) it is important to achieve coordination among all land sector to ensure the total land base is remaining constant over time, given that some land area will be lost and gained within individual sectors during each inventory year due to land-use change.

Note that it will not be possible to determine the amount of cultivated annual croplands converted to grasslands with aggregated activity data (Approach 1). Therefore, grassland stock change factors will be applied, without consideration for the slower rate of C gain in recently converted annual croplands, which may lead to an over-estimation of C gain over a 20-year time period, particularly using the Tier 1 method (see Choice of Stock Change and Emission Factors for additional discussion). This caveat should be acknowledged in the reporting documentation, and it is *good practice* for future inventories to gather additional information needed to estimate the area of grassland recently converted from croplands, particularly if soil C is a key source category.

For biochar C amendments, the activity data for the Tier 2 method includes the total quantities of biochar distributed for amendment to mineral soils. These data must be disaggregated by production type, where production type is defined as a process utilizing a specific feedstock type, and a specific conversion process. Changes in soil C associated with biochar amendments is considered to occur where it is incorporated into soil. However, due to the distributed nature of the land sector in which this can take place, inventory compilers may not have access to data on when or where biochar C amendments occur. Inventory compilers may be able to compile data on the total amount of biochar applied to grassland mineral soils from biochar producers, importers, exporters, distributors, and/or from those applying biochar to grassland in the country. Note that exported biochar is not included in the total amount of biochar amended to soils in the country. Additionally, activity data on the amount of biochar amendments may be disaggregated by climate zones and/or soil types if country-specific factors are disaggregated by these environmental variables. The additional climate and soil activity data may be obtained with a survey of biochar distributors and land managers.

Tier 3

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

For biochar C amendments, the additional activity data required to support a Tier 3 method will depend on which processes are represented and environmental variables that are required as input to the model. Priming, soil GHG emissions, and plant production responses to biochar all vary with biochar type, climate, and soil type. Furthermore, soil GHG emissions and plant production responses also vary with crop type and management. Therefore, Tier 3 methods may require environmental data on climate zones, soil types, grassland vegetation and management systems (such as nitrogen fertilizer application rates, and whether soils are flooded for paddy rice production), in addition to the amount of biochar amendments in each of the individual combinations of strata for the environmental variables. More detailed activity data specifying the process conditions for biochar production or the physical and chemical characteristics of the biochar may also be required (such as surface area, cation exchange capacity, pH, and ash content).

Organic soils

No refinement.

The *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* provides additional guidance that updates the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. See Section 2.3 of the *2013 Wetlands Supplement* for guidance on Tier 1, 2, and 3 approaches for land use conversions associated with drained organic soil.

6.3.3.4 CALCULATION STEPS FOR TIER 1

Mineral soils

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

Step 1: Organize data into inventory time periods based on the years in which activity data were collected (e.g., 1990 and 1995, 1995 and 2000, etc.)

Step 2: Determine the land-use and management by mineral soil types and climate regions for land at the beginning of the inventory period, which can vary depending on the time step of the activity data (0-T; e.g., 5, 10 or 20 years ago).

Step 3: Select the native reference C stock value (SOC_{REF}), based on climate and soil type from Table 2.3, for each area of land being inventoried. The reference C stocks are the same for all land-use categories to ensure that erroneous changes in the C stocks are not computed due to differences in reference stock values among sectors.

Step 4: Select the land-use factor (F_{LU}), management factor (F_{MG}) and C input levels (F_I) representing the land-use and management system present before conversion to grassland. Values for F_{LU}, F_{MG} and F_I are given in the respective section for the land-use sector (Cropland in Chapter 5, Grassland in Chapter 6, Settlements in Chapter 8, and Other land in Chapter 9).

Step 5: Multiply these values by the reference soil C stock to estimate 'initial' soil organic C stock ($SOC_{(0-T)}$) for the inventory time period.

Step 6: Estimate SOC_0 by repeating Steps 1 to 4 using the same native reference C stock (SOC_{REF}), but with land-use, management and input factors that represent conditions (after conversion to grassland) in the last (year 0) inventory year.

Step 7: Estimate the average annual change in soil organic C stock for the area over the inventory time period ($\Delta C_{Mineral}$)

Step 8: Repeat Steps 1 to 6 if there are additional inventory time periods (e.g., 1995 to 2000, 2001 to 2005, etc.).

A numerical example is given below for land conversion of cropland.

Using Equation 2.25 (Chapter 2), default stock change factors and reference C stocks, a case example is given below for estimating changes in soil organic C stocks associated with *Land Converted to Grassland*.

> **Example:** For tropical moist, volcanic soil that has been under long-term annual Cropland, with intensive tillage and where crop residues are removed from the field, carbon stocks at the beginning of the inventory time period (1990 in this example), $SOC_{(0-T)}$ are:
>
> 70 tonnes C ha^{-1} ● 0.90 ● 1 ● 0.92 = 58.0 tonnes C ha^{-1}.
>
> Following conversion to improved (e.g., fertilised) pasture, carbon stocks in the last year of inventory (2010 in this example) (SOC_0) are:
>
> 70 tonnes C ha^{-1} ● 1 ● 1.17 ● 1 = 81.9 tonnes C ha^{-1}.
>
> Thus the average annual change in soil C stock for the area over the inventory time period is calculated as:
>
> (81.9 tonnes C ha^{-1} – 58.0tonnes C ha^{-1}) / 20 yrs =1.2 tonnes C ha^{-1} yr^{-1}.

Organic soils

No refinement.

The 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands provides additional guidance that updates the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. See Section 2.3 of the 2013 Wetlands Supplement for guidance on Tier 1, 2, and 3 approaches for land use conversions associated with drained organic soil.

6.3.3.5 UNCERTAINTY ASSESSMENT

No refinement.

6.3.4 Non-CO_2 greenhouse gas emissions from biomass burning

No refinement.

6.4 COMPLETENESS, TIME SERIES, QA/QC, AND REPORTING

No refinement.

Annex 6A.1 Estimation of default stock change factors for mineral soil C emissions/removals for Grassland

Default stock change factors have been updated in Table 6.2 based on an analysis of a global dataset of experimental results for grazing intensity to a 30cm depth. Management change was defined as high-intensity grazing from low to moderate grazing intensity. The grazing intensity categories were those used by the authors of the published studies and so are their interpretation of the relative livestock grazing stocking density in relation to the grassland productivity and resilience. Management factors represent the effect on C stocks after 20 years following the management change. Data were compiled from published literature based on the following criteria: a) must be an experiment with a control and treatment; b) provide soil organic C stocks or the data needed to compute soil organic C stocks (bulk density, OC content, gravel content); c) provide depth of measurements; d) provide the number of years from the beginning of the experiment to C stock sample collection; and c) provide location information. There were 31 published studies with 176 observations of grassland management (i.e., high intensity grazing versus low to moderate intensity grazing). There was insufficient data to develop reliable factors by climate or soil.

Semi-parametric mixed effect models were developed to estimate the new factors (Breidt et al., 2007). Several variables were tested including depth, number of years since the management change, climate, and the first-order interactions among the variables. Variables and interactions terms were retained in the model if they met an alpha level of 0.05 and decreased the Akiake Information Criterion by two. For depth, data were not aggregated to a standardized set of depths but rather each of the original depth increments were used in the analysis (e.g., 0-5 cm, 5-10 cm, and 10-30 cm) as separate observations of stock changes. Similarly, time series data were not aggregated, even though those measurements are taken from the same plots. Consequently, random effects were included to account for the dependencies in times series data and among data points representing different depths from the same study.

Special consideration was given to representing depth increments in order to avoid aggregating data across increments from the original experiments. Data are collected by researchers at various depths that do not match among studies. We created a custom set of covariates, which are functions of the increment endpoints. These functions come from integrating the underlying quadratic function over the increments. This approach was needed in order to make statistically valid inferences with the semi-parametric mixed effect model techniques, and to avoid errors associated with aggregating data into a uniform set of depth increments.

Using this customized approach, we estimated grassland management factors to a 30 cm depth. Uncertainty is quantified based on the prediction error for the model, and represents a 95 percent confidence interval for each of the factor values. The resulting confidence intervals can be used to construct probability distribution functions with a normal density for propagating error through the inventory calculations.

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