CHAPTER 3

CONSISTENT REPRESENTATION OF LANDS

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3 CONSISTENT REPRESENTATION OF LANDS

Description of Refinement: In this section, updates (U), elaborations (E) and new guidelines (NG) are produced that provide a sound scientific basis for representing land area, land use change and related emissions and removals in the AFOLU sector. It treats specifically how to combine different data sources and types of information (with a special focus on remote sensing data and products), the coherence between national land-use classification systems and IPPC land-use categories, uncertainty and accuracy of activity data, and the specificities of remote sensing data. *These guidelines* provide general guidance to assist the inventory developer in the implementation.

Note

Grey highlighted text reflects original 2006 text.

~~Strikethrough text is original 2006 Guideline text to be deleted.~~

White highlighted text is proposed new update/elaboration/guidance text from 2019 Refinement.

Green text is Description of Refinement

Yellow text are captions to figures, tables and equations, and references to other IPCC sections.

3.1 INTRODUCTION

No refinement

3.2 LAND-USE CATEGORIES

No refinement

Description of Refinement: While No Refinement was mandated, an elaboration (E) is introduced on the clarification of the managed land proxy.

In addition, there is a placeholder to further revise the text pending on the outcome of the refinement proposed for interannual variability (IAV) in Chapter 2.

The six broad land-use categories described below form the basis of 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-categories describing special circumstances significant to emissions estimation, and where data are available. 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 use of **Approaches** for representing land-use area data described in subsequent sections.

The definitions of land-use categories may incorporate land cover type, land use, or a combination of the two. Care needs to be taken in inferring land use from the land cover characteristics and vice versa. For example, in some countries, significant areas of Forest Land category may be grazed, and firewood may be collected from scattered trees in the Grassland category. Further, on a single unit of land, land-use can change multiple times during an inventory period. These areas with different use may be significant enough for countries to consider them separately as additional sub-categories. Countries should ensure that land is not accounted for in more than one category or sub-category, in order to avoid double-counting of land areas.

For convenience, the categories are referred to as land-use categories. These particular categories have been selected 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.

Countries will use their own definitions of these categories, which may or may not refer to internationally accepted definitions, such as those by FAO, Ramsar[1], etc. Only broad and non-prescriptive definitions are provided for the land-use categories and of managed and unmanaged lands. Countries should describe and apply definitions consistently for the national land area over time.

The sum of all land (managed and unmanaged) and fresh water areas normally remains constant through time, with land uses changing within the total area. However, in some cases the land or total area may change over time, for example due to land reclamation or inundation due to sea-level rise. In such cases it is good practice to document the cause of the change and consistently report the gain or loss of new land areas in the inventory.

Where the land or total area changes due to methodological reasons, it is good practice to document the cause of these changes and demonstrate they do not lead to errors in the reporting of land areas and emissions and removals.

Countries should describe the methods and definitions used to determine areas of managed and unmanaged lands. Managed land is land where human interventions and practices have been applied to perform production, ecological or social functions. All land definitions and classifications should be specified at the national level, described in a transparent manner, and be applied consistently over time. Emissions/removals of greenhouse gases do not need to be reported for unmanaged land. However, it is good practice for countries to quantify, and track over time, the area of unmanaged land so that consistency in area accounting is maintained as land-use change occurs.

"*Consideration by authors continues as to whether lands can move from managed to unmanaged, with available literature being assessed. Text on this issue will be provided in the second order draft (SOD). Text options that are being considered by authors, among others include: 1) "Lands can move from unmanaged to managed, but cannot move from managed to unmanaged*" *and* 2) "*Lands may be moved from managed to unmanaged where no human intervention has occurred for at least 20 years and all anthropogenic emissions and removals on the land have ceased for at least 20 years. Lands moved from managed to unmanaged should continue to be monitored for any future interventions that would make them managed again"*

Countries may develop country specific methods for addressing issues of interannual variability (IAV) to disaggregate anthropogenic and non-anthropogenic emissions and removals (see Section 2.X). Countries using country specific methods should describe the methods and definitions used to determine IAV and how these are applied to land areas in the inventory. Countries should report the area of land where the IAV methods are being applied. For the cases where IAV methods are only applied under certain circumstances (e.g. certain wildfires) and for a period of time, it is good practice to report the land areas entering and leaving the IAV categories.

As the resolution of the national land use, mapping may be For the cases where the national land use mapping is more coarse than the definitions used to describe the land-use categories (e.g., if the forest definition applied by a country includes a minimum area, of say one hectare for example, yet the available land-use mapping minimum unit size is five hectares) it is possible that there will be small (unidentified) areas of one land-use category reported under another. These small areas may be reported under the mapped land use when they remain in the same category. If they are converted to another land-use category (e.g., a small area of Forest Land converted to another use is identified within an area previously mapped as Cropland) and this is identified (e.g., by a permit application for the activity) then they should be reported under the appropriate land-use conversion (i.e., Forest Land converted to another specified land use) and subtracted from the original (previously misclassified) land-use (remaining) area.

The land-use categories for greenhouse gas inventory reporting are:

(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

[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.

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 brushes 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 (e.g., peatlands) 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.

(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.

LAND-USE CONVERSIONS

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

FF	=	Forest Land Remaining Forest Land	LF	=	Land Converted to Forest Land
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. 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.

The broad land-use categories listed above may be further stratified (as described in Section 3.3.2) 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 3.3.2 of this chapter.

The initial reporting year for inventories is 1990. Emissions and removals from the AFOLU sector in 1990 will be the result of land use conversions that occurred both in and prior to 1990 (lag emissions). To accurately report on the areas of land in the conversion categories in 1990 typically requires estimates of land use change prior to 1990. The length of the time series will depend on available data and the reporting rules selected by a country, in particular how long land remains in the converted categories before moving to a remaining category.

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

Description of Elaboration: In Section 3.3. the 2006 text has been reviewed and refined to expand guidance on how to integrate different data types and sources for the consistent representation of lands, in order to improve transparency, consistency and accuracy of land-use, land-use change and related GHG emissions and removals estimates. The refinement includes new guidance on how to combine the data, how to derive IPCC land-use categories (including land-use classification and stratification proceses) and tracking and distinguishing land-use changes. Case study examples have been incorporated demonstrating how parties have combined and worked with different types of data and sources of information in order to classify land use and attribute land-use conversions. Annex 3.A.1 has been updated with new land-use datasets and 3.A.2 have also been refined, including the elaboration and actualization of the existing text (e.g. RS data preprocessing and classification methods) and new guidance on time series consistency in data processing.

This section describes three Approaches (as per the 2006 IPCC Guidelines) that may be used to represent areas of land use using the categories defined in the previous section. They 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 is not spatially explicit). Approach 3 extends Approach 2 by allowing land-use conversions to be tracked on a spatially explicit basis.

The Approaches are not presented as hierarchical tiers and do not necessarily imply any increase or decrease in accuracy but reflect collection methods and attributes and, therefore, appropriate ways to use the data. In circumstances, for example where multiple changes in land use occur on single units of land, accuracy for both the areas of land reported and emissions and removals will likely be increased by applying Approach 3. Otherwise, accuracy is often affected as much or more by the quality of application of the Approach as by the Approach itself. The Approaches are not mutually exclusive, and the mix of Approaches selected by a country should reflect emissions estimation needs and national circumstances. One Approach may be applied uniformly to all areas and land-use categories within a country, or different Approaches may be applied to different regions or categories or in different time intervals. In all cases, countries should characterize and account for all relevant land areas in a country consistently and as transparently as possible.

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 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

Inventory requires 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 3.3.2.2 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 artifact 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 (examples are provided in Annex 3A.1, but generally report on the basis of land cover only, and not land use) (See Section “Combining land use classification and global databases”). It is preferable that data used should be capable of producing input to uncertainty calculations (See Section 3.x. Evaluation of activity data generated from RS techniques and estimation of uncertainties).

When using land-use data, inventory compilers should:

- Harmonize definitions between the existing independent databases and also 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 3.3should 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 analyzed 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 category)	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.

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

Initial / Final	Forest Land (unman-aged)	Forest Land (managed, temperate continental)	Forest Land (managed, boreal conifer-ous)	Grassland (unim-proved)	Grass-land (im-proved)	Cropland	Wetlands	Settle-ments	Other Land	Final area
Forest Land (unman-aged)	5									5
Forest Land (managed, temperate continental)		4		1	2	1				8
Forest Land (managed, boreal coniferous)			6							6
Grassland (unim-proved)		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

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

Approach 3 is characterized by spatially-explicit observations of land-use categories and land-use conversions, often tracking patterns at specific point locations and/or using gridded map products, such as derived from remote sensing data ~~imagery~~. The data may be obtained by various sampling, wall-to-wall mapping techniques, or combination of the two methods. An overview of potential methods for developing Approach 3 datasets is provided in Annex 3A.4.

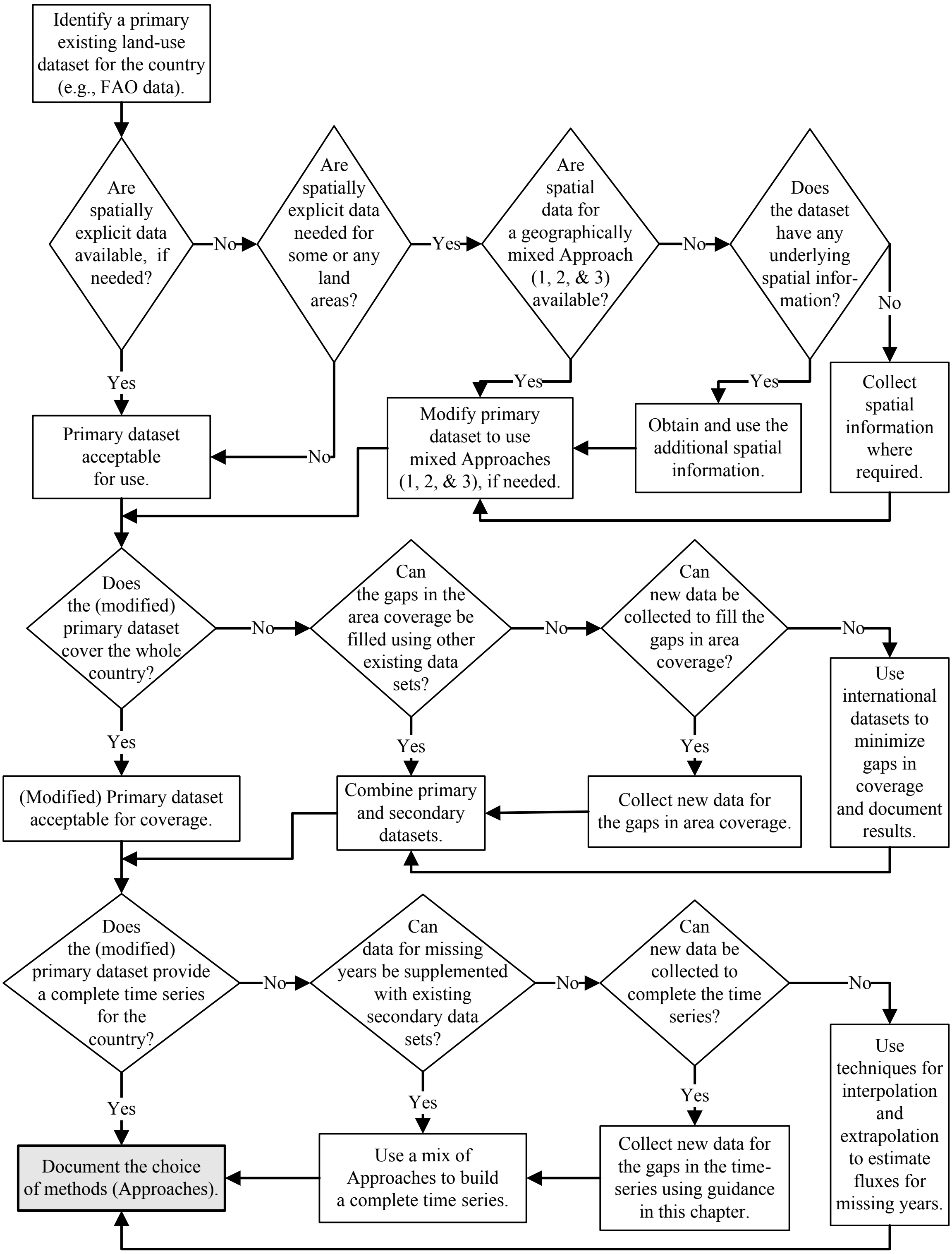
Approach 3 data can be summarized in tables similar to Tables 3.5 and 3.6. The main advantage of spatially-explicit data is that analysis tools such as Geographic Information Systems can be used to link multiple spatially-explicit data sets (such as those used for stratification) and describe in detail 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.

3.3.2 Using the data

Figure 3.1 is a decision tree to assist in describing and/or obtaining the data on land-use areas. 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.

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



METHODS FOR LAND USE AND LAND-USE CHANGE ESTIMATION

Sample-based, spatial explicit and spatially referenced methods can be used to estimate land-use area and land-use conversions. Spatially explicit land representation refers to a set of grid cells or small polygons (see Annex 3A.4). Spatially referenced method refers to point data with coordinate locations including sample-based methods. Data collected by survey is often not referenced spatially to a specific location.

Spatially explicit (wall-to-wall) methods

The continually increasing volume and quality of data available from remote sensing allows countries to develop wall-to-wall maps of land cover and land cover change that can be used to estimate land use and land use change. There are a number of potential applications for RS products application to derive consistent land-use and land-use change estimates, including:

- identifying land cover and land-cover change, for example, forest cover change and multiple land cover change types;
- attribution of change to specific disturbances; and,
- stratification of land use and land use change into more homogenous units to improve the estimation of emissions.

To be useful for inventory reporting, spatially explicit approaches also need to be time-series consistent i.e., to be able to track lands to determine the previous and current land uses. When using spatially explicit systems it is *good practice* to:

- ensure that estimates of change are not influenced by misalignment of images or artifacts in data (such as cloud cover);
- when creating composite products to remove areas of no data (for example, due to cloud or sensor errors) ensure that the image dates do not cross over into different seasons;
- document and use the timing of the images to ensure that land use change is reported in the correct period and that the images do not cross over. For example, a 2005 map that uses data from 2002-2008, then a 2010 map that uses 2008-2012;
- evaluate the final products to ensure:
    - (i) time-series consistency;
    - (ii) consistent representation of land uses;
    - (iii) accuracy of the final land use and land use change products (note that assessing the accuracy of cover change only will not do this); and,
    - (iv) consistency with the methods for estimating emissions and removals.

Spatially referenced methods

Sample based

Sample based approaches refer to methods that directly estimate land use and land use change from samples. Samples may be obtained from ground surveys (such as a National Forest Inventory or national land survey) or remote sensing (for example, satellites, aerial photography or LiDAR).

All national systems for land-use estimation and classification require the use of samples. Samples can be used to calibrate and evaluate other land use products (in particular wall-to-wall mapping methods) or to directly estimate land areas and/or emissions and removals (see Section 2.x Tier 3 measurement systems). **Error! Reference source not found.** provides a case study for the estimation of land-use and land-use changes based on ground measurements.

A key issue when selecting a sampling design is that the sample size must be large enough to produce sufficiently precise estimates of land use and land use change, given the policy requirement and the costs involved. No matter the sample method applied (ground or remote sensing), it is *good practice* to ensure that:

- sufficient samples are collected to identify both land use and land use changes;
- samples collected or re-measured with sufficient temporal frequency to ensure land use changes are identified;
- where the samples are not also used to estimate carbon stocks (for example, if using remote sensing methods) that the sample units are consistent with those used to develop estimates of emissions and removals (for example, emissions factors or Tier 3 models);
- where samples are collected on a subset of the IPCC land use categories, the methods are able to be applied consistently with other data to ensure consistent representation of lands; and,
- where sampling methods have changed through time, these do not lead to inconsistencies in the reporting of areas of land use and land use change.

BOX 3.1
CASE 1: ESTIMATING LAND USE AND LAND-USE CHANGE FROM GROUND MEASUREMENTS (SWEDEN)

Land use and land-use change can be monitored based on field inventoried sampling units without using maps or remote sensing products (SEPA 2017). One way is to use a sampling frame (the frame can be based on a map but the map does not necessary need to be used for improving the estimates) consisting of the total land and fresh water area for a party. The sampling units can be distributed based on a systematic grid with randomized location in the frame (Annex 3A.3.3). A permanent design (the same sample units are re-inventoried in a periodic cycle) has been proved to be efficient when estimating changes (Annex 3A.3.3). Stratification into assumed homogenous strata is another way to further improve the accuracy of estimates (Annex 3A.3.3). The distribution of the sampling units can be spatially explicit (Annex 3.3.1.3) in the sense that their locations are identified using satellite positioning systems. This, combined with the permanent design makes it possible to estimate both gross and net land use transfers to provide a land use matrix. The area-based sampling combined with the ht-estimator, makes a sampling unit representative of a certain area and all sample units together the total land and fresh water area (Horvitz & Thompson 1952).

Land use may be interpolated per sample unit for the years between consecutive inventories. If a land use conversion is registered at the re-inventory, the year of conversion can be assessed based on information about the sample unit (e.g. From fresh stumps, vegetation, shoots, dead tops or branches) or by selecting a random year of conversion during the period. Any changes in biomass from e.g. Deforestation should be matched to the year of land use conversion. Such a design makes it possible to match changes in carbon pools to land use and land-use change and trace them back in time. If trees and dead wood are positioned on the gps-located sampling units, changes in carbon pools can be perfectly matched to land use categories even for sample units delineated into more than one land use category. Few countries have a ground-based design that covers all land and fresh water areas before the base year and onwards. Then land use and land-use changes may have to be extrapolated e.g. From the trend for each land use category and land-use change category. Most national forest inventories are field-based but may lack of sample units on non-forest land. If this is the case, the present design has to be complemented with data from other sources. The method for this is relatively laborious and thereby costly. Some advantages are that the method is simple, transparent, consistent, theoretically unbiased and a declaration of quality can be estimated from a variance estimator (Annex 3A.3.2). The sample variance can be controlled by increasing the sampling intensity and, if carbon pools are simultaneously assessed, the model error seems to be relatively small (e.g. (BREIDENBACH *ET AL.* 2014; STÅHL *ET AL.* 2014). The model error is introduced by using empirical models rather than destructive measurements to assess the carbon on the sample units.

Land unit or stand-based

Many countries may have access to list 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 do not include spatial information. For example, within a region information on the area, species, type and management of all forest areas (stands) of may be available to the inventory compiler as a table, but the exact location of the stand is unavailable. When using land unit methods it is *good practice* to:

- ensure that the area of the land units is consistent with 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,
- ehere possible, compare the area estimates to other estimates obtained from other methods, such as sample-based methods.

COMBINING MULTIPLE DATA SOURCES

Remote Sensing (RS) products have been and are increasingly being used by countries (GFOI 2016) as a source of information to estimate land use and land use change. The most common use of these products is to detect forest cover and cover change. However, 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 RS data is useful for identifying land cover and where a change in cover has occurred, the resulting products often do not provide information on why change occurred (drivers), the impact of that change, the actual land uses and the likely associated emissions. Combining RS 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 classes over time.

Typically, countries will combine a variety of different data sources and approaches to estimate land areas and activities. 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). Combinations of data sources may also occur within a type of data. For example, 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 not completed (i.e. some years are missing and are supplemented with other statistics), a land use class or strata is missing (e.g. sugar cane 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 time scale of the data sources;
- ensure consistency between different time or spatial scales in the data sources;
- ensure that all data is in the same map projection, that rasters and/or polygon boundaries align and are within official national boundaries;
- ensure that land conversion areas are consistent with each other across the entire time series e.g. losses in the area of forest land categories are consistent with areas of forest land converted to cropland, grassland, settlements, wetlands, and other land;
- ensure that the land conversion period applied across all categories is the same;
- 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;
- eover data gaps to derive consistent time series of land-use and land-use change; and,
- improve the accuracy of land-use and land-use change estimates.

Spatially explicit approaches in particular are commonly combined with other spatial data to produce emissions estimates. For example, maps of forest and/or soil types, climate data and information on land management practices. These are several issues that are common to GIS databases that hold multiple data layers (Merchant & Narumalani 2009), especially when combining vector and raster data sources of different spatial and temporal resolutions. As such, when using multiple different spatial datasets it is *good practice* to ensure that:

- all data layers are all registered to a common base maps align to prevent errors due to misalignment such as slivers or areas of false change along the edges of different classes;
- reprojection of data sources does not cause significant error particularly when applied across large areas such as a country or continent (Seong 2003);
- when combining data of different pixel sizes (for example, climate data 1km, with satellite data at 30m) that the data align; and,
- if resampling is conducted to ensure pixel alignment (for example, resampling Landsat from nominal 30m to 25m) this is done prior to classification.

Integrating spatially explicit (Approach 3) data with non-spatially explicit data

While sampling (ground based) and spatially- explicit methods can stand alone for the estimation of land-use and land-use change, commonly additional sources of information are required to cover data gaps, increase the accuracy of the estimation and generate consistent time-series. Examples of integration of spatially and non-spatially explicit data are provided in Box 3.2. Box 3.3 provides high-level guidance on how to combine spatially explicit and spatially referenced data.

BOX 3.2
CASE 2: STRATIFICATION AND MODEL-ASSISTED APPROACHES WHERE AUXILIARY INFORMATION FROM RS E.G. PIXELS (WALL-TO-WALL OR SAMPLE) IS USED TO IMPROVE THE ESTIMATES.

(GFOI 2016) presents two examples illustrating methods for the estimation of activity data, one based on a stratification approach (Cochran 1977; Olofsson *et al.* 2013; Olofsson *et al.* 2014) for a map with categorical predictions, and the other based on a model-assisted approach (Särndal *et al.* 1992; Sannier *et al.* 2014) for a map with continuous predictions.

An important distinction between the approaches illustrated in the two examples concerns the use of the map data. In the first example, the pixel-level map data are in the form of allocation to discrete classes and are used only to construct strata, to calculate stratum weights, and to reduce the variance of the area estimate relative to the variance of the estimate based only on the reference observations.

With the stratified estimator for the first example, the within-stratum estimates are based entirely on the reference observations. In the second example, the map data are used as a continuous, segment-level, auxiliary variable. The model-assisted estimator facilitates greater exploitation of the relationship between the segment-level reference proportion of area and the segment-level map proportion of area. Consequently the model-assisted estimator requires compensation for the effects of segment-level model prediction error, but it also exerts a greater influence on the final estimates via a greater reduction in the variance error of the area estimate.

The model-assisted approach is more useful when the mapped response variable is continuous and when the relationship between reference data and map data used as auxiliary information can be exploited to increase precision.

This approach has been applied by some countries for estimating areas of forestland converted to other lands and other lands converted to forestlands (e.g., Bhutan, Democratic Republic of Congo and Bangladesh) using the SEPAL tools (SEPAL 2015). It is yet to be applied for all inventory categories and sub-categories. When applying this method it is important to ensure that sampling considers all the strata required to estimate emissions and removals in the national greenhouse gas inventory, such as forest and soil types and climate zones.

BOX 3.3
CASE 3: COMBINING INCOMPLETE SPATIALLY-EXPLICIT DATA AND ANCILLARY INFORMATION FOR LAND-USE CHANGE ATTRIBUTION AND CATEGORIZATION (ARGENTINA)

In the case of non-annex 1 countries, access to RS data and in-country processing capabilities may be scarce. Data gaps in RS information need to be covered by splicing techniques, other types of data sources, assumptions and decision rules. In the cases where no consistent land-use maps nor statistics are available at the national level, land-use conversions can be estimated through changes in land-use area (Approach 2 and 3).

The land use change matrix can be constructed based on the combination of deforestation maps (spatial explicit), national agricultural statistics (non-spatial explicit) and decision rules (assumptions) for the attribution of land-use conversions (MAyDS 2017) (Table 3.7). To combine the data, stratified forestland cover in raster format is converted to polygons at the administrative level (e.g. municipality). This can be performed by using digital maps of national administrative boundaries and combining the data into a GIS platform. When land-use data is not available for the complete time-series calculations can be performed to assure land use consistency.

Decision rules can be applied to attribute deforestation to cropland and grassland, the conversion of grasslands into cropland and vice-versa. Examples of attribution rules are described in the decision tree in

Figure **3.2**., including the stratification of grasslands into pasture and natural area. The decision tree firstly differentiate between deforested and non-deforested areas to attribute the increase in cropland area. Changes in forest and cropland area are further explained by changes in pastureland. When deforested area is not sufficient to explain the change in managed lands (i.e. cropland and pastures) the difference is attributed to natural grasslands.

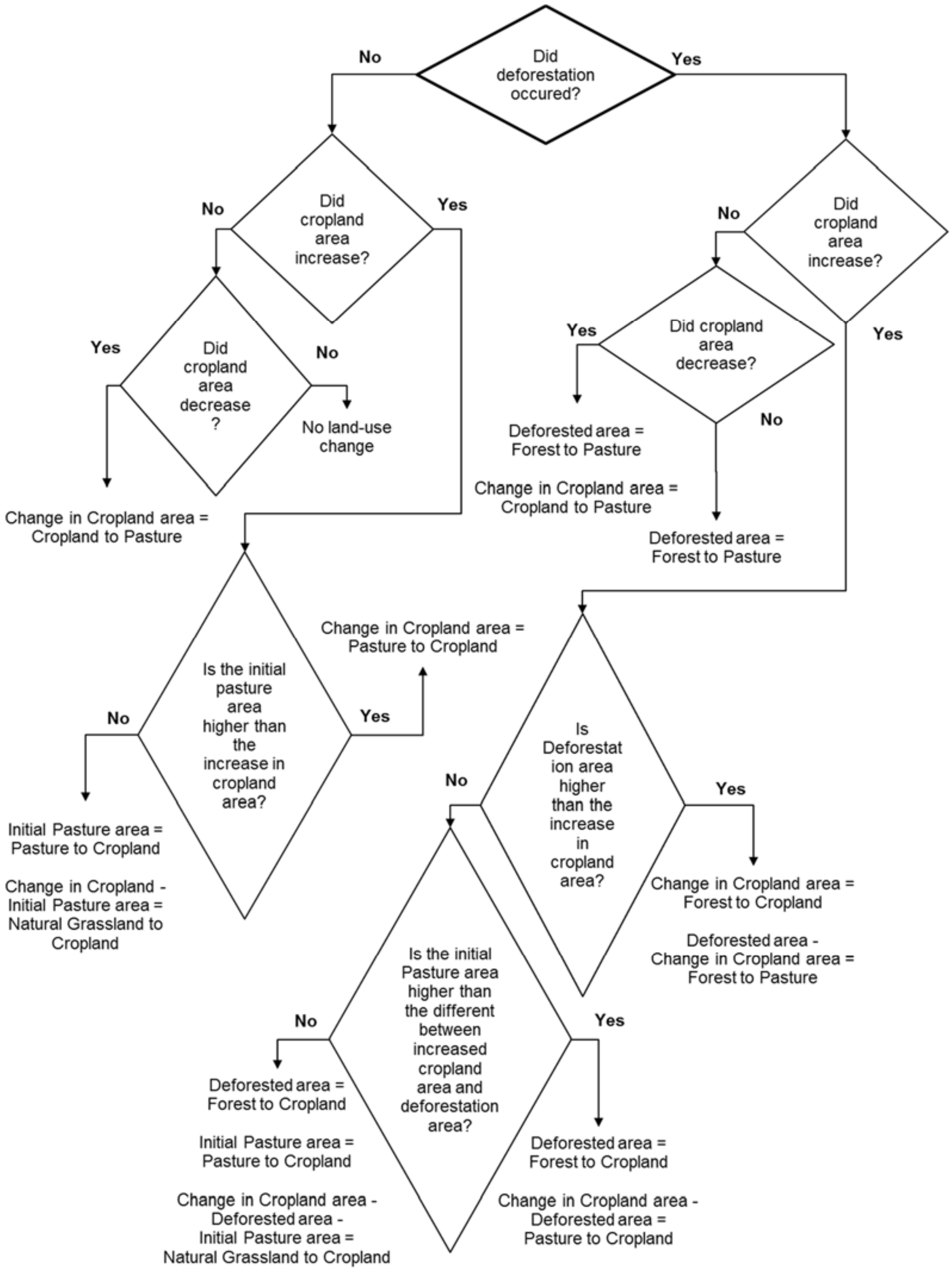
Due to the lack of spatially explicit data, bias (e.g. in the estimation of natural grasslands and pasture area) and errors (e.g. due to miss-classification of deforested area) may occur in the estimation of area and the attribution of land use change. National livestock statistics can be used for instance, as a proxy to verify that changes in pasture and natural grassland is consistent with changes in livestock. Ground measurement, aerial photography and other types of data can further be used to evaluate the accuracy of the attribution of land use change.

TABLE 3.7
EXAMPLE OF DATA COMBINATION FOR THE ATTRIBUTION OF LAND USE CHANGE.

Data	Type of data	Comments	Formula
Deforested area	Satellite image	Only change in native forestland area is monitored	Activity data
Initial effective cropland area	Statistic	Adjusted for double-cropping and pasture crops	Activity data

Final effective cropland area	Statistic	Adjusted for double-cropping and pasture crops	Activity data
Initial Pasture area	Previous estimation	Estimated in 2002	Estimated in previous inventory (Final Pasture area in t-1)
Final Pasture area	Calculation	-	Forestland to Pasture + Cropland to Pasture– Pasture to Cropland
Initial Natural Grassland area	Calculation	Used to adjust area when the increase in cropland area is not sufficient to explain change in area	Change in Cropland area – Deforested area – Initial Grassland Pasture area = Natural Grassland to Cropland
Final Natural Grassland area	Assumption	There are no natural grassland statistics	0

Figure 3.2 Example of decision tree for land-use change classification with combination of 1) RS data, 2) National Statistics and 3) Attribution rules.



DERIVATION OF IPCC LAND-USE CATEGORIES

Use of existing national data

Most Parties have at least some national data that can be used for reporting land areas. This data may be used alone or in combination with other data to derive IPCC land use classes. Defining the equivalence between national land use classes and IPPC land-use categories can be a difficult task, as national products are often developed for other purposes and do not necessarily match the IPCC definitions. For example, the definition of forest land cover in RS products may differ from the national definition, and existing forest type maps are unlikely to map to new remote sensing products. and the stratification of forest land into different forest types.

In developing IPCC land use categories from national land use and land cover information, it is *good practice* to:

- refine the national land-use categories and the rules applied to track them in the inventory (Table 3.8);

- establish and document procedures to convert national land use and land cover categories into IPCC land use categories;
- describe how multiple data sources are combined to classify land-use and how the methods ensure consistent representation of lands and prevent errors of omission or commission through time;
- demonstrate that the land use categories definitions cover the entire variability of land cover and land uses of the country territory;
- if the data and methods available allows to make such a distinction, describe how temporary forest cover loss is distinguished from permanent land use change, and how temporary forest cover loss due to disturbances (e.g., forest fires) is distinguished from harvesting;
- report an equivalence table between the national land-use classification scheme and the IPCC land-use categories defined in Section 3.2. of the IPCC 2006 Guidelines;
- report what land cover elements, and according to what classification rules, including by using additional information, they are used to identify land use categories and attributions and assumptions made to match land-use categories for the national classification system and the IPCC 2006 Guidelines; and,
- evaluate the accuracy and consistency of the land cover and land use classification system, including errors, biases, and estimate the uncertainty and main consequences of the matching process.

Converting land cover into land use

Although the terms land cover and land use are often used interchangeably, they are different. Land cover can be defined as the physical material at the surface of the earth, such as trees, water, or building. Both remote sensing data and ground surveys typically estimate land cover at a point or multiple points through time. To derive the IPCC land use classes requires a combination of information including land cover, past land cover, management purpose and a series of reporting rules set out in these guidelines. Inferring land use from land cover at a specific point in time may lead to misclassification of land use. In sample based systems the land cover data is usually supplemented with additional information on use, such as identification of recent activities and knowledge of the site history. For remote sensing, additional data will be needed to estimate land use. This can be further complicated as some cases RS products are not be able to distinguish between similar land-uses, for example:

- crops and annual grasses may look the same and cannot be easily categories into cropland or grassland; and,
- agro-forestry and silvo-pastoral (forest grazing) systems which may looks similar to both forestland and grasslands.

The IPCC land uses also include several reporting rules with parameters that can be selected by individual countries (Table 3.8). These rules mean that although cover may change or be different at one or more points in time, the land use may remain the same. For example, following forest harvesting the land cover may be dominated by grasses, but the land remains as Forestland. Therefore, it is important that inventory compilers have a clear understanding on how IPCC land-use categories have to be derived from land-cover interpretation. For the derivation to be accurate it is good practice to clearly document the country-specific rules applied in the inventory and apply these consistently both spatially and temporally.

TABLE 3.8
RULES IN THE IPCC GUIDELINES FOR CLASSIFYING LAND USE.

IPCC land use categories and sub-categories	Decision required	Document
Forestland	• Definition of forest to be applied: o canopy cover (10-30%), potential to reach a minimum height in situ (2-5 m), minimum area (< 1 ha) and minimum width (m). • Predominant land use	• Decision on the forest cover thresholds and how they are applied consistently through time.
Forestland remaining forestland and forestland converted to other lands	• Where cover is lost, is it deforestation or forest harvesting	• The criteria used to distinguish harvesting or forest disturbance that will be followed by the re-establishment of forest from deforestation.
Forestland remaining forestland and forestland converted to other lands	• Where cover is lost, it is human induced or due to natural processes	How human induced cover loss is separated from natural loss, and where areas of loss due to natural processes are reported.
Forestland remaining forestland	• How long without forest cover due to temporary conditions before moving to another land use? • How to report these areas?	10 years Temporary forest
Cropland remaining cropland and Grassland remaining grassland	• Should lands moved between land use categories due to short-term or opportunistic management practice? • How long before a land does move if the cycle finishes?	Cropland includes crop-pasture rotational systems 5 years
Croplands and forest lands	• Should orchards and other woody plants that meet the structural forest definitions be reported as Cropland or Forestland	Decisions on which category they will be assigned to and how this will be handled consistently in the inventory
Croplands	• How to report areas of double cropping	Define double-cropping as strata in cropland land-use classification and show that any double cropping is not double counted in cropland area estimates
Forestland and Grasslands	• Where to report lands subject to integrated forestry/cattle ranching/grazing activities. systems or forest grazing to be applied: forest cover, animal intensity, stratification required	Decisions on which category they will be assigned to and how this will be handled consistently in the inventory
Forestland and Cropland	• Which categories to include areas of agro-forestry	Decisions on allocating lands based on factors such as crop types, forest cover and use, % ha with agro activities
Settlements	• How to report areas in settlements that could also be classed as other land uses, such as parks and small semi-urban farms.	Decisions on what defines a settlement, and how lands within settlements are treated in emissions estimation
Wetlands	• Separate wetlands from water area	Wetlands are inventoried and georeferenced in wetlands reported under the RAMSAR convention.

Where insufficient information is available on land-use types and histories, classifying land use from land cover may involve stratification, supplementary information and re-scaling processes. When using such approaches in converting land cover into land-use classification, it is *good practice* to:

- stratify land in homogeneous areas for current and historical land cover and land cover changes;
- use supplementary information to distinguish between temporary and permanent land cover change. Such information may include forest management plans, land tenure information, information on the typical causes

as well as drivers of land use change in a region, and the location and size of the area with land cover change. For example, if a land cover change somewhere well within a large managed forest block, it is much more probably that a forest cover loss is due to normal forest management than due to deforestation; and,

- use re-scaling techniques as necessary.

Covering data gaps in land use with splicing techniques

National inventories require annual estimates of emissions and removals. Ideally, annual data would be able to estimate annual changes for all land-uses. In practice, such data is not available 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 splicing techniques to cover these gaps.

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

- clearly define, document and report the years where land cover and land use data is missing;
- ehere the number of years between data varies (for example, 5 years for one period, 2 years for others) demonstrate that this does not bias the estimates of land use change;
- clearly justify the choice of the splicing technique used to fill the gap between years of land cover data;
- when using interpolation methods, if the land use category on a sample unit/on land 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, the extrapolation should be based on recent trends or relationships to auxiliary data. If based on trends then the country should justify of the length of the time-series used to develop the trend;
- describe and provide reference to the method used for interpolation/extrapolation of land-cover change;
- when possible, clearly estimate, document and report the uncertainty linked to the RS annual data available and the uncertainty linked to the periods where this data is not available; and,
- report the limitations and consequences of covering land cover data gaps with slicing techniques.

Further, in the case of remote sensing data, some areas of land may not be covered with data in every epoch. 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.

Combining land use classification and global databases

Accuracy of global products varies regionally due to factors including differential sensitivity of detection at biome and eco-regional scales, change dynamics and data richness. In general, use of global maps will produce activity data estimates with lower accuracy and precision than are attainable by national mapping of comparable quality, because the latter can be tuned to national land use definitions and make use of knowledge and auxiliary data available at the national level. However as set out in Section 3.x, correcting for estimated bias at a given level of precision depends on the combination of mapping (whether global or national) and reference data.

Therefore, when correcting for estimated bias in global datasets, it is *good practice* to:

- compensate lower accuracy associated with global datasets by using more ground or other reference data;
- evaluate the level of accuracy of the global dataset by comparing (e.g. in a pixel by pixel base) the land-use class with sub-national spatial explicit information; and,
- ensure that the samples represent the strata being used for emissions estimation.

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) the need for information on the drivers of land use/ cover change 3) whether national mapping capacity already exists and 4) 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 both products cover 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.

Figure 3.3 Decision tree for classifying land use and land use change through time (see description for process).

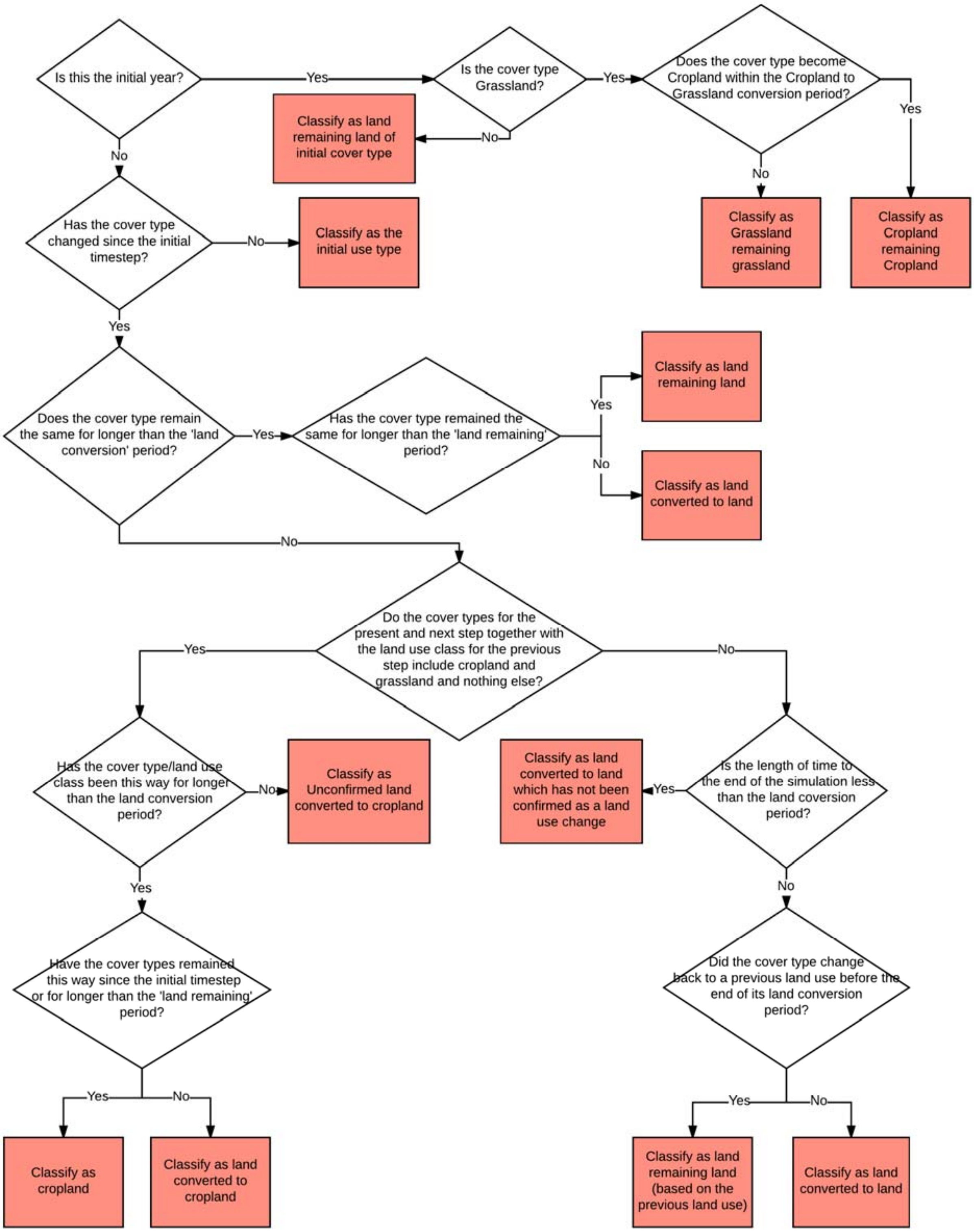


Figure 3.3 provides a process for allocating lands to different land use classes when using Approach 3 spatially explicit methods. The decision tree is applied annually, but also considers both the past and future land uses when allocating lands to each IPCC category and sub-category. This time-series approach is required to be able to correctly apply the IPCC reporting rules. Every land unit is assumed to have information on the vegetation type (which can vary by country) for each year of the simulation, including the initial type. Each of the nationally specific vegetation types are associated with an IPCC cover type which is used in the land use decision process, to decide which land use category to assign for each year. The decision tree allocates all of the IPCC land use categories and their sub-classifications of land use 'remaining' land use and land use 'converted to' land use. The key nationally determined reporting decisions are:

- how long remains in a ‘converted to’ sub-category before it moves to the ‘remaining’ sub-category;
- the time before land that was considered temporally destocked moved to a ‘converted to’ sub-category; and,
- how to class areas of land that include fallow or pasture cover in between cropping or harvesting cycles.

3.3.2.1 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, cropland, grassland) into sub-categories (e.g. tropical/dry forest, crop types, improved or unimproved pastures). Stratification is commonly applied to increase the accuracy of emissions and removals estimates. In addition to provide clear improvement in the accuracy of the estimation of emissions and removals, strata need to be sufficiently distinct to be identifiable and the boundaries of strata can change over time e.g. if the frontier of disturbance moves into areas of previously undisturbed forest.

Stratification is also useful to:

- assist in the management of uncertainties and to plan continuous improvement of the inventory;
- increase the flexibility in reporting of monitored data, for example, effectiveness of policies tailored to specific strata (forest types, risk types);
- enable tailoring of specific methods or data collection processes in different strata. For example, it is much more difficult to measure deforestation using traditional optical methods in fragmented dryland forests than contiguous moist tropical forests;
- distinguish between managed and unmanaged land in the various categories; and,
- track areas under conversion across time series, especially to deal with subsequent changes.

Stratification~~This~~ 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 3.9 provides some examples of possible data types and assumptions to stratify land use and land-cover.

TABLE 3.9
EXAMPLES OF AUXILIARY DATA AND POSSIBLE ASSUMPTIONS THAT CAN HELP WITH LAND USE STRATIFICATION.
(based on (GFOI 2016).

Issue	Data	Possible assumption
Determine if change in forest cover is temporary de-stocking or a land-use conversion from forestland	Maps of forest management areas	Forest cover lost due to clearing or harvesting in forest management areas is considered temporary and tracked to ensure forest cover returns. Forest cover loss due to clearing or harvesting outside these areas is considered conversion.
Determine if the forest type or species changes	Maps of plantation management areas, private plantation areas.	Forest areas in these can be considered plantations
Determine if the forest cover is natural or a planted forest	Species (or natural/ plantation splits) and the network of planted trees in high resolution maps	Plantation species will be established in known plantation regions. Natural species will have been cleared for other uses
Separate forest cover loss due to conversion or harvesting from loss due to other causes	Fire maps Pest attack	Change that occurs at the same time as fire is a fire
Is forest cover loss due to clearing or other processes?	Maps of National parks and protected areas	Changes are natural, unless otherwise noted (only if there is strongly controlled management of these areas)
Separate crop types and management practices	Climate or soils types	Certain crops and management practice can occur in certain regions (e.g. no crops in a desert, no-tillage farming in low organic matter soils)
Separate implanted pasture from natural managed grasslands	Livestock statistics Agricultural census	Land with high concentration of animals (more than 3 animals/ha) are pastures Producers in a certain region use pastures (e.g. in cropland rotation).

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

- assess the possibility to obtain reliable data to classify land-use categories into sub-categories that is available over time;
- establish clear definitions for land-use strata;
- ensure that strata area covers the total land area of the category being stratified;
- ensure that the strata =have the attributed required to make estimates of emissions and removals (for example, emissions factors or model parameters); and,
- review the effect of the stratification to determine if further stratification would improve the estimates or 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 ancillary 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, these 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 stratified land-use data. A typical example is using project and activities data (e.g. city-level GHG emissions accounting and reporting, mitigation actions/activities such as REDD-plus and CDM at the sub-national/corporate/project level and ccalculations to highlight mitigation potentials such as life cycle assessment of products, projects or activities) (See Annex 2.A.1. Consistent use of IPCC Guidelines for activity reporting). In other cases, statistical/ancillary information may be available at the aggregated national level, so down-scaling of attributes may occur to assign for example, management practices to particular land units. Then, *good practice* for the re-scaling processes include:

- determine the type of data that needs re-scaling;
- clearly define, document and report the down-scaling/up-scaling processes, including the rules and assumptions made to transform global/national data into local and vice versa;
- when down-scaling is required, assure that the down-scaled variables can be assigned to individual land units;
- when up-scaling is required, assure that the up-scaled variables are representative of the region and country conditions; and,
- determine the uncertainty linked to the re-scaling process and assess the consequences on land-use stratification and GHG emissions and removal estimates.

IDENTIFICATION AND TRACKING OF LAND-USE CHANGE AND DISTURBANCE

There are a number of cases where the identification and tracking of land-use change may be particularly difficult. It may occur, for example, that forest cover loss is either permanent due to deforestation (i.e., land is actually converted from forest land to non-forest land) or it is only temporary due to management (i.e. no change in land use takes place because the forest is expected to be regenerated or regenerate itself). Distinguishing between permanent and temporary land cover change may lead to nationally specific land-use classification and stratification schemes which are then categorized into the IPCC classes according to national definitions (see section below). Land cover changes might also be associated with multiple land use changes on single land units (see section below). Finally, differences in land cover between two surveys may be caused from phenology phases of the vegetation or from the impact of management practices within the same land use (e.g. dry/wet seasons, pre/post-harvest pictures).

Attribution of change

Attribution is the process of associating observed land-cover changes with underlying causes of disturbance. Knowledge of the cause of disturbance is needed not only to estimate land use change but also to estimate the associated GHG emissions and removals because different disturbance types have different impacts on carbon stocks and non-CO_2 emissions. Auxiliary data is commonly required to allocate land-cover change to the underlying cause of disturbance.

Reporting rules can also be applied for land-use change attribution, There are a number of different reporting rules for each land use conversion that can help countries to determine how land use change is categorized. These rules are shown in Table 3.10.

TABLE 3.10
EXAMPLES OF RULES TO APPLY FOR LAND-USE CHANGE CATEGORIZATION.

Land use change category	Decision required	Example
Managed land is converted to unmanaged land	Is land set aside? Is land degenerating?	If set aside after 10 years, then is unmanaged. If naturally degenerated, after 5 years is unmanaged
Forestland converted to other lands	How many years without forest cover before the land is moved to a new land use category?	Australia: 8 years for plantations
Forestland converted to other lands	Is human induced loss of forest cover deforestation or harvesting? Is forest conversion temporal or permanent?	Australia: if lost in Public Forests then assumed harvesting.
Forestland converted to other lands	Natural regrowth of forest following clearing while still under another land use	Lands kept in the dominant category (grassland)
All converted to categories	Number of years before land moves to a remaining category	Default is 20 years, but can be varied depending on country circumstance

An example to distinguishing temporary and permanent forest conversions is provided based on the interpretation of land tenure and land policy data (**Error! Reference source not found.**).

BOX 3.4
CASE 4: APPROACH TO DISTINGUISH TEMPORARY AND PERMANENT FOREST LAND CONVERSIONS (KENYA)

Land use and land cover changes can be illegal by encroachments or legal through excisions and degazettement. Forests in many countries fall under different tenures with unique management systems. The IPCC guidelines of 20 years of recording change apply differently depending on tenure and policy guidelines. If a forest land use/cover changes to non-forest while tenure remains public, then that parcel of land is still reported under forest. However, if a forest land use/cover changes to non-forest due to a degazettement or excision for national interest (e.g. dam construction), then the parcel is not reported under forest but in the new use. If a private forest land changes to a non-forest land use/cover (e.g. cropland or settlement), then that parcel is no longer reported under forest land category. The Cabinet Secretary may, by notice in the Gazette, declare any community or private forest, which in the opinion of the Service is mismanaged or neglected, to be a provisional forest. Such a parcel of land is therefore reported under forest category from the day of notice.

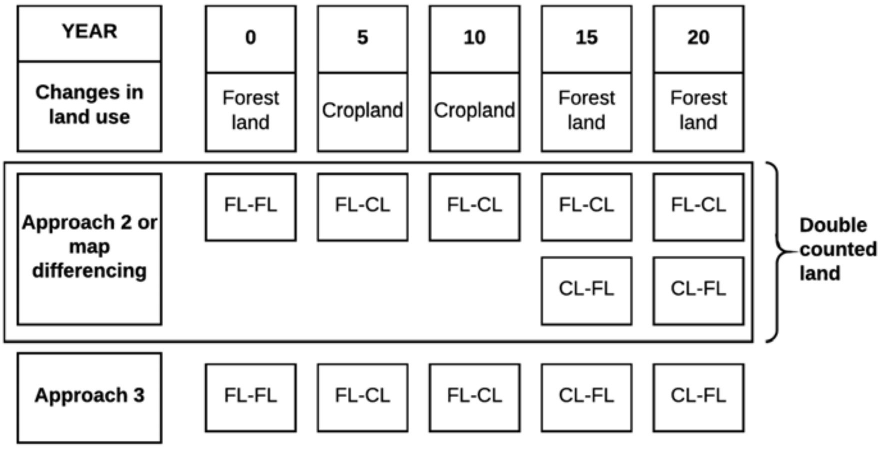
Multiple land-use changes on a single unit of land

When using Approach 3 methods it becomes possible to detect multiple change in land use on a single unit of land through time. Such changes cannot be determined using Approach 2 methods or where maps or samples of land use are differenced. Where multiple changes are occurring, using Approach 2 or map differencing methods will lead to double counting of land areas. For example, if an area of Forestland is converted to Cropland, then 5-years later it is converted back to Forestland, they will be reported under both Forestland converted to Cropland and cropland converted to Forestland (Figure 3.4). Incorrectly allocating lands can also lead to error in the estimation of emissions and removals.

For a consistent representation of multiple land-use changes on a single unit of land it is *good practice* to:

- determine if multiple changes in land use on a single unit of land are occurring;
- if multiple changes are occurring, use the time series of data to ensure land areas are correctly reported; and,
- where multiple changes in land use are occurring, ensure that emissions factors and/or models are correctly applied to those lands, in particular those applied through time (e.g., soil carbon, forest growth) to prevent bias in the estimates of emissions and removals.

Figure 3.4 Example of potential double counting of land using Approach 2 or map/sample differencing methods.



3.3.2.2 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

Description of Refinement: This section provide new guidance on how to use, combine and integrate different approaches and tiers to derive consistent emissions and removals estimated from land-use change. A special reference is made to the use of biomass maps.

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 *Volume 4, Chapter 2, Overview of carbon stock change estimation*.

The change in carbon stocks for a land-use can be estimated using direct measurements (stock difference), emissions factors (Tier 1 and 2) and Tier 3 models (gain-loss methods) or any consistent combination of all three. All gain-loss methods require the use of land-use data and other data as described above to be scaled to the total land-use at the country level. As the different Approaches provide different levels of detail, the methods for estimating emissions will need to be tailored to the available land-use data. When considering how to apply different gain-loss methods using the different Approaches it is important to consider the broad types of emissions:

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

It is important to remember that an inventory can use any logical and consistent mix of Approaches 1, 2 and 3 for representing all land areas. The exact combination will depend on data availability, the spatial and temporal variability in land use and land use change, and the relative importance of the land-use category in the inventory.

3.4.1.1 Approach 1 gain-loss methods

Approach 1 data provide estimates of area in each land-use category at points in time, but do not provide estimates of land use change between categories. Approach 1 data can be combined with the stock-difference method to estimate emissions and removals for each land use category, however, it would not be possible to attribute the emissions and removals to individual land use change categories. When applying gain-loss methods, in particular Tier 1 methods, to Approach 1 data where there have been changes in land-use (i.e., the total areas of land uses is changing through time), two options are available to estimate carbon stock changes for land converted to another land use.

The first option is to approximate the carbon stock change for each land use category based on the difference in the land category area between the activity data time periods (Equation 3.1). The second option is to use ancillary data or expert judgement to provide an estimate of the land uses prior to conversion (Equation 3.2). This also makes it difficult to apply Tier 3 models when using Approach 1 data, unless the Tier 3 models are used to develop reference carbon stocks. When using Approach 1 data in combination with gain loss methods, estimates of the changes in carbon stock for each land-use between two times can be calculated as in Equation 3.1.

Equation 3.1

Annual change in carbon stocks in pools due to conversion (Method 1)

$$\Delta C_{Conv\,P} = \sum_{i} \frac{[C_{Pi} \times A_{iCur}] - [C_{Pi} \times A_{iPrev}]}{T}$$

Equation 3.2

Annual change in carbon stocks in pools due to conversion (Method 2)

$$\Delta C_{Conv\,P} = \sum_{i} \frac{C_{Pi} - C_{Pf}}{T}$$

Where

$\Delta C_{Conv\,P}$ = annual change in carbon stocks in pool P due to change in the area of the land use category

i = land use stratum at the most recent activity data observation

f = previous land use stratum before conversion

Cpi = Reference Carbon stock for carbon pool *P* and land use stratum *i*

Cpf = Reference Carbon stock for carbon pool *P* and land use stratum *f*

A_{iCur} = the current land area of land use stratum *i*

A_{iPrev} = the area of land use stratum *i* in the previous time step

T = the time in years in the period between the previous and current land use activity data observations

This method will result in all lag emissions being reported in the time period. Over time the total emissions and removals will balance, but this will create biased results within reporting periods, especially where rates of land-use change vary over time. As such, where there are large areas of land-use change it is *good practice* to use area estimation methods that support reporting at either Approach 2 or Approach 3.

3.4.1.2 APPROACH 2 GAIN-LOSS METHODS

Approach 2 data include changes in land-use categories, but cannot easily track units of land on which multiple changes in land-use occur. However, in many countries land-use change is not frequent and does not occur more than once over short periods. In such circumstances Approach 2 will provide greater accuracy than Approach 1 without the complexity of moving to Approach 3. Approach 2 data allow for the use of emissions estimation methods that account for emissions and removals both in the year of the activity and also lag emissions from past activities.

Approach 2 data can be used with any combination of Tier 1 and 2 emissions factors or Tier 3 models. While data are different, the core method of estimating emissions and removals is similar (Equation 2.16 in the existing guidance). For areas of land, the emissions estimation method is applied.

When using Tier 3 models, the model will typically be applied for each sub-category of land, with the sum of the models for each year being used to estimate total changes in carbon stocks.

3.4.1.3 APPROACH 3 GAIN-LOSS METHODS

Spatially explicit Approach 3 data can allow changes in land use to be determined at finer temporal and spatial resolutions than other methods. Approach 3 data can be used in two ways 1) summarised to spatially referenced Approach 2 data to simplify the processes of estimating emissions and removals or 2) using the time series of data for all land units for estimating emissions and removals and then summing the results.

When developing spatially referenced data from spatially explicit data, it is *good practice* to consider the time-series of data and to show that these summaries do not lead to double counting of conversions due to multiple changes in land use or activities on single land units.

Using the time-series of data for all land units to capture multiple changes in land use increases the complexity and interconnectedness of the system for estimating emissions. While it is possible to use multiple different methods using different Tiers that can be applied in spatially explicit approaches, it is important to ensure that all the emission estimation methods can work together. For some carbon pools, such as aboveground biomass, using different methods and models for different land uses or sub-categories of land use (for example, forest type) will not create any inconsistencies even when land use changes. However, other pools, in particular soil carbon, require that the emission estimation methods be able to work together. For example, if two or more methods are used for estimating soil carbon emissions for different land-uses, then the stocks and estimated stock changes needs 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.

There is no specific equation that can be readily applied. Rather, emissions and removals when using Approach 3 spatially explicit methods are typically estimated using an integrating tool that uses Tier 1, 2 and 3 data as selected by the country and applies it using a time-series summing method.

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. In general, these methods require calibration using ground-based data. Saturation of the signal may be a problem, especially in tropical countries because the correlation between biomass and the remote sensing data may not be of sufficient accuracy at high biomass densities.

A recent review of the utility of biomass maps in estimating emissions and removals (GFOI 2016) suggests that existing large-scale biomass maps derived from remote sensing data need extensive in-country testing based on field estimates of biomass based on adequate plot size, sufficient spatial sampling, and use of appropriate allometrics to confirm that they are reliable for application in specific forest types and at the spatial scale of interest. (see also Section X.X_Biomass).

The use of biomass maps also 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 countries should consider the following:

- maps need to be consistent with national land use and classification system, in particular to match the national land-use definition chosen by the country; and,
- wehere data is used to estimate biomass for use as an emissions factor, then only use data that is also defined as the same land-use category.

3.5 UNCERTAINTIES ASSOCIATED WITH THE APPROACHES

Description of Elaboration: Even though "No Refinement" was mandated in Section 3.5 authors have decided to include the proposed refinement on Activity Data uncertainty (as requested) in this section. The elaborated text in this Section is to be read in conjunction with Vol. 1_Ch 3 Uncertainties.

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 3.11 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 3.11
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 • 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 ACTIVITY DATA GENERATED FROM REMOTE SENSING TECHNIQUES AND ESTIMATION OF UNCERTAINTIES

The IPCC definition of *good practice* requires that emissions inventories should satisfy two criteria: (1) there are neither over- nor under-estimates as far as can be judged, and (2) uncertainties are reduced as far as is practicable (IPCC 2003).

Validation of the activity data generated from remote sensing techniques typically includes assessment of the accuracy of the final products, the estimation of area and generation of associated confidence intervals. Although confusion or error matrices and map accuracy indices can inform issues of systematic errors and precision, they do not directly produce the information necessary to construct confidence intervals (GFOI 2016). A confidence interval expresses the uncertainty of a sample-based estimate and is formulated as a sample-based estimate of the parameter plus/minus the sample-based estimate of the standard error of the parameter estimate, multiplied by the confidence level. Confidence intervals at the 95%-level are interpreted as meaning that 95% of such intervals, one for each set of sample data, include the true value of the parameter. The width of a confidence interval is closely related to precision, a measure of the uncertainty addressed by the second IPCC criterion.

The accuracy of land use land cover change detection can be assessed using methods similar to those used to validate single scene land use land cover classification, but additional considerations exist. It is usually easier to identify errors of commission in change products because often only a small proportion of the land area will have experienced change, and often within a limited geographic area (GOFC-GOLD 2016; S.P. & S.M. 2016). Stratified sampling methodologies may therefore prove more cost-effective to validate the relatively rare event of changes in LULC within an image (Lowell 2001; GFOI 2016). A transition error matrix can be used to report the accuracy with which transitions between LULC categories are detected (S.P. & S.M. 2016). This allows for assessment of uncertainty for each transition (e.g. forest to cropland, forest to grassland) and for partitioning of uncertainty attributable to the change detection process versus classification (van Oort 2007; GFOI 2016).

Table 3.12 provide a summary of remote sensing activities to determine change in land-use and land cover at different uncertainty levels.

TABLE 3.12
SUMMARY OF REMOTE SENSING ACTIVITIES TO DETERMINE CHANGE IN LULC AT VARIOUS UNCERTAINTY LEVELS
(S.P. & S.M. 2016).

Activity	Higher Uncertainty	Mid-range uncertainty	Lower uncertainty	Key References
Data Acquisition	Approach 1 or 2 with minimal or no data collection (using existing aggregated datasets such as census or existing maps)	Approach 2 with disaggregated datasets (existing or developed); Approach 3 with coarse or mid-resolution imagery	Approach 3 with mid-resolution imagery and supplementary data; Approach 3 with high resolution imagery	(Ravindranath & Ostwald 2008; De Sy *et al.* 2012)
LULC classification	Broad LULC categories developed through subjective (non-empirical) survey methods; not spatially explicit.	Broad LULC categories with simple subclasses or strata; classified using visual interpretation or pixel based techniques with limited or imagery-based training data; spatially explicit.	Empirically – derived LULC categories and strata; supervised classification using pixel-based, object-based or machine learning techniques with field-derived training data, spatially explicit	(Vincikovà *et al.* 2010; GOFC-GOLD 2016)
LULC change detection	Arithmetic calculation of change in total land area for each LULC class using data generated by Approach 1	Arithmetic calculation of change in total land area for each class and transitions between LULC classes using data generated by Approach 2 or; post classification comparisons with coarse or mid-resolution imagery	Spatially explicit change detection using post-classification comparison, image comparison, bitemporal classification or other GIS-based approaches	(van Oort 2007; Huang & Song 2012)

When remote sensing data are used to develop wall-to-wall LULC maps, two types of error exist: errors of inclusion (commission errors) and errors of exclusion (omission errors). Accuracy should be assessed using a statistically valid method, the most common method being statistical sampling of independent higher quality validation sample units or reference data (e.g. pixels, polygons, sites) for comparison against classified sample units (Congalton 1991).

The role of *reference data*, also characterized as *accuracy assessment data*, is to evaluate systematic classification errors and estimate uncertainty, thereby providing the information necessary for construction of confidence intervals (GFOI 2016). Direct observations of ground conditions by field crews are often considered the most reliable source of reference data, but interpretations of aerial photography and satellite data are also used. When the source of reference data is not direct ground observations, it is *good practice* to:

- source reference data that is at least the same and preferably of greater quality with respect to both resolution and accuracy than the remote sensing-based map data; and
- collect reference data using a probability sampling design.

Probability sampling designs to consider are simple random (SRS), systematic (SYS), stratified random (simple random sampling within strata) or systematic (systematic sampling within strata) (STR), and two-stage and cluster sampling. A key issue when selecting a sampling design is that the sample size for each activity must be large enough to produce sufficiently precise estimates of the area of the activity, given country specific specifications (cross reference to Sampling section).

Evaluation of activity data needs to be considered in the context of the entire emissions estimation system as considering elements in isolation will likely lead to bias in the emissions inventory. It is *good practice* to:

- ensure accuracy assessment methods allow for the consistent representation of lands, in particular maintaining time series consistency;
- provide information on the accuracy of IPCC land use classifications rather than intermediate products; as such, evaluation should not be done on the maps, but on the products that are the result of the maps, national specific circumstances and the strata used;
- ensure that all the land classifications and stratifications for emissions factors/models for all pools and gases are sampled; and,
- conduct bias correction on the full time series of data, not via map differencing, to ensure that:
    - the application of the bias correction methods do not introduce bias in other areas, and;
    - the principles of consistent representation of lands are maintained.

Annex 3A.1 Examples of international land cover dataset [2]

In recent decades, satellite remote sensing has for a lot of countries become the primary source for global LCLUC information and several global products from satellite are currently (most of them freely) available. Earlier products include the GLC2000 produced from SPOT VEGETATION (Bartholomé & Belward 2005), the MODIS Vegetation Continuous Fields product (Hansen *et al.* 2000) and the GlobCover product produced from MERIS data (Arino *et al.* 2007). Now the Land Cover product is being created as part of the European Space Agency Land Cover Climate Change Initiative, and the 30 m GlobeLand30 data product (Friedl *et al.* 2010), as well as global PALSAR products by JAXA in different spatial resolutions.

TABLE 3A.1.1
EXAMPLES OF INTERNATIONAL AVAILABLE 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 Data
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. CCI land cover classes can be grouped into the six IPCC land use categories to detect change.	Time series analysis of Landsat data at 30 m spatial resolution to characterize global forest extent and change from 2000 to 2016.	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 in the global 25 m spatial resolution PALSAR-2/PALSAR mosaic
Classification scheme	The system was designed as 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 2016.	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 as the natural forest with an area larger than 0.5 ha and forest cover over 90% (FAO definition).
Data format (vector/raster)	Raster	Raster	Raster	Raster

TABLE 3A.1.1 (CONTINUED)
EXAMPLES OF INTERNATIONAL LAND COVER DATASETS

	(A)	(B)	(C)	(D)

[2] These datasets primarily describe land cover and/or land cover change, and may not necessarily translate directly into IPCC land use categories.

Spatial coverage	Global	Global	Global	Global
Data acquisition year	Annual from 1992 to 2015	Annual from 2000 to 2016	Annual from 2001 to 2013	2007, 2008, 2009, 2010, 2015, 2016
Spatial resolution or grid size	300 m	30 m	500 m	25 m, 100 m, and 1000 m
Revision interval (for time-series datasets)	Annual (1992-2015) – baseline 10-year global land cover map	Annual time series from 2000 to 2016	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.	Quality controls – to be confirmed?
Contact address and reference URL	http://maps.elie.ucl.ac.be/CCI/viewer/download.php	http://earthenginepartners.appspot.com/science-2013-global-forest	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:
    - 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.
    - 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.
    - 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.
    - 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 are available for consistent country-specific representation of land use change. Advances in a) spatial and temporal 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, USGS, JAXA, ESA, etc., have led to improved global RS data collection and free distribution of moderate resolution public good datasets to all countries.

Determination of *fitness for use* of remote sensing and other geospatial data, products, and tools is the responsibility of the user; the producer on the other hand should provide the user with sufficient metadata to 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, and a detailed treatment (e.g., (Thenkabail 2015; Jensen 2016) 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) onboard satellites, or installed in aircraft. 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 (computer-based) 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 otherwise. Archives of past remote sensing data also span several decades and can therefore be used to reconstruct past 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 areas that can guide the selection of sampling schemes and the number of samples to be collected. The challenges of remote sensing are related to the problem of interpretation: the images need to be consistently and reliably translated into meaningful information on land use. Depending on the satellite sensor(s) involved, the acquisition of data may be impaired by the presence of atmospheric clouds and haze. It is possible to construct cloud free images through various approaches by excluding cloudy pixels using time series data. Another concern, particularly when comparing data over long time periods, is that remote sensing systems may change over time. Further guidance is given below 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 nominal spatial resolution of 30 × 30 m. In choosing appropriate spatial resolution for land representation, it is critical to consider the minimum mapping unit for a given country. For example, using a satellite data with a spatial resolution of 500m will not be suitable for a country whose minimum mapping unit is 0.5 ha.

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 wavelength ranges for those bands are narrower. Different sensors have different characteristics which serve different needs depending on the application. In general, the greater the spectral resolution, the greater the ability of the sensor to separate different variables and detect change. Many of the higher spatial resolution commercial satellites have lower spectral resolution.

Temporal

Temporal resolution refers to the length of time required for a satellite to revisit a land area of interest. The revisit period of a satellite sensor is usually several days (e.g., 16 days for Landsat 8). Because of some degree of overlap in the imaging swaths of adjacent orbits for most satellites and the increase in this overlap with increasing 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. Relatively high temporal resolution is critical for the development of image time series that contain far more information relevant to human activity.

Radiometric

Radiometric resolution refers to sensitivity of a sensor. For example, radiometric resolution of Landsat 8 is 12 bit, which means, this sensor can detect up to 4,096 different levels of light intensity, whereas Landsat 5 has only 256 (8 bit) levels of sensitivity. In general higher sensitivity leads to better discrimination of land cover.

Types of remote sensing (RS) data

The most commonly used types of RS data are: 1) aerial photographs, 2) satellite imagery using visible and/or near-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 related changes do not lead to false classification.

Important criteria for selecting remote sensing data and products are:

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

1. Aerial photographs

Analysis of aerial photographs 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 sensor systems have a spatial resolution of 20 – 30 meters. At a spatial resolution of 30 meters, for example, units as small as 1ha can be identified. Data from higher resolution satellites are also available.

3. Radar imagery

The most common type of radar data are 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.

4. Lidar

Light detection and ranging (LIDAR) uses the same principles as radar. The LIDAR instrument transmits light out to a target. The transmitted light interacts with and is changed by the target. Some of this light is reflected/scattered back to the instrument where it is analysed. The change in the properties of the light enables some property of the target to be determined. The time for the light to travel out to the target and back to the LIDAR is used to determine the range to the target. There are three basic types of LIDAR: range finders, differential absorption LIDAR, and doppler.

Satellite data pre-processing

Imagery captured by airborne or spaceborne sensor must be corrected for radiometric, geometric and topographic distortions prior to using this data for land use classification. The level and detail of processing depends on sensor system such as optical or radar, and type of correction (including inter-sensor calibration) that may be required. As development of RS time series has advanced in recent years, there has been a shift away from large area RS workflows operating at the individual per-scene scale (e.g., for hundreds of Landsat 8 scenes covering a single country). Per-scene processing is disadvantaged by unique atmospheric conditions and temporal resolutions that result in scene boundary artifacts in resulting products. In contrast, there is value in utilization of seamless radiometrically corrected large-scale composites (Roy *et al.* 2010; Hansen & Loveland 2012; Hansen *et al.* 2013; Teillet 2015). Optical imagery is often 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 RS preprocessing capabilities may not be practical. Fortunately, major RS 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 useful in 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 to the present.

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 not uncommon to source data from multiple sources and sensors, which, if not accounted properly, may result in inconsistent products, unstable for land cover studies. It is therefore good practice to reprocess the entire time series data when new data or methods become available such as:

- availability of improved ground control points (GCPs) and reference data;
- 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); and,
- correction of errors;

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

- Overlap technique 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, obtain data from old and new sensors 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 most recent Sentinel-2 sensors.

- Interpolation technique can be used where availability of RS data from historic archives is limited. In such cases best available data for intermittent years in the time series can be interpolated to gap fill the missing data.
- Other techniques such as merging of different 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 RS data obtained in the same seasons throughout the time series to minimise errors due to seasonal changes.

Ground reference data

In order 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 the remotely sensed data with ground reference data (often called ground truth data). Ground reference data can either be collected independently, or be 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-truthed than other areas. This can only be done by using ground reference data, preferably from actual ground surveys collected independently. High-resolution photographs or satellite data may also be useful for referencing and verification purposes.

Integration of remote sensing and GIS

~~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.~~

Full use of remote sensing generally requires integration of the extensive coverage that remote sensing can provide with reference 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).

Land use classification using remotely sensed data

Classification of land cover using remotely sensed data may be done by visual or digital (computer based) analysis. Each one 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 over the past decade, along with the associated technical computer development, making hardware, software and also the satellite data readily available at low or no cost in most countries, although capacity to use these data and facilities may have to be outsourced, particularly in mapping at 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. Most image processing packages include several algorithms for image classification. Common image classification algorithms include maximum likelihood, decision trees (such as random forest), support vector machines and neural networks. Many of these are available in standard image processing and statistical software packages (e.g., R, Orfeo, QGIS, and GDAL).

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 an NFI, 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.

Classification can be done by visual interpretation, but this 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 is often less than 5 ha. Further, differencing visually interpreted maps to develop change estimates will typically lead to large amounts of error including slivers. It is also very difficult to make improvements to the resulting maps, especially once the time series gets longer than 3 or 4 maps. Therefore, visual interpretation of satellite data is not the most preferred choice for land classification.

This may be overcome by using automated algorithms in either unsupervised or supervised approaches 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 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 map. Close examination of the classification results often reveals issues and problems that can be resolved by changes 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 applied to the entire time series to improve the accuracy and consistency of output data.

While satellite data is good at depicting the land cover change, they are not so good at identifying permanent land use changes from those of temporary loss of cover. It is therefore good practice to ensure that all land cover changes identified by satellite data must be verified using high resolution imagery, ground checking 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.* 2014).

Detection of land-use conversion using RS

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 ancillary information is needed to determine land-use conversion.

Change detection is one of the most common uses of remote sensing, 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 to Grassland (Woodcock *et al.* 2001). Methods use the change in a spectral bands or indices as the basis of the change detection process (Lambin & Strahlers 1994; Coppin *et al.* 2004).

Use of time series data can also help make the distinction between permanent land use change and temporary destocking.

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).

From-to change has some important advantages but also has some limitations (Jensen 2016). Direct mapping of change categories has important benefits. Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO) National Carbon Accounting System – Land Cover Change Project (NCAS-LCCP) is an excellent example of how change can be confirmed from the time series information (Caccetta *et al.* 2007). Other examples to consider include Shimabukuro *et al.* (1998); 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 use 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 RS 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 Global Positioning Systems (GPS) 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

No refinement

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