CHAPTER 3

CONSISTENT REPRESENTATION OF LANDS

Authors

Shanti Reddy (Australia), Luis Panichelli (Argentina), Robert Michael Waterworth (Australia), Sandro Federici (San Marino), Carly Green (Australia), Inge Jonckheere (Belgium), Serah Kahuri (Kenya), Werner Alexander Kurz (Canada), Robert de Ligt (Australia), Jean Pierre Ometto (Brazil), Hans Petersson (Sweden), Endo Takahiro (Japan), Thomas Paul (New Zealand), Jason Tullis (USA), Zoltan Somogyi (Hungary), Mehul Pandya (India), Marcelo Theoto Rocha (Brazil), Kei Suzuki (Japan).

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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 the information available in Approach 2 by allowing land-use conversions to be tracked 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:

GG	=	Grassland Remaining Grassland	LG	=	Land Converted to Grassland
CC	=	Cropland Remaining Cropland	LC	=	Land Converted to Cropland
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 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.

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[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

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, in particular when minimum area requirements are used for one or more land-use categories. For example, when applying minimum area definitions, a land-use change may occur as a consequence of an area becoming smaller or larger than the selected minimum area (e.g., if the minimum definition for Forest Land is 1 ha, and a forest area drops from 1.0 ha to 0.9 ha – conversion from Forest Land, or if a non-forest area is 0.9 ha and planting raises this to 1 ha – conversion to Forest Land). While this can result in a change in land-use, it is *good practice* to demonstrate that the methods applied in the inventory do not systematically over- or underestimate emissions and removals by assuming that the entire area has been affected (e.g., emissions and removals are only counted for the areas that actually have changed).

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 the net losses or 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 without spatially-explicit location data, often based on political boundaries (i.e., locations of specific land-use and land-use conversions are not known). 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.

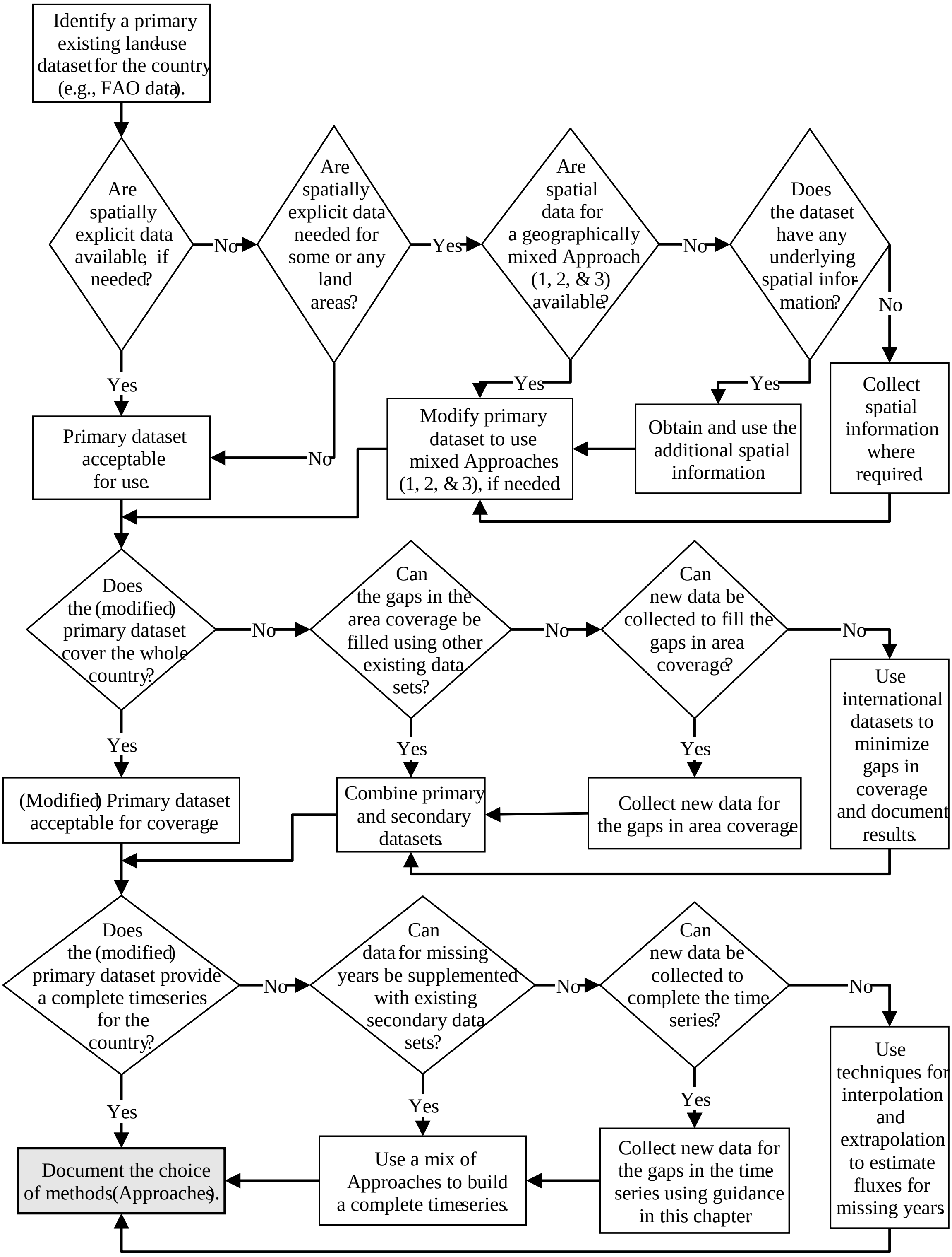
There are numerous sources of data and methods to process data that can be used to derive activity data. It is not necessarily the data itself that determines of the approach. For example, depending on how the data is used, a time-series of data could be used to generate information at Approaches 1, 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.

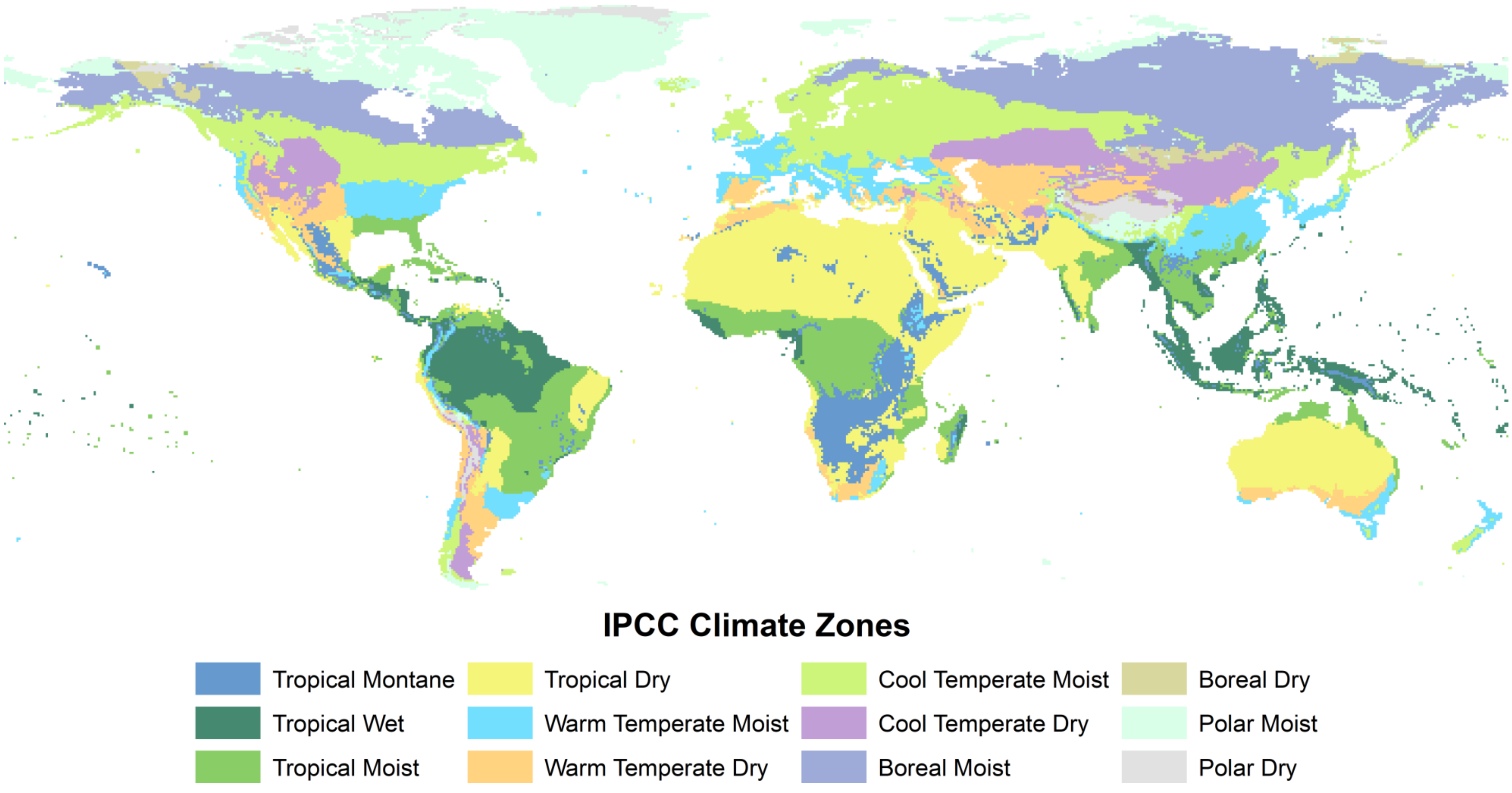


Figure 3A.5.2 Classification scheme for default climate regions. The classification is based on elevation, mean annual temperature (MAT), mean annual precipitation (MAP), mean annual precipitation to potential evapotransporation ratio (MAP:PET), and frost occurrence.

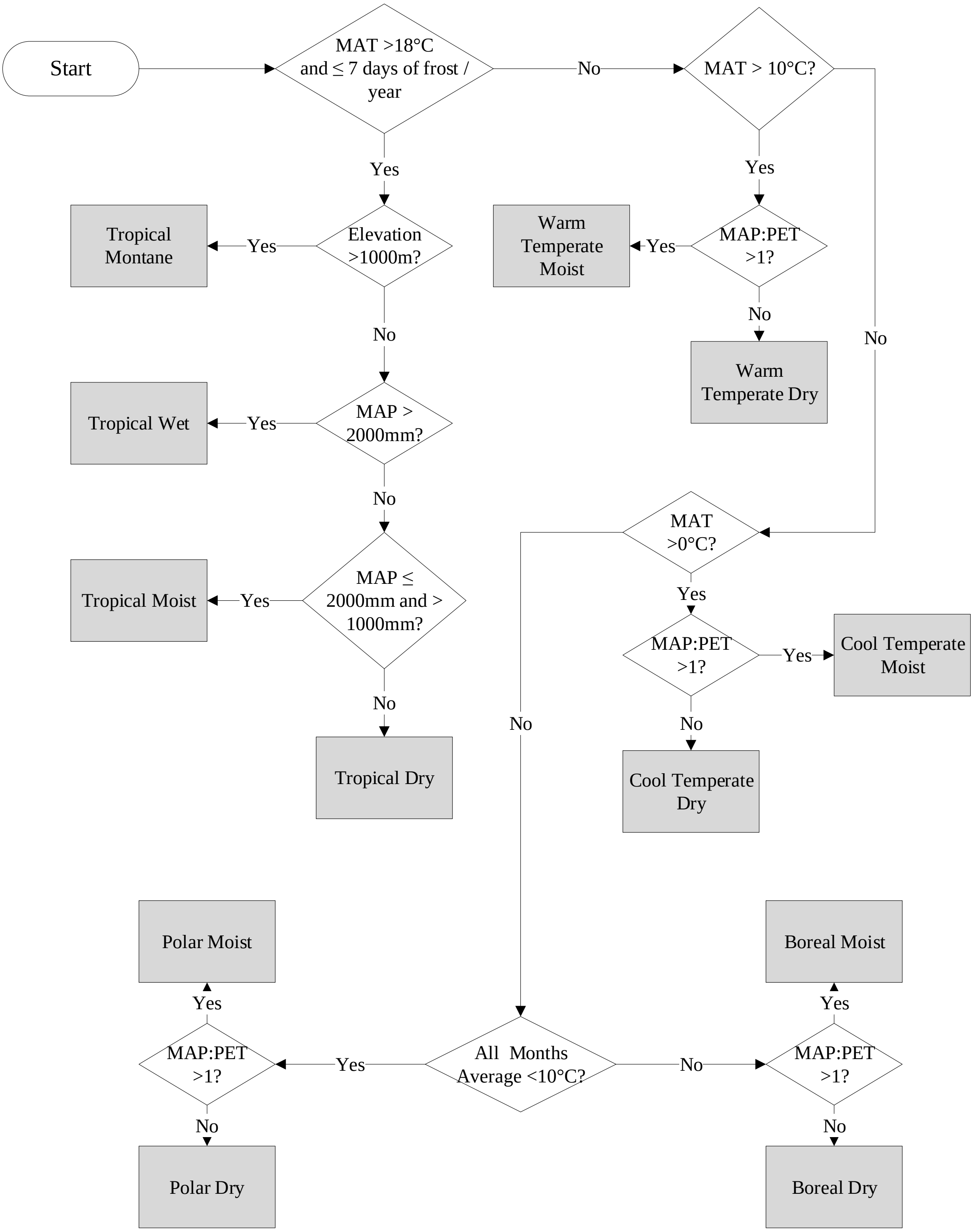


Figure 3A.5.3 Classification scheme for mineral soil types based on USDA taxonomy

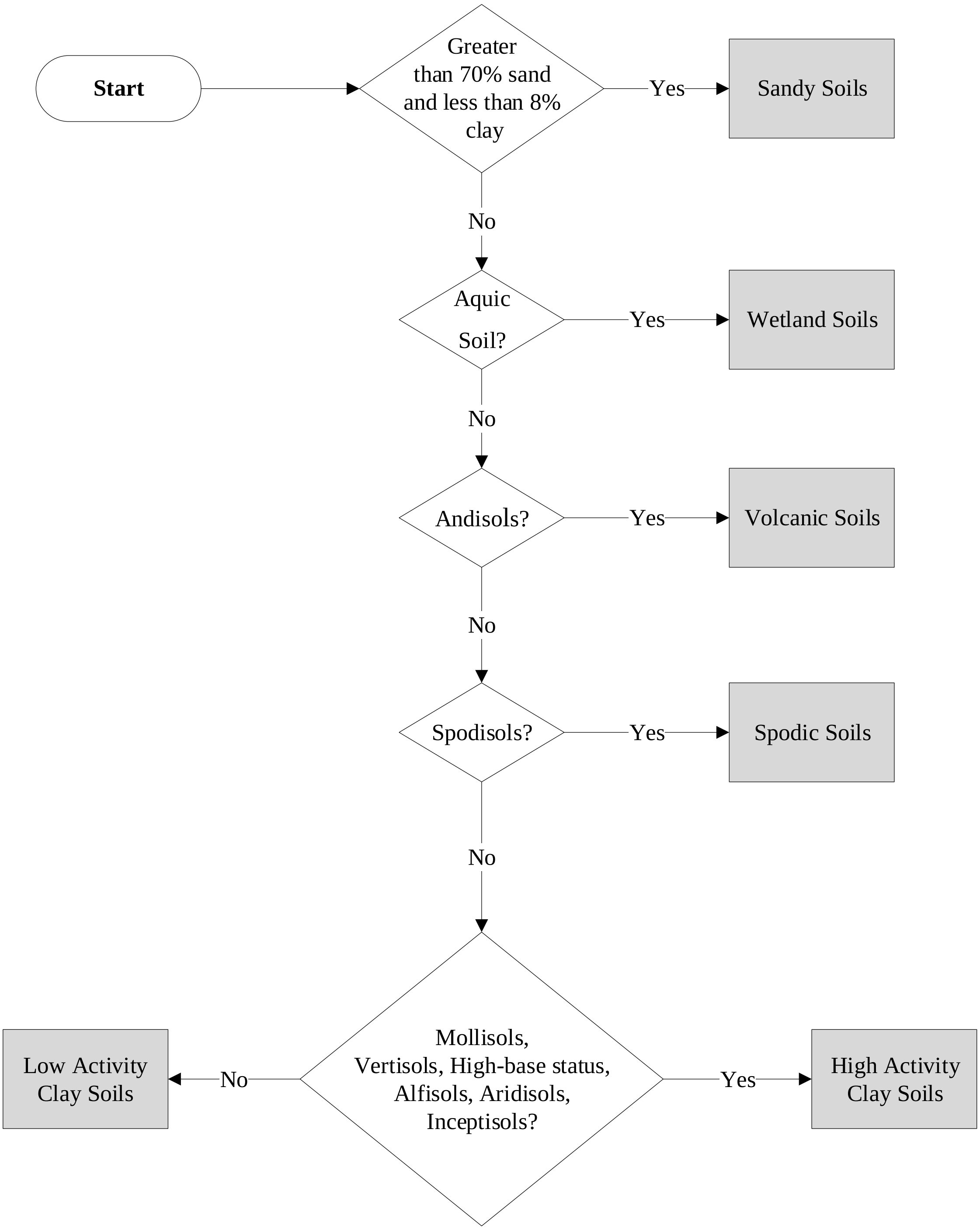
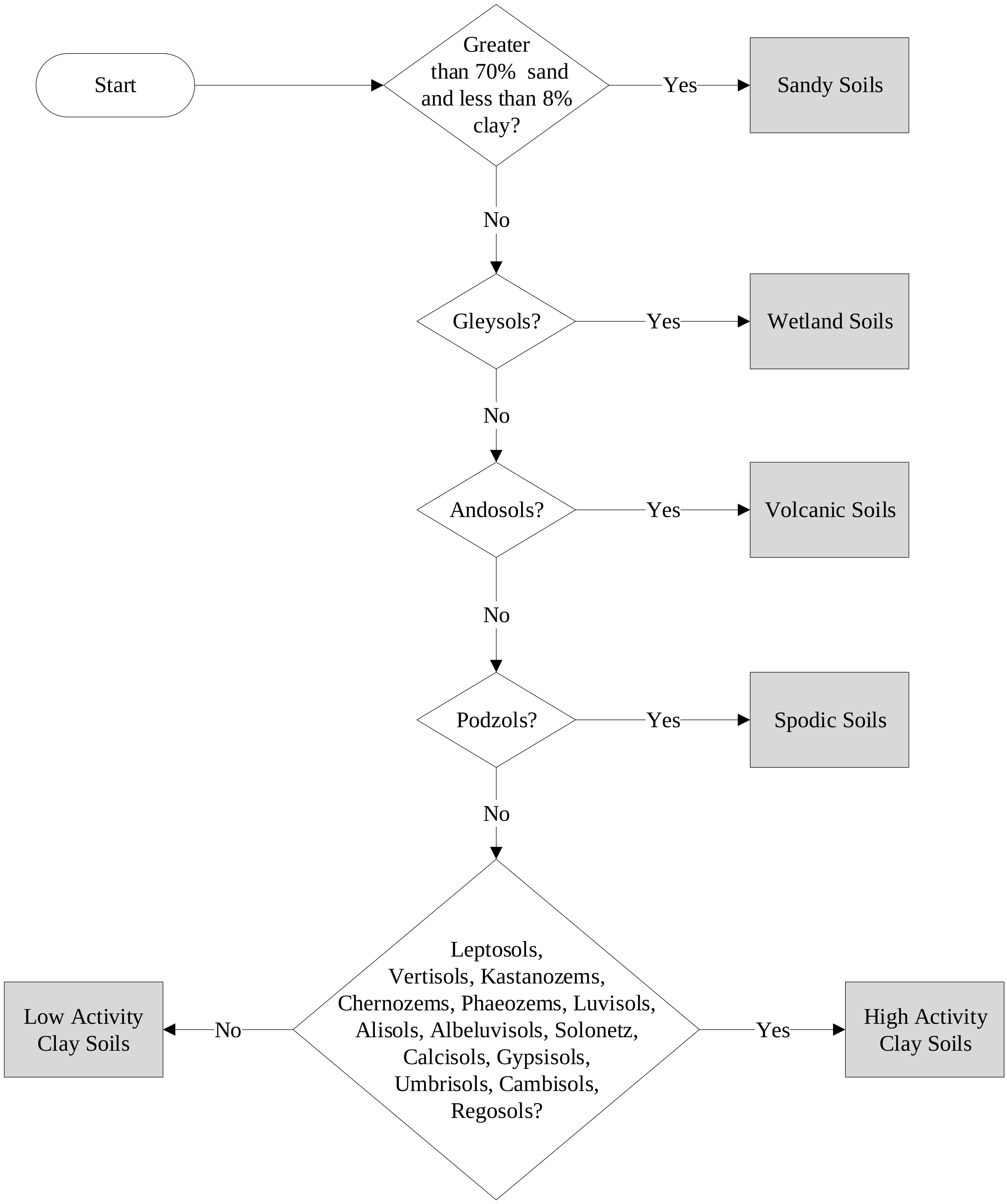


Figure 3A.5.4 Classification scheme for mineral soil types based on World Reference Base for Soil Resources (WRB) classification.



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

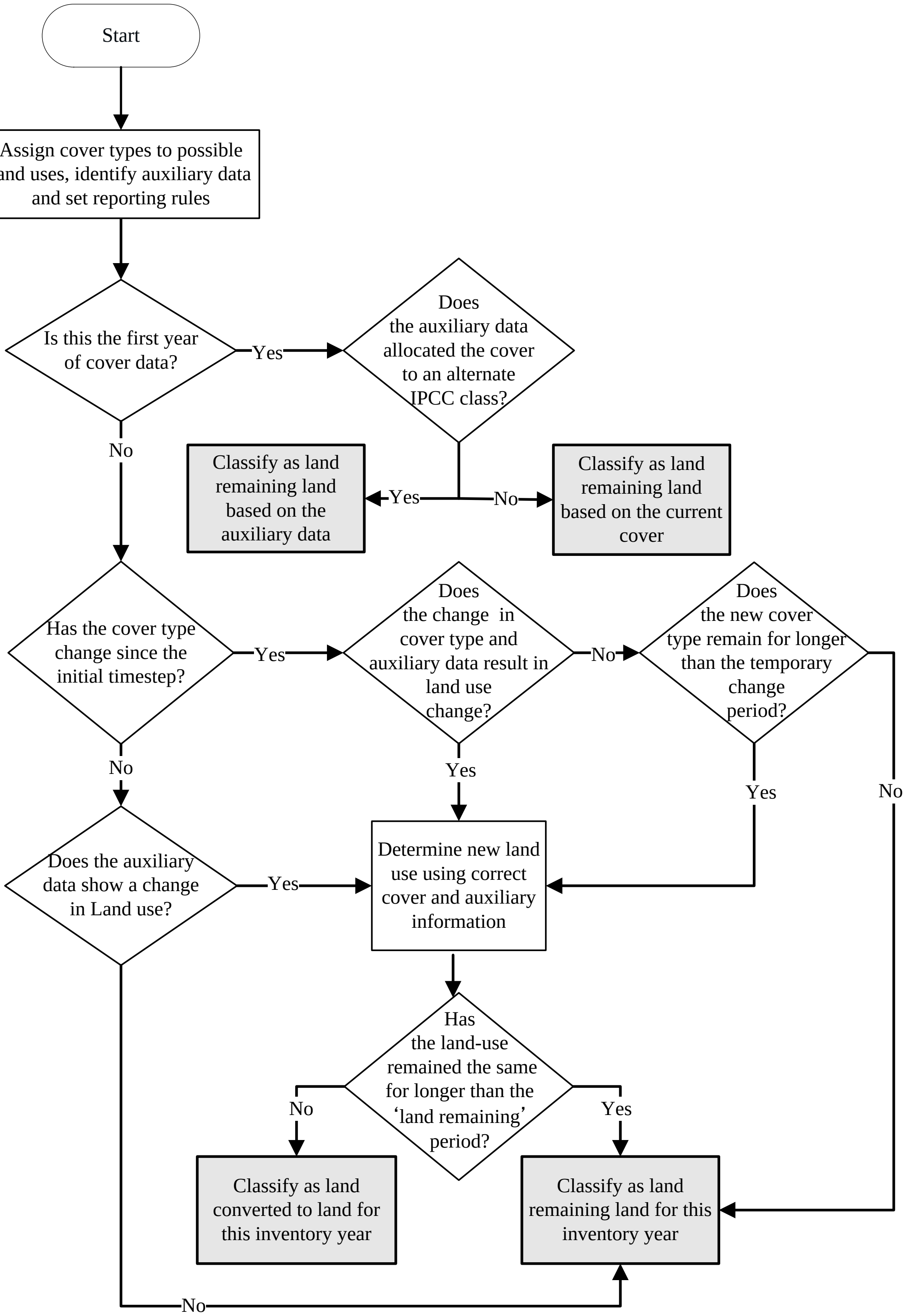
Land cover does change.

- 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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