3.4 GRASSLAND

Grassland as defined in Chapter 2 covers about one-quarter of the earth's land surface (Ojima *et al.*, 1993) and span a range of climate conditions from arid to humid. Grasslands can vary greatly in their degree and intensity of management, from extensively managed rangelands and savannahs – where animal stocking rates and fire regimes are the main management variables – to intensively managed (e.g. with fertilization, irrigation, species changes) continuous pasture and hay land. Grasslands generally have a vegetation dominated by perennial grasses, with grazing as the predominant land use, and are distinguished from "forest" by having a tree canopy cover of less than the threshold used in the forest definition.

Belowground carbon dominates in grassland, mainly in roots and soil organic matter. For a given climate regime, grassland often has higher soil carbon contents than other vegetation types. Grazing and fire are common perturbations that grassland has evolved with; consequently both the vegetation and soil carbon are relatively resistant to moderate disturbances from grazing and fire regimes (Milchunas and Lauenroth, 1993). In many grasslands, the presence of fire is a key factor in preventing the invasion of woody species which can significantly affect ecosystem carbon stores (Jackson *et al.*, 2002).

The Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (*IPCC Guidelines*) deal with biomass and soil carbon stock changes for land-use conversions between grassland and other land uses (e.g., cropland), soil carbon stock changes due to management changes between improved and unimproved pasture, and CO_2 emissions for wetlands that are drained and from liming of pasture.

This report complements the *IPCC Guidelines* by:

- Elaborating on the methodologies needed to address C stock changes in the two main pools in grassland: living biomass and soils;
- Explicitly including impacts of natural disturbances and vegetation fires on managed grassland; and
- Covering comprehensively the estimation of land use conversion to grassland.

In this section, guidance on the use of basic and advanced methodologies for inventorying and reporting emissions and removals for grassland remaining grassland and land converted to grassland is provided for biomass and soil carbon pools. Methods for non-CO_2 emissions are also covered. Methodologies follow a hierarchical tier structure where Tier 1 methods use default values, typically with limited disaggregation of area data. Tier 2 corresponds to use of country-specific coefficients and/or finer scale area disaggregation, which will reduce uncertainty in emission/removal estimates. Tier 3 methods refer to the use of more complex country-specific approaches. Where possible, default values from the *IPCC Guidelines* are updated and new default values are provided based on the most up-to-date research findings.

3.4.1 Grassland Remaining Grassland

Carbon stocks in permanent grassland are influenced by human activities and natural disturbances, including harvesting of woody biomass, rangeland degradation, grazing, fires, rehabilitation, pasture management, etc. Annual production of biomass in grassland can be large, but due to rapid turnover and removals through grazing and fire, standing stock of aboveground biomass rarely exceeds a few tonnes per hectare. Larger amounts can accumulate in the woody component of vegetation, in root biomass and in soils. The extent to which carbon stocks increase or decrease in each of these pools is affected by management practices such as those described above.

This section provides guidance on estimating carbon stock changes in grassland remaining grassland (GG) for two carbon pools: living biomass and soils. At this time, not enough information is available to develop default coefficients for estimating the dead organic matter pool. The total annual carbon stock change in grassland remaining grassland is therefore the sum of annual estimates of carbon stock changes in each carbon pool—living biomass and soils—as shown in Equation 3.4.1. Estimation techniques for each pool are described separately below.

EQUATION 3.4.1
ANNUAL CHANGE IN CARBON STOCKS IN GRASSLAND REMAINING GRASSLAND

$$\Delta C_{GG} = \Delta C_{GG_{LB}} + \Delta C_{GG_{Soils}}$$

Where:

ΔC_{GG} = annual change in carbon stocks in grassland remaining grassland, tonnes C yr^{-1}

$\Delta C_{GG_{LB}}$ = annual change in carbon stocks in living biomass in grassland remaining grassland, tonnes C yr^{-1}

$\Delta C_{GG_{Soils}}$ = annual change in carbon stocks in soils in grassland remaining grassland, tonnes C yr^{-1}

To convert tonnes C to Gg CO_2, multiply the value by 44/12 and by 10^{-3}. For the convention (signs), refer to Section 3.1.7 or Annex 3A.2 (Reporting Tables and Worksheets).

TABLE 3.4.1
TIER DESCRIPTIONS FOR SUBCATEGORIES UNDER GRASSLAND REMAINING GRASSLAND

Sub-categories \ Tier	Tier 1	Tier 2	Tier 3
Living Biomass	Assume there is no change in carbon stocks.	Use country-specific values for carbon accumulation and removal rates and annual or periodic surveys to estimate the areas under different classes of grassland by climate region.	Use country-specific approach at fine spatial scale (e.g., modeling, measurement)
Soils	For changes in soil carbon from mineral soils use default coefficients. The areas must be stratified by climate and soil type. For changes in soil carbon from organic soils use default coefficients and stratify the areas by climatic region. For emissions from liming, use default emission factors.	For both mineral and organic soils use some combination of default and/or country-specific coefficients and area estimates of increasingly finer spatial resolution. For emissions from liming, use emission factors differentiated by forms of lime.	Use country-specific approach at fine spatial scale (e.g., modeling, measurement)

3.4.1.1 CHANGE IN CARBON STOCKS IN LIVING BIOMASS

Although the methods used for estimating biomass changes are conceptually similar between grassland, cropland, and forest (described in detail in Section 3.2.1.1), grasslands are unique in a number of ways. Grasslands are subject to frequent vegetation fires that can influence savannah thickening[1], mortality and regrowth, and root to shoot ratio. Other management activities, such as tree and brush removal, pasture improvement, tree planting (silvopastoralism), as well as overgrazing and degradation can influence biomass stocks. For woody species in savannahs (grassland with trees), the allometric relationships differ from those used in forests because of large numbers of multi-stem trees, large number of shrubs, hollow trees, high proportion of standing dead trees, high root-to-shoot ratios and coppicing regeneration.

3.4.1.1.1 METHODOLOGICAL ISSUES

Equation 3.4.2 shows the summary equation for estimating changes in carbon stocks in living biomass in grassland remaining grassland. Depending on the methodological tier being used and data availability, grassland can be disaggregated by type, region or climate zone.

EQUATION 3.4.2
ANNUAL CHANGE IN CARBON STOCKS IN LIVING BIOMASS IN GRASSLAND REMAINING GRASSLAND

$$\Delta C_{GG_{LB}} = \sum_c \sum_i \sum_m \Delta C_{GG_{LB(c,i,m)}}$$

Where:

$\Delta C_{GG_{LB}}$ = annual change in carbon stocks in living biomass in grassland remaining grassland summed across all grassland types *i*, climate zones *c*, and management regimes *m*, tonnes C yr^{-1}

$\Delta C_{GG_{LB(c,i,m)}}$ = change in carbon stocks in living biomass for a specific grassland type *i*, climate zone *c* and management regime *m*, tonnes C yr^{-1}

[1] Savannah thickening is a general term referring to an increase in the density and biomass of woody species in grassland ecosystems over time due to changes in fire and/or grazing regimes as well as climate changes. For example, in the south-central US woody biomass encroachment/thickening on grasslands is estimated to have increased biomass stocks by around 0.7 tonnes d.m. ha^{-1} yr^{-1} over a several year period (Pacala *et. al*. 2001)

The living biomass pool in grassland includes above- and belowground carbon stocks in woody and herbaceous (grasses and forbs) vegetation. However, carbon stocks in the aboveground herbaceous component are usually small and relatively insensitive to management; thus aboveground grass biomass is only considered for estimating non-CO_2 emissions from burning. Carbon stocks in belowground biomass of grasses are larger and more sensitive to management changes and are therefore included in estimates of carbon stock changes in living biomass of grassland.

3.4.1.1.1.1 Choice of Method

All countries should strive for improving inventory and reporting approaches by advancing to the highest tier possible given national circumstances. It is *good practice* for countries to use a Tier 2 or Tier 3 approach if carbon emissions and removals in grassland remaining grassland is a key category and if the sub-category of living biomass is considered significant based on principles outlined in Chapter 5. Countries should use the decision tree in Figure 3.1.1 to help with the choice of method.

Tier 1: In grassland where management practices are static, biomass carbon stocks will be in an approximate steady-state (i.e. carbon accumulation through plant growth is roughly balanced by losses through decomposition and fire). In grassland where management changes are occurring over time (e.g. through savannah thickening, tree/brush removal for grazing management, improved pasture management or other practices), the stock changes can be significant. However, information is not available to develop broadly applicable default rates of change in living biomass carbon stocks in grassland for these different management regimes. Therefore, the Tier 1 assumption is no change in living biomass carbon stocks.

Tier 2: At Tier 2, carbon stock changes are estimated for above- and belowground biomass in perennial woody vegetation and for belowground biomass of grasses, as summarised in Equation 3.4.3.

EQUATION 3.4.3
ANNUAL CHANGE IN CARBON STOCKS IN LIVING BIOMASS IN GRASSLAND REMAINING GRASSLAND

$$\Delta C_{GG_{LB(c,i,m)}} = (\Delta B_{perennial} + \Delta B_{grasses}) \bullet CF$$

Where:

$\Delta C_{GG_{LB(c,i,m)}}$ = change in carbon stocks in living biomass for a specific grassland type i, climate zone c and management regime m tonnes C yr^{-1}

$\Delta B_{perennial}$ = change in above- and belowground perennial woody biomass, tonnes d. m. yr^{-1}

$\Delta B_{grasses}$ = change in belowground biomass of grasses, tonnes d. m. yr^{-1}

CF = carbon fraction of dry matter (default = 0.5), tonnes C (tonnes d.m.)$^{-1}$

Changes in living biomass (ΔB) can be estimated in one of two ways: using annual rates of growth and loss (Equation 3.4.4) or (b) with biomass stocks at two points in time (Equation 3.4.5).

EQUATION 3.4.4
ANNUAL CHANGE IN LIVING BIOMASS (RATE APPROACH)

$$\Delta B_i = A_i \bullet (G - L)$$

Where:

ΔB_i = annual change in living biomass in grassland of type i, tonnes d. m. yr^{-1}

A_i = area of grassland of type i, ha

G = average annual biomass growth, tonnes d. m. ha^{-1} yr^{-1}

L = average annual biomass loss, tonnes d. m. ha^{-1} yr^{-1}

The biomass difference approach (Equation 3.4.5) can be applied where data on biomass stocks are estimated at regular time intervals through some types of national inventory system. The difference between total biomass stocks at two points in time is calculated. This value is divided by the number of years between measurements to generate an annual rate of change in biomass stocks.

EQUATION 3.4.5
ANNUAL CHANGE IN LIVING BIOMASS (DIFFERENCE APPROACH)

$$\Delta B = (B_{t_2} - B_{t_1}) / (t_2 - t_1)$$

Where:

ΔB = annual change in living biomass, tonnes d. m. yr^{-1}

B_{t_2} = biomass at time t_2, tonnes d. m.

B_{t_1} = biomass at time t_1, tonnes d. m.

Tier 2 methods involve country- or region-specific estimates of biomass stocks by major grassland types and management activity and estimates of stock change as a function of major management activity (i.e. grazing and fire regimes, productivity management).

Either of the approaches described above can be used to estimate changes in above- and belowground biomass. In long-established grassland, changes in biomass are likely only in response to relatively recent changes (e.g. within the past 20 yrs) in management practices. Therefore, it is *good practice* to associate estimates of biomass change with specific management conditions, categorized if possible by climate and grassland type. For example, when using the rate approach, the area of semi-arid grassland under intensive grazing should be multiplied by coefficients (G and L) that are specific to semi-arid intensively grazed grassland. If the difference approach is used, then biomass stocks should be measured or estimated separately for different grassland types under specific management regimes. A stratification of management regimes/grassland conditions could include categories such as: native, extensively managed grassland, grassland subject to woody encroachment, moderately and severely degrading grassland, intensively managed, improved pastures (see broadly defined management conditions in Section 3.4.1.2. on Changes in Carbon Stocks in Soils).

While Equations 3.4.4 and 3.4.5 can be used to estimate changes in belowground biomass stocks directly, belowground biomass stocks are often approximated using expansion factors applied to aboveground biomass stocks. Such expansion factors are ratios of belowground to aboveground biomass, otherwise known as root to shoot ratios. The ratios may vary by grassland type, climate region, and management activity. Equation 3.4.6 demonstrates how to estimate total (above- and belowground) biomass stocks. Note that aboveground biomass (B_{AG}) must be estimated first and then applied in Equation 3.4.6. Total biomass stock (B_{Total}), belowground biomass stock (B_{BG}), or aboveground biomass stock (B_{AG}) from Equation 3.4.6 can be used in Equations 3.4.5 to estimate changes in biomass stocks over time.

EQUATION 3.4.6
TOTAL BIOMASS

$$B_{Total} = B_{AG} + B_{BG}$$

and

$$B_{BG} = B_{AG} \bullet R$$

Where:

B_{Total} = total biomass, including above- and belowground, tonnes d. m.

B_{AG} = aboveground biomass, tonnes d. m.

B_{BG} = belowground biomass, tonnes d. m.

R = root-to-shoot ratio, dimensionless

Tier 3: Tier 3 involves inventory systems using statistically-based sampling of carbon stocks over time and/or process models, stratified by climate, grassland type and management regime. For example, validated species-specific growth models that incorporate management effects such as grazing intensity, fire, and fertilization, with corresponding data on management activities, could be used to estimate net changes in grassland biomass carbon stocks over time. Models can be used together with periodic sampling-based stock estimates similar to those used in detailed forest inventories could be applied to estimate stock changes as in Equation 3.4.5 to make spatial extrapolations for grassland areas

3.4.1.1.1.2 Choice of Emission/Removal Factors

Tier 1: At Tier 1, the default assumption is no change in biomass stocks. Therefore, no default emission/removal factors are provided.

Tier 2: Some data are available to assist in making estimates at Tier 2. The factors needed for a Tier 2 estimate are: biomass growth (G) and loss (L) or biomass stocks at multiple points in time (B_t, B_{t-1}), and expansion factors for belowground biomass.

The rate-based approach (Equation 3.4.4) requires derivation of loss rates (i.e. L in Equation 3.4.4), for woody biomass (e.g. losses from harvest or bush removal) and belowground biomass of herbaceous species (e.g. due to pasture degradation) , and net growth rates (e.g. from savannah thickening or pasture improvements) of woody and belowground biomass (G in Equation 3.4.4). To develop carbon growth and loss coefficients from reported carbon stock values, estimates for at least two points in time are needed. The change in carbon stocks between two time periods are then calculated and this amount is divided by the number of years during the time period to develop an annual rate. Rates of change should be estimated in response to changes in specific management/land use activities (e.g. pasture fertilization, shrub removal, savannah thickening). Results from field research should be compared to estimates of carbon growth and losses from other sources to verify that they are within documented ranges. Reported carbon growth and loss rates may be modified based on additional data and expert opinion, provided clear rationale and documentation are included in the inventory report. (Note: It is important, in deriving estimates of biomass accumulation rates, to recognize that *net* changes in biomass stocks will occur primarily during the first years (e.g. 20 years) following changes in management. After which time biomass stocks will tend towards a new steady-state level with little or no change in biomass stocks occurring unless further changes in management conditions occur).

Region- or country-specific data on biomass stocks over time are needed for use in Equation 3.4.5. These can be obtained through a variety of methods, including estimating density (crown coverage) of woody vegetation from air photos (or high resolution satellite imagery) and ground-based measurement plots. Species composition, density and above- vs. below-ground biomass can vary widely for different grassland types and conditions and thus it may be most efficient to stratify sampling and survey activities by grassland types. General guidance on survey and sampling techniques for biomass inventories is given in Chapter 5 (Section 5.3).

Default estimates of above-ground biomass stocks and annual above-ground productivity are provided in Table 3.4.2. These are globally-averaged valued, by major climate zones, and are not intended as a basis for Tier 2 estimates of biomass stock change but can serve as defaults for estimating non-CO_2 emissions from burning (see Section 3.4.1.3) and for a first-order comparison with country-derived biomass stock estimates.

TABLE 3.4.2
DEFAULT ESTIMATES FOR STANDING BIOMASS GRASSLAND (AS DRY MATTER) AND ABOVEGROUND NET PRIMARY PRODUCTION, CLASSIFIED BY IPCC CLIMATE ZONES

IPCC Climate zone	Peak aboveground live biomass (tonnes d.m. ha^{-1})			Aboveground net primary production (ANPP) (tonnes d.m. ha^{-1} yr^{-1})		
	Average	No. of studies	Error[1]	Average	No. of studies	Error[1]
Boreal - Dry & Wet [2]	1.7	3	± 75%	1.8	5	± 75%
Cold Temperate - Dry	1.7	10	± 75%	2.2	18	± 75%
Cold Temperate -Wet	2.4	6	± 75%	5.6	17	± 75%
Warm Temperate – Dry	1.6	8	± 75%	2.4	21	± 75%
Warm Temperate –Wet	2.7	5	± 75%	5.8	13	± 75%
Tropical - Dry	2.3	3	± 75%	3.8	13	± 75%
Tropical - Moist & Wet	6.2	4	± 75%	8.2	10	± 75%

Data for standing live biomass are compiled from multi-year averages reported at grassland sites registered in the ORNL DAAC NPP database [http://www.daac.ornl.gov/NPP/html_docs/npp_site.html]. Estimates for above-ground primary production are from: Olson, R. J., J. M. O. Scurlock, S. D. Prince, D. L. Zheng, and K. R. Johnson (eds.). 2001. NPP Multi-Biome: NPP and Driver Data for Ecosystem Model-Data Intercomparison. Sources available on-line at [http://www.daac.ornl.gov/NPP/html_docs/EMDI_des.html]).

[1] Represents a nominal estimate of error, equivalent to two times standard deviation, as a percentage of the mean.

[2] Due to limited data, dry and moist zones for the boreal temperature regime and moist and wet zones for the tropical temperature regime were combined.

Estimating below-ground biomass can be an important component of biomass surveys of grassland but field measurements are laborious and difficult and thus expansion factors to estimate below-ground biomass from above-ground biomass are often used. Adaptations to fire and grazing have led to higher root-to-shoot ratios compared to many other ecosystems; thus forest-based biomass expansion factors cannot be applied without modification. Root-to-shoot ratios show wide ranges in values at both individual species (e.g. Anderson *et al.*, 1972*)* and community scales (e.g. Jackson *et al.*, 1996; Cairns *et al.*, 1997*)*. Thus it is recommended to use, as far as possible, empirically-derived root-to-shoot ratios specific to a region or vegetation type. Table 3.4.3 provides default root-to-shoot ratios for major grassland ecosystems of the world; these data can be used as defaults when countries do not have more regionally specific information to develop country-specific ratios. Ratios for woodland/savannah and shrublands are also included for use by countries that include these lands in the grassland section of their inventory.

Tier 3: Tier 3 approaches, e.g. using a combination of dynamic models along with inventory measurements of biomass stock changes, do not employ simple stock change or emission factors *per se*. Estimates of emissions/removals using model-based approaches derive from the interaction of multiple equations that estimate the net change of biomass stocks within the models. Key criteria in selecting appropriate models are that they are capable of representing all of the management practices that are represented in the activity data. It is critical that the model be validated with independent observations from country or region-specific field locations that are representatives of the variability of climate, soil and grassland management systems in the country.

TABLE 3.4.3
DEFAULT EXPANSION FACTORS (ROOT-TO-SHOOT [R:S] RATIOS)
FOR THE MAJOR SAVANNAH/RANGELAND ECOSYSTEMS OF THE WORLD

	Vegetation type	Approximate IPCC climate zone[1]	R:S ratio	n	Error[2]
Grassland	Steppe/tundra/prairie grassland	Boreal (Dry & Wet), Cold Temperate Wet, Warm Temperate Wet	4.0	7	± 150%
	Semi-arid grassland	Dry (Cold Temperate, Warm Temperate and Tropical)	2.8	9	± 95%
	Sub-tropical/ tropical grassland	Tropical Moist & Wet	1.6	7	± 130%
Other	Woodland/savanna		0.5	19	± 80%
	Shrubland		2.8	9	± 144%

[1] Classification of the source data was by grassland biome types and thus correspondence to the IPCC climate zones are approximations.

[2] Error estimates are given as two times standard deviation, as a percentage of the mean.

3.4.1.1.1.3 Choice of Activity Data

Activity data in this section refer to estimates of land areas (A_i) of long-term grassland (i.e. not recently converted from other land uses). In addition, countries will need to estimate area burned each year to estimate non-CO_2 emissions. Chapter 2 provides general guidance on approaches for obtaining and categorizing area by different land use classes. For estimating emissions and removals from this source, countries need to obtain area estimates for grassland, disaggregated as required to correspond to the available emission factors and other parameters. Because Tier 1 assumes no net change in grassland biomass through growth and losses, there is no need to develop activity data at Tier 1, except to estimate non-CO_2 emissions associated with burning (Section 3.4.1.3). Guidance below is for developing activity data for Tiers 2 and 3 methods.

Annual or periodic surveys are used in conjunction with the approaches outlined in Chapter 2 to estimate the average annual area of land in grassland. The area estimates are further sub-divided into general climate regions and management practices to match the G and L values. International statistics such as FAO databases, *IPCC Guidelines*, and other sources can be used to estimate the area of land in grassland. Area of grassland burning can be estimated from knowledge of the average fire frequency for different grassland types or from more accurate assessments, such as use of remote sensing to inventory burned areas.

To improve estimates, more detailed annual or periodic surveys are used to estimate the areas of grassland stratified by grassland types, climatic regions and management regimes. If finer resolution country-specific data are only partially available, countries are encouraged to extrapolate to the entire land base of grassland using sound assumptions from best available knowledge.

Tier 3 requires high-resolution activity data disaggregated at sub-national to fine grid scales. Similar to Tier 2, land area is classified into specific grassland types by major climate, and management categories. If possible, spatially explicit area estimates are used to facilitate complete coverage of the grassland and ensure that areas are not over- or underestimated. Furthermore, spatially explicit area estimates can be related to locally relevant carbon accumulation and removal rates, and restocking and management impacts, improving the accuracy of estimates.

3.4.1.1.1.4 Uncertainty Assessment

Because Tier 1 assumes no change in grassland biomass, it is not relevant to develop uncertainty estimates for Tier 1. Guidance below is for developing uncertainty estimates for Tiers 2 and 3 methods.

Sources of uncertainty include the degree of accuracy in land area estimates (A_i), fraction of land area burned ($f_{burned,i}$), carbon increase and loss (G and L), carbon stock (B), and expansion factor (EF) terms. It is *good practice* to calculate error estimates (i.e., standard deviations, standard error, or ranges) for each of these country-defined terms and to use these estimates in a basic uncertainty assessment. Default uncertainty estimates provided in Table 3.4.3 can be used for the biomass expansion factors.

Tier 2 approaches may also use finer resolution activity data, such as area estimates for different climatic regions or for grassland management systems within national boundaries. The finer-resolution data will reduce uncertainty levels when associated with carbon accumulation factors defined for those finer-scale land bases.

This information can be used with a measure of uncertainty in area estimates from Chapter 2 to assess the uncertainty in estimates of carbon emissions and removals in grassland biomass using the Tier 1 methodology for uncertainty analysis in Chapter 5.2 (Identifying and quantifying uncertainties).

3.4.1.2 CHANGE IN CARBON STOCKS IN SOILS

3.4.1.2.1 METHODOLOGICAL ISSUES

The *IPCC Guidelines* provide methods for estimating CO_2 Emissions and Uptake by Soils from Land-Use and Management (Section 5.3) that can be applied to all land uses, including grassland. The methodology considers organic carbon stock changes (CO_2 emissions or removals) for mineral soils, CO_2 emissions from organic soils (i.e. peat or muck soils) converted to pastures and emissions of CO_2 from liming of grassland soils.

For carbon stock changes in mineral soils, the *IPCC Guidelines* define soil carbon stocks as organic carbon incorporated into mineral soil horizons to a depth of 30cm and do not include C in surface residue (i.e. dead organic matter) or changes in inorganic carbon (i.e. carbonate minerals). In most grassland soils, surface residue represents a minor stock compared with carbon within the soil.

The summary Equation 3.4.7 for estimating the change in carbon stocks in soils is shown below:

EQUATION 3.4.7
ANNUAL CHANGE IN CARBON STOCKS IN SOILS IN GRASSLAND REMAINING GRASSLAND

$$\Delta C_{GG_{Soils}} = \Delta C_{GG_{Mineral}} - \Delta C_{GG_{Organic}} - \Delta C_{GG_{Liming}}$$

Where:

$\Delta C_{GG_{Soils}}$ = annual change in carbon stocks in soils in grassland remaining grassland, tonnes C yr^{-1}

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

$\Delta C_{GG_{Organic}}$ = annual change in carbon stocks in organic soils in grassland remaining grassland (estimated as net annual flux), tonnes C yr^{-1}

$\Delta C_{GG_{Liming}}$ = annual C emissions from lime application to grassland, tonnes C yr^{-1}

For Tier 1 and 2 methods, changes in dead organic matter and inorganic carbon stocks should be assumed to be zero. If dead organic matter is included in a Tier 3 approach, measurements should be based on the lowest amounts present during an annual cycle to avoid including newly senesced plant material that represents a transient organic matter pool. Selection of the most suitable tier will depend on: (i) availability and detail of activity data on grassland management and changes in management over time, (ii) availability of suitable information to estimate base C stocks and stock change and emission factors, and (iii) availability of dedicated national inventory systems designed for soils.

All countries should strive for improving inventory and reporting approaches by advancing to the highest tier possible given national circumstances. It is *good practice* for countries to use a Tier 2 or Tier 3 approach if carbon emissions and removals in grassland remaining grassland is a key category and if the sub-category of soil organic matter is considered significant based on principles outlined in Chapter 5. Countries should use the decision tree in Figure 3.1.1 to help with the choice of method.

3.4.1.2.1.1 Choice of Method

The method used to estimate carbon stock changes in mineral soils is different from the method used for organic soils. It is also possible that countries will use different Tiers to prepare estimates of the separate components on this subcategory, given availability of resources. Thus, mineral soils, organic soils, and emissions from liming are discussed separately below.

Mineral Soils

For mineral soils, the estimation method is based on changes in soil C stocks over a finite period following changes in management that impact soil C, as shown in Equation 3.4.8. Previous soil C stocks ($SOC_{(0-T)}$) and soil C stocks in the inventory year (SOC_0) for the area of a grassland system in the inventory are estimated from reference carbon stocks (Table 3.4.4) and stock change factors (Table 3.4.5), applied for the respective time points. Here a grassland system refers to a specific climate, soil and management combination. Annual rates of emissions (source) or removals (sink) are calculated as the difference in stocks (over time) divided by the inventory time period. The default time period is 20 years.

EQUATION 3.4.8

ANNUAL CHANGE IN CARBON STOCKS IN MINERAL SOILS FOR A SINGLE GRASSLAND SYSTEM

$$\Delta C_{GG_{Mineral}} = [(SOC_0 - SOC_{(0-T)}) \bullet A] / T$$

$$SOC = SOC_{REF} \bullet F_{LU} \bullet F_{MG} \bullet F_I$$

Where:

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

SOC_0 = soil organic carbon stock in the inventory year, tonnes C ha^{-1}

$SOC_{(0-T)}$ = soil organic carbon stock T years prior to the inventory, tonnes C ha^{-1}

T = inventory time period, yr (default is 20 yr)

A = land area of each parcel, ha

SOC_{REF} = the reference carbon stock, tonnes C ha^{-1}; see Table 3.4.4

F_{LU} = stock change factor for land use or land-use change type, dimensionless; see Table 3.4.5

F_{MG} = stock change factor for management regime, dimensionless; see Table 3.4.5

F_I = stock change factor for input of organic matter, dimensionless; see Table 3.4.5

The types of land use and management factors supplied are broadly defined and include: 1) a land use factor (F_{LU}) that reflects C stock levels relative to native ecosystems, 2) a management factor (F_{MG}) that represents broad categories of improved and degraded grassland and 3) an input factor (F_I) representing different levels of C inputs to soil, which is implemented for improved grassland only. If the area was in other land use (e.g. forest land, cropland) at the beginning of the inventory period, then guidance provided under Section 3.4.2, Land Converted to Grassland, should be followed.

The calculation steps for determining SOC_0 and $SOC_{(0-T)}$ and net soil C stock change per ha of land area are as follows:

Step 1: Select the reference carbon stock value (SOC_{REF}), based on climate and soil type, for each area of grassland being inventoried.

Step 2: Select the management condition of the grassland (F_{MG}) present at beginning of the inventory period (e.g. 20 years ago) and the C input level (F_I). These factors, multiplied by the reference soil C stock, provide the estimate of 'initial' soil C stock ($SOC_{(0-T)}$) for the inventory period. Note for Grassland Remaining Grassland the land use factor (F_{LU}) always equals 1.

Step 3: Calculate SOC_0 by repeating step 2 using the same reference carbon stock (SOC_{REF}) and F_{LU}=1, but with management and input factors that represent conditions in (current) inventory year.

Step 4: Calculate the average annual change in soil C stock for the area over the inventory period ($\Delta C_{GG_{Mineral}}$)

Example: For an Ultisol soil in a tropical moist climate, SOC_{Ref} (0-30 cm) is 47 tonnes C ha^{-1}. Under management resulting in an unimproved, moderately overgrazed pasture, the soil carbon stock at the beginning of the inventory period (default is 20 yr previous) is ($SOC_{Ref} \bullet F_{LU} \bullet F_{MG} \bullet F_I$) = 47 tonnes C ha^{-1} ● 1 ● 0.97 ● 1 = 45.6 tonnes C ha^{-1}. Improved pasture with fertiliser addition (F_{MG} = 1.17) is the management condition in the (current) inventory year, yielding a soil carbon stock estimate of 47 tonnes C ha^{-1} ● 1 ● 1.17 ● 1 = 55 tonnes C ha^{-1}. Thus the average annual change in soil C stock for the area over the inventory period is calculated as (55 tonnes C ha^{-1} – 45.6 tonnes C ha^{-1}) / 20 yrs = 0.47 tonnes C ha^{-1} yr^{-1}.

Tier 1: For Tier 1, default reference carbon stocks and stock change factors are used (as shown in Equation 3.4.8) for major grassland systems in a country, stratified by the default climate and soil types (Equation 3.4.9). For the aggregate area of grassland remaining grassland, stock changes can be calculated either by tracking management changes and calculating stock changes on individual parcels of land (Equation 3.4.9A) or by calculating aggregate soil carbon stocks at the start and end of the inventory period from more general data on the area distribution of grassland systems (Equation 3.4.9B). Aggregate results will be the same with either approach, the main difference being that attribution of the effects of specific changes in management requires activity data that tracks management changes on specific areas of land. Default values for this calculation are described in Section 3.4.1.2.1.2.

EQUATION 3.4.9
ANNUAL CHANGE IN CARBON STOCKS IN MINERAL SOILS IN TOTAL GRASSLAND REMAINING GRASSLAND

$$\Delta C_{GG_{Mineral}} = \sum_c \sum_s \sum_i [(SOC_0 - SOC_{(0-T)}) \bullet A]_{c,s,i} / T \qquad (A)$$

$$\Delta C_{GG_{Mineral}} = \sum_c \sum_s \sum_i (SOC_0 \bullet A)_{c,s,i} - \sum_c \sum_s \sum_i (SOC_{(0-T)} \bullet A)_{c,s,i} / T \qquad (B)$$

Where:

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

SOC_0 = soil organic carbon stock in the inventory year, tonnes C ha^{-1}

$SOC_{(0-T)}$ = soil organic carbon stock T years prior to the inventory, tonnes C ha^{-1}

T = inventory time period, yr (default is 20 yr)

A = land area of each parcel, ha

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

Example: The following example shows calculations for aggregate areas of grassland soil carbon stock change using Equation 3.4.9B. In a tropical moist climate on Ultisol soils, there are 1Mha of permanent grassland. The native reference carbon stock (SOC_{Ref}) for the climate/soil type is 47 tonnes C ha^{-1}. At the beginning of the inventory calculation period (i.e. 20 yrs earlier) the distribution of grassland systems was 500,000 ha of unmanaged native grassland, 400,000 ha of unimproved, moderately degraded grazing land and 100,000 ha of heavily degraded grassland. Thus initial soil carbon stocks for the area were: 500,000 ha ● (47 tonnes C ha^{-1} ● 1 ● 1 ● 1) + 400,000 ha ● (47 tonnes C ha^{-1} ● 1 ● 0.97 ● 1) + 100,000 ha ● (47 tonnes C ha^{-1} ● 1 ● 0.7 ● 1) = 45.026 million tonnes C. In the (current) inventory year, there are: 300,000 ha of unmanaged native grassland, 300,000 ha of unimproved, moderately degraded grazing land, 200,000 ha of heavily degraded grassland, 100,000 ha of improved pasture receiving fertiliser, and 100,000 ha of highly improved pasture receiving fertiliser together with irrigation. Thus total soil carbon stocks in the inventory year are: 300,000 ha ● (47 tonnes C ha^{-1} ● 1 ● 1 ● 1) + 300,000 ha ● (47 tonnes C ha^{-1} ● 1 ● 0.97 ● 1) + 200,000 ha ● (47 tonnes C ha^{-1} ● 1 ● 0.7 ● 1) + 100,000 ha ● (47 tonnes C ha^{-1} ● 1 ● 1.17 ● 1) + 100,000 ha ● (47 tonnes C ha^{-1} ● 1 ● 1.17 ● 1.11) = 45.960 million tonnes C. The average annual stock change over the period for the entire area is: (45.960 – 45.026) million tonnes C/20 yr = 0.934 million tonnes/20 yr = 46,695 tonnes per year soil C stock increase.

Tier 2: For Tier 2, the same basic equations as in Tier 1 are used but country-specific values for reference carbon stocks and/or stock change factors are used. In addition, Tier 2 approaches will likely involve a more detailed stratification of management systems if sufficient data are available.

Tier 3: Tier 3 approaches, using a combination of dynamic models along with detailed soil C emission/stock change inventory measurements, will likely not employ simple stock change or emission factors *per se*. Estimates of emissions using model-based approaches derive from the interaction of multiple equations that estimate the net change of soil C stocks within the models. A variety of models designed to simulate soil carbon dynamics exist (for example, see reviews by McGill *et al.*, 1996; Smith *et al.*, 1997).

Key criteria in selecting an appropriate model are that the model is capable of representing all of the management practices that are represented and that model inputs (i.e. driving variables) are compatible with the availability of country-wide input data. It is critical that the model be validated with independent observations from country or region-specific field locations that are representatives of the variability of climate, soil and management systems in the country. Examples of appropriate validation data sets include long-term grassland experiments (e.g. Conant *et al.*, 2001) or long-term measurements of ecosystem carbon flux for grassland systems, using techniques such as eddy covariance (Baldocchi *et al.*, 2001). Ideally, an inventory system of permanent, statistically representative grassland plots, that include major climatic regions, soil types, and management systems and system changes, would be established where repeated measures of soil carbon stocks could be made over time. Recommended re-sampling frequencies in most cases should not be less than 3 to 5 years (IPCC, 2000b). Where possible, measurements of soil carbon stocks should be made on an equivalent mass basis (e.g. Ellert *et al.*, 2001). Procedures should be implemented to minimize the influence of spatial variability with repeated sampling over time (e.g. Conant and Paustian, 2002a). Such inventory measurements could be integrated with a process model-based methodology.

Organic Soils

The methodology for estimating carbon stock change in organic soils used for managed grassland is to assign an annual loss rate of C due to the drainage and other management perturbations in adapting these soils to managed grassland [2]. Drainage and pasture management practices stimulate the oxidation of organic matter previously built up under a largely anoxic environment (although emission rates are lower than under annual cropland use where repeated tillage further stimulates decomposition). The area of grassland organic soils under each climate type is multiplied by the emission factor to derive an estimate of annual C emissions, as shown in Equation 3.4.10 below:

EQUATION 3.4.10

CO_2 EMISSIONS FROM CULTIVATED ORGANIC SOILS IN GRASSLAND REMAINING GRASSLAND

$$\Delta C_{GG_{Organic}} = \sum_c (A \bullet EF)_c$$

Where:

$\Delta C_{GG_{Organic}}$ = CO_2 emissions from cultivated organic soils in grassland remaining grassland, tonnes C yr^{-1}

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

EF = emission factor for climate type *c* (see Table 3.4.6), tonnes C ha^{-1} yr^{-1}

Tier 1: For Tier 1, default emission factors (Table 3.4.6) are used along with area estimates for organic soils under grassland management within each climate region present in the country (Equation 3.4.10). Area estimates can be developed using the guidance in Chapter 2.

Tier 2: The Tier 2 approach uses Equation 3.4.10 where emission factors are estimated from country-specific data, stratified by climate region, as described in Section 3.4.1.2.1.2. Area estimates should be developed following the guidance Chapter 2.

Tier 3: Tier 3 approaches for organic soils will include more detailed systems integrating dynamic models and measurement networks as described above for mineral soils.

Liming

The *IPCC Guidelines* include application of carbonate containing lime (e.g. calcic limestone ($CaCO_3$) or dolomite $CaMg(CO_3)_2$) to soils as a source of CO_2 emissions. In humid regions, intensively managed pastures may be periodically limed to reduce soil acidity. A simplified explanation of the process is that when carbonate lime is dissolved in soil, the base cations (Ca^{++}, Mg^{++}) exchange with hydrogen ions (H^+) on soil colloids (thereby reducing soil acidity) and the bicarbonate formed ($2HCO_3$) can react further to evolve CO_2 and water

[2] Natural, 'wetland' grasslands that may be used for seasonal grazing but have not been artificially drained should not be included in this category.

(H_2O). Although the liming effect generally has a duration of a few years (after which lime is again added), depending on climate, soil and management practices, the *IPCC Guidelines* account for emission as CO_2 of all the added carbonate carbon in the year of application. Thus the basic methodology is simply the amount of lime applied times an emission factor that varies slightly depending on the composition of the material added.

EQUATION 3.4.11

ANNUAL CARBON EMISSIONS FROM AGRICULTURAL LIME APPLICATION

$$\Delta C_{GG_{Liming}} = M_{Limestone} \bullet EF_{Limestone} + M_{Dolomite} \bullet EF_{Dolomite}$$

Where:

$\Delta C_{GG_{Liming}}$ = annual C emissions from agricultural lime application, tonnes C yr^{-1}

M = annual amount of calcic limestone ($CaCO_3$) or dolomite ($CaMg(CO_3)_2$), tonnes yr^{-1}

EF = emission factor, tonnes C (tonne limestone or dolomite)$^{-1}$ (These are equivalent to carbonate carbon contents of the materials (12% for $CaCO_3$, 13% for $CaMg(CO_3)_2$))

Tier 1: For Tier 1, the total amount of carbonate containing lime applied annually to grassland soil and an overall emission factor of 0.12 can be used to estimate CO_2 emissions, without differentiating between variable compositions of lime material. Note that while carbonate limes are the dominant liming material used, oxides and hydroxides of lime, which do not contain inorganic carbon, are used to a limited extent for agricultural liming and should not be included here (CO_2 is produced in their manufacture but not following soil application).

Tier 2: A Tier 2 approach could entail differentiation of different forms of lime and specific emission factors if data are available, since different carbonate liming materials (limestone as well as other sources such as marl and shell deposits) can vary somewhat in their carbon content and overall purity.

Tier 3: A Tier 3 approach could entail a more detailed accounting of emissions stemming from lime applications than is assumed under Tiers 1 and 2. Depending on climate and soil conditions, biocarbonate derived from lime application may not all be released as CO_2 in the soil or from drainage water – some can be leached and precipitated deeper in the soil profile or be transported to deep groundwater, lakes and oceans and sequestered. If sufficient data and understanding of inorganic carbon transformation for specific climate-soil conditions are available, specific emission factors could be derived. However, such an analysis would likely necessitate including carbon fluxes associated with primary and secondary carbonate minerals in soil and their response to grassland management practices.

3.4.1.2.1.2 Choice of Emission/Removal Factors

Mineral soils

When using either the Tier 1 or Tier 2 method, the following emission/removal factors are needed for mineral soils: reference carbon stock (SOC_{REF}); stock change factor for land-use change (F_{LU}); stock change factor for management regime (F_{MG}); and factor for input of organic matter (F_I).

Reference carbon stocks (SOC_{REF})

Soils under native vegetation that have not been subject to significant land use and management impacts are used as a baseline or reference to which management-induced changes in soil carbon can be related.

Tier 1: Under Tier 1, it is *good practice* to use the default reference carbon stocks (SOC_{REF}) provided in Table 3.4.4. These are updated from those provided in the *IPCC Guidelines* with the following improvements: i) estimates are statistically-derived from recent compilations of soil profiles under native vegetation, ii) 'Spodic' soils (defined as boreal and temperate zone podzols in WRB classification, Spodosols in USDA classification) are included as a separate category, iii) soils within the boreal climate region have been included.

Tier 2: For Tier 2, reference soil C stocks can be determined from measurements of soils, for example, as part of a country's soil survey and mapping activities. Advantages include more representative values for an individual country and the ability to better estimate probability distribution functions that can be used in a formal uncertainty analysis. Accepted standards for sampling and analysis of soil organic carbon and bulk density should be used.

Stock change factors (F_{LU}, F_{MG}, F_I)

Tier 1: Under Tier 1, it is *good practice* to use default stock change factors **(F_{LU}, F_{MG}, F_I)** provided in Table 3.4.5.

These are updated from the *IPCC Guidelines*, based on statistical analysis of published research. Where sufficient data exists, separate values were computed for temperate and tropical grassland. All grasslands (excluding those on organic soils) are assigned a base or (land use) factor of 1. Four categories of grassland management condition are defined (unimproved/non-degraded, moderately degraded, severely degraded and improved – see definitions in Table 3.4.5). Improved grasslands are defined as sustainably (non-degraded) managed grassland that receive at least one type of external input (e.g. improved species, fertilization, or irrigation) to increase productivity. For improved grasslands there are two levels for the input factor value, 'nominal' (which denotes the base case (F_I=1) where there is no *additional* management improvement, beyond that required for classification as improved grassland) and 'high', in which at least one addition improvement has been implemented (e.g. fertilization plus irrigation), representing highly intensive grassland management. Values for the moderately degraded grassland category were based on studies reporting conditions or treatments representative of overgrazing and/or degradation. However, in many cases, particularly in the tropics, pasture degradation is associated with a loss of more palatable grass species and replacement by 'weedy' species (often woody plants). Although this constitutes degradation from the standpoint of use for grazing, negative impacts on soil C may be less severe (as indicated by the small reduction in F_{LU} for moderately degraded grassland, relative to the native condition). In the *IPCC Guidelines* there was only one category specified for degraded grassland with a much lower value for F_{MG} (0.7), implying severe degradation and high soil C loss. There are insufficient studies in the literature to re-estimate a factor value for this condition and thus the previous value has been retained to represent this severely degraded condition.

Tier 2: For Tier 2 applications, stock change factor values can be estimated from long-term experiments or other field measurements (e.g., field chronosequences) for a particular country or region. Advantages include more accurate and representative values for the country of interest and the ability to estimate probability distribution functions for factor values that can be used in a scientific uncertainty analysis. There are few replicated long-term experiments investigating the impacts of grassland management on soil C stocks, and thus uncertainties of emission factors for grassland management are greater than those for permanent cropland. Many studies evaluate stock differences in paired plots and it is important that the plots being compared have similar land use/management histories prior to implementation of experimental management treatments. If sufficient sequestration rate and land management data are available, factor values may be calculated for specific grassland management practices (e.g., fertilisation, sowing improved grass and legume species, grazing management, etc.).

Information compiled from published studies and other sources should include C stock (i.e., mass per unit area to a specified depth) or all information needed to calculate SOC stocks, i.e., percent organic matter together with bulk density. If the percent organic matter and not the percent organic carbon are reported, a conversion factor of 0.58 for the carbon content of soil organic matter can be used. Other information that must be included in the analysis is the soil type (e.g., WRB or USDA Soil Taxonomy Reference), depth of measurement, and time frame over which the management difference has been expressed. Stock change factors should encompass sufficient depth to include the full influence of management changes on soil C stocks and correcting for possible changes in bulk density (Ellert *et al.*, 2001). It is *good practice* to include a minimum depth of at least 30 cm (i.e., the depth used for Tier 1 calculations); stock changes over deeper depths may be desirable if a sufficient number of studies are available and if statistically significant differences in stocks due to land management are demonstrated at those depths.

Organic soils

When estimating emissions from organic soils that have been modified through artificial drainage and other practices for use as managed grassland, an emission factor (EF) is required for different climatic regimes.

Tier 1: For Tier 1, default emission factors, unchanged from the *IPCC Guidelines*, are provided in Table 3.4.6. Natural, 'wetland' grasslands that may be used for seasonal grazing but have not been artificially drained are excluded.

Tier 2: For Tier 2, there are limited literature data on emissions from organic soils used for managed grassland; published studies usually make estimates based on subsidence, with a limited number of direct measurements of CO_2 fluxes from grassland organic soils (Ogle *et al.*, 2003). Processes that contribute to subsidence include erosion, compaction, burning, and decomposition, only the latter of which should be included in the emission factor estimate. If using subsidence data, appropriate regional conversion factors to determine the proportion of subsidence attributable to oxidation should be used, based on studies measuring both subsidence and CO_2 flux. In the absence of such information, a default factor of 0.5 for oxidation-to-subsidence, on a gram-per-gram equivalent basis, is recommended based on reviews by Armentano and Menges (1986). If available, direct measurements of carbon fluxes are recommended as providing the best means of estimating emission rates from organic soils.

TABLE 3.4.4
DEFAULT REFERENCE (UNDER NATIVE VEGETATION) SOIL ORGANIC C STOCKS (SOC_{REF})
(TONNES C PER HA FOR 0-30 CM DEPTH)

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

Note: Data are derived from soil databases described by Jobbagy and Jackson (2000) and Bernoux *et al.* (2002). Mean stocks are shown. A default error estimate of 95% (expressed as 2X standard deviations as percent of the mean) are assumed for soil-climate types. NA denotes 'not applicable' because these soils do not normally occur in some climate zones.

# indicates where no data were available and default values from *IPCC Guidelines* were retained.

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

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

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

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

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

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

TABLE 3.4.5
RELATIVE STOCK CHANGE FACTORS FOR GRASSLAND MANAGEMENT
[SEE SECTION 3.4.7 FOR METHODS USED TO ESTIMATE THE STOCK CHANGE FACTORS]

Factor	Level	Climate regime	*IPCC Guidelines* default	GPG revised default	Error [1,2]	Definition
Land use (F_{LU})	All	All	1.0	1.0	NA	All permanent grassland is assigned a land use factor of 1.
Management (F_{MG})	Nominally managed (non –degraded)	All	1.0	1.0	NA	Represents, non-degraded and sustainably managed grassland, but without significant management improvements.
Management (F_{MG})	Moderately degraded grassland	Temperate /Boreal	NA	0.95	± 12%	Represents overgrazed or moderately degraded grassland, with somewhat reduced productivity (relative to the native or nominally managed grassland) and receiving no management inputs.
		Tropical	NA	0.97	± 10%	
Management (F_{MG})	Severely degraded	All	0.7	0.7	± 50%	Implies major long-term loss of productivity and vegetation cover, due to severe mechanical damage to the vegetation and/or severe soil erosion.
Management (F_{MG})	Improved grassland	Temperate /Boreal	1.1	1.14	± 10%	Represents grassland which is sustainably managed with moderate grazing pressure and that receive at least one improvement (e.g. fertilization, species improvement, irrigation).
		Tropical	1.1	1.17	± 10%	
Input (applied only to improved grassland) (F_I)	Nominal	All	NA	1.0	NA	Applies to improved grassland where no additional management inputs have been used.
Input (applied only to improved grassland) (F_I)	High	Temperate /Boreal	NA	1.11	± 8%	Applies to improved grassland where one or more additional management inputs/improvements have been used (beyond that required to be classified as improved grassland).
		Tropical	NA	1.11	± 8%	

[1] ± two standard deviations, expressed as a percent of the mean; where sufficient studies were not available for a statistical analysis a default, based on expert judgement, of ± 50% is used. NA denotes 'Not Applicable', for factor values that constitute reference values or where factor values were not previously estimated for the *IPCC Guidelines*.

[2] This error range does not include potential systematic error due to small sample sizes that may not be representative of the true impact for all regions of the world.

TABLE 3.4.6
ANNUAL EMISSION FACTORS (EF) FOR MANAGED GRASSLAND ORGANIC SOILS

Climatic temperature regime	*IPCC Guidelines* default (tonnes C ha^{-1} yr^{-1})	Error [#]
Cold Temperate	0.25	± 90%
Warm Temperate	2.5	± 90%
Tropical/sub-tropical	5.0	± 90%

[#] Represents a nominal estimate of error, equivalent to two times standard deviation, as a percentage of the mean

Liming
See discussion under Section 3.4.1.2.1.1.

3.4.1.2.1.3 Choice of Activity Data

Mineral Soils
The area of grassland under different management practices (A) is required for estimating mineral soil emissions/removals.

For existing grassland, activity data should record changes or trends in management practices or utilization of the grassland that affect soil carbon storage by impacting production. Two main types of activity data exist: (i) aggregate statistics compiled at a national level or for administrative areas within countries (e.g., provinces, counties, districts), or (ii) point-based land use and management inventories making up a statistically-based sample of a country's land area. The use of both sorts of activity data is described in Chapter 2, and the use of the methods set out there with the three tiers described here will depend on the spatial and temporal resolution required. For Tier 1 and Tier 2 inventories, activity data need to be stratified by major climatic differences and soil types, since reference soil C stocks vary significantly according to these factors. For application of dynamic models and/or a direct measurement-based inventory in Tier 3, similar or more detailed knowledge of the combinations of climate, soil, topographic and management data are needed, but the exact requirements will be in part dependent on the model used.

Globally available land use statistics such as FAO's databases (http://www.fao.org/waicent/portal/glossary_en.asp) provide annual compilations of total land area by major land use types, without any additional details for grassland management, climate, or soil. Thus FAO or similar country-total data would require additional in-country information to stratify areas by management, climate, and soil types. If such information has not already been compiled, an initial approach would be to overlay available land cover/land use maps (of national origin or from global datasets such as IGBP_DIS) with soil maps of national origin or global sources such as the FAO Soils Map of the World. Where possible land areas associated with a characteristic grassland management should be delineated and associated with the appropriate general (i.e., degraded, native, or improved) or specific (e.g., fertilization or grazing intensity) management factor values. Soil degradation maps may be a useful source of information for stratifying grassland according to management (e.g. Conant and Paustian, 2002b).

National land use and resource inventories, comprised of a collection of permanent sample points where data is collected at regular intervals, have some advantages over aggregate pastoral and land use statistics. Inventory points can more readily be associated with a particular grassland management system and the soil type associated with the particular location can be determined by sampling or by referencing the location to a suitable soil map. Inventory points selected based on an appropriate statistical design also enable estimates of the variability associated with activity data, which can be used as part of a formal uncertainty analysis. The principles of sampling are described in Chapter 2 and an example of a point-based resource inventory is the National Resource Inventory in the U.S. (Nusser and Goebel, 1997).

Organic Soils

The area of cultivated organic soils by climate regime (A) is required to estimate organic soil emissions. Similar databases and approaches as those outlined above can be used for deriving area estimates. An overlay of soils maps showing the spatial distribution of histosols (i.e. organic soils) with land cover maps showing grassland area can provide initial information on areas with organic soils under grassland. Country-specific data on drainage projects combined with soil maps and surveys can be used to get a more refined estimate of relevant areas of managed grassland on organic soils.

3.4.1.2.1.4 Uncertainty Assessment

An assessment of uncertainty requires that uncertainty in per area emission/removal rates as well as uncertainty in the activity data (i.e. the land areas involved in land-use and management changes), and their interaction be estimated.

Where available, estimates of the standard deviation (and sample size) for the revised global default values developed in this report are provided in the tables; these can be used with the appropriate estimates of variability in activity data to estimate uncertainty, using the guidance provided in Chapter 5 of this report. Inventory agencies should be aware that simple global defaults have a relatively high level of uncertainty associated with them when applied to specific countries. In addition, because the field studies available to derive the global defaults are not evenly distributed across climate regions, soil types and management systems, some areas – particularly in tropical regions – are underrepresented. For the Tier 2 methods, probability density functions (i.e. providing mean and variance estimates) can be derived for stock change factors, organic soil emission factors and reference C stocks as part of the process of deriving region- or country-specific data. Uncertainty in soil emission and removal rates can be reduced by field studies of management influences on soil C stocks for major grassland types and management regimes. Where chronosequence data are used, uncertainty in the carbon stock changes estimates can be relatively high and thus it is desirable to use the mean of several 'replicate' studies to derive more representative values.

3.4.1.3 NON-CO_2 GREENHOUSE GAS EMISSIONS

Coverage of Non-CO_2 gases in *IPCC Guidelines*

The *IPCC Guidelines* and *GPG2000* (Chapter 4, Agriculture) already address the following emissions:

- N_2O emissions from application of mineral and organic fertilisers, organic residues and biological nitrogen fixation in managed grassland;
- N_2O, NOx, CH_4 and CO emissions from grassland (savanna) burning in the tropics; and
- CH_4 emissions from grazing livestock.

It is *good practice* to follow the existing *IPCC Guidelines (Chapter 4, Agriculture) and GPG2000* to estimate and report these fluxes in the *Agriculture* section.

Additional sources of emissions and removals, not included in *IPCC Guidelines (Chapter 4, Agriculture) and GPG2000*, include N_2O emissions from organic nitrogen mineralization in drained, organic grassland soils[3], changes reduced uptake of CH_4 in managed grassland soils and emissions from burning in temperate grassland. Insufficient data on N_2O emissions from enhanced mineralization of organic nitrogen on organic grassland soils and management-induced reductions in CH_4 sinks in grassland soils preclude recommending specific methodologies at this time. In most circumstances they are likely to represent minor fluxes and as more research is done and additional information becomes available, a fuller consideration of these sources may be possible.

For grassland burning occurring in grassland outside the tropics (and hence not included in *IPCC Guidelines (Chapter 4, Agriculture) and GPG2000*), methods to estimate N_2O, NO_x, CH_4 and CO released from grassland burning are described in Section 3.2.1.4. Default estimates for standing biomass, used to estimate the quantity of fuel consumed, can be obtained from Table 3.4.2. Note that the amount of biomass that can serve as fuel can vary considerably according to the time of year and grazing regime and thus country-specific biomass estimates that correspond to when and where grassland burning occurs are recommended.

3.4.2 Land Converted to Grassland

The carbon implications of the conversion from other land uses (mostly forest land, cropland, and to lesser degree wetlands and seldom settlements) to grassland is less clearcut than the case of conversion to cropland. Literature on the main conversion type (from forest land to grassland in the tropics) provides evidence for net gains as well as net losses in soil carbon, and the effect of management on the soil carbon changes of grassland after conversion is critical (see for example Veldkamp, 2001). Conversion of land from other uses and from natural states to grassland can result in net emissions (or net uptake) of CO_2 from both, biomass and soil. Emissions from biomass are addressed in Section 3.4.2.1 and those from soil in Section 3.4.2.2. The calculation of carbon stock changes in biomass as a result of land use conversions to grassland is found in the *IPCC Guidelines* in Section 5.2.3. (Forest and Grassland Conversion).

Methods described in this section are designed to account for changes in biomass and soils stocks associated with the land use conversion and the establishment of new grassland. Subsequent stock changes should be estimated under *Grassland Remaining Grassland*.

The summary equation for carbon stock changes in Lands Converted to Grassland is shown below in Equation 3.4.12. Two sub-categories are estimated for the category of *Lands Converted to Grasslands*: living biomass and soil organic matter. Table 3.4.7 summarises the tiers for each of the carbon subcategories.

EQUATION 3.4.12
TOTAL CHANGE IN CARBON STOCKS IN LAND CONVERTED TO GRASSLAND

$$\Delta C_{LG} = \Delta C_{LG_{LB}} + \Delta C_{LG_{Soils}}$$

Where:

ΔC_{LG} = total change in carbon stocks in land converted to grassland, tonnes C yr^{-1}

$\Delta C_{LG_{LB}}$ = change in carbon stocks in living biomass in land converted to grassland, tonnes C yr^{-1}

[3] Emissions from fertilization and manuring on these grasslands *are* included in *IPCC Guidelines (Chapter 4, Agriculture) and GPG2000.*

$\Delta C_{LG_{Soils}}$ = change in carbon stocks in soils in land converted to grassland, tonnes C yr^{-1}

3.4.2.1 CHANGE IN CARBON STOCKS IN BIOMASS

3.4.2.1.1 METHODOLOGICAL ISSUES

This section provides *good practice* guidance for calculating CO_2 emissions and removals in biomass due to the conversion of land from natural conditions and other uses to grassland, including deforestation and conversion of cropland to pasture and grazing lands. The carbon emissions and removals in biomass in land use conversion to grassland result from the removal of existing and replacement with different vegetation. This process may result in increases or decreases in carbon stocks in biomass depending on the type of land use conversion. This is different from the concepts underlying carbon stock changes in biomass of grassland remaining grassland where changes are tied to management practices.

Generically, the methods to quantify emissions and removals of carbon due to conversion of other land uses to grassland require estimates of the carbon stocks prior to and following conversion (depending on whether previous land use was forest land, cropland, wetlands) and the estimates of the areas of land converted during the period over which conversion has an effect. As a result of conversion to grassland, it is assumed that the dominant vegetation is removed entirely, after which some type of grass is planted or otherwise established (e.g. in establishment of pasture). Alternatively, grassland can result from the abandonment of the preceding land use e.g. cropland, and the area is taken over by grassland. Vegetation that replaces that which was cleared during conversion should be accounted for using this methodology in conjunction with the methods in Section 3.4.1.

3.4.2.1.1.1 Choice of Method

Tier 1: The Tier 1 method follows the approach in *IPCC Guidelines* Section 5.2.3. Forest and Grassland Conversion where the amount of carbon removed is estimated by multiplying the area converted annually by the difference between average carbon stocks in biomass prior to and following conversion, accounting for carbon in biomass that replaces cleared vegetation. It is *good practice* to account completely for all land conversions to grassland. Thus, this section elaborates on the method such that it includes each initial land use, including but not limited to forests. All countries should strive for improving inventory and reporting approaches by advancing to the highest tier possible given national circumstances. It is *good practice* for countries to use a Tier 2 or Tier 3 approach if carbon emissions and removals in land converted to grassland is a key category and if the sub-category of living biomass is considered significant based on principles outlined in Chapter 5. Countries should use the decision tree in Figure 3.1.2 to help with the choice of method.

Equation 3.4.13 summarises the major elements of a first order approximation of carbon stock changes from land use conversion to grassland. Average carbon stock change on a per area basis is estimated for each type of conversion. The average carbon stock change is equal to the carbon stock change due to the removal of biomass from the initial land use (i.e., carbon in biomass immediately after conversion minus the carbon in biomass prior to conversion), plus carbon stocks from biomass growth following conversion. As stated in the *IPCC Guidelines*, it is necessary to account for any vegetation that replaces the vegetation that was cleared during land use conversion. The *IPCC Guidelines* combine carbon in biomass after conversion and carbon in biomass that grows on the land following conversion into a single term. In this method, they are separated into two terms, C_{After} and C_{Growth} to increase transparency. At Tier 1, carbon stocks in biomass immediately after conversion (C_{After}) are assumed to be zero, i.e., the land is cleared of all vegetation before grass or woody vegetation is seeded, planted or naturally regenerated. Average carbon stock change per area for a given land use conversion is multiplied by the estimated area of lands undergoing such a conversion in a given year. In subsequent years, carbon stock changes in living biomass of grassland, resulting from management changes, are counted following the methodology in Section 3.4.1.1 (Change in Biomass in: Grassland Remaining Grassland).

TABLE 3.4.7
TIER DESCRIPTIONS FOR SUBCATEGORIES UNDER LAND CONVERTED TO GRASSLAND

Tier / Sub-categories	Tier 1	Tier 2	Tier 3
Living biomass	Use default coefficients to estimate carbon stock change in biomass resulting from land use conversions and for carbon in biomass that replaces cleared vegetation.	Use at least some country-specific carbon stock parameters to estimate carbon stock changes from land use conversion to grassland. Apportion carbon from biomass removal to burning, decay, and other nationally important conversion processes. Estimate non-CO_2 trace gas emissions from the portion of biomass burned both on-site and off-site. Use area estimates that are disaggregated to nationally relevant climate zones and other boundaries to match country-specific carbon stock parameters.	Use country-specific approach at fine spatial scale (e.g., modeling, measurement).
Carbon stocks in soil	For changes in soil carbon from mineral soils use default coefficients. The areas must be stratified by climate and soil type. For changes in soil carbon from organic soils use default coefficients and stratify the areas by climatic region. For emissions from liming, use default emission factors.	For both mineral and organic soils use some combination of default and/or country-specific coefficients and area estimates of increasingly finer spatial resolution. For emissions from liming, use emission factors differentiated by forms of lime.	Use country-specific approach at fine spatial scale (e.g., modeling, measurement).

The basic steps in estimating carbon stock changes in biomass from land conversion to grassland are as follows:

1. Estimate the average area of land undergoing a transition from non-grassland to grassland during a year ($A_{conversion}$), separately for each initial land use (i.e., forest land, cropland, etc.) and final grassland type.
2. For each type of land use transition to grassland, use Equation 3.4.13 to estimate the resulting change in carbon stocks. Default data in Section 3.4.2.1.1.2 for C_{After}, C_{Before}, and C_{Growth} can be used to estimate the total stock change on a per area basis for each type of land use transition. The estimate for stock change on a per area basis can then be multiplied by the appropriate area estimates from step 1.
3. Estimate the total carbon stock change from all land use conversions to grassland by summing the individual estimates for each transition.

The default assumption for Tier 1 is that all carbon in biomass is lost to the atmosphere through decay processes either on- or off-site. As such, Tier 1 calculations do not differentiate immediate emissions from burning and other conversion activities.

EQUATION 3.4.13
ANNUAL CHANGE IN CARBON STOCKS IN LIVING BIOMASS IN LAND CONVERTED TO GRASSLAND

$$\Delta C_{LG_{LB}} = A_{Conversion} \bullet (L_{Conversion} + \Delta C_{Growth})$$

$$L_{Conversion} = C_{After} - C_{Before}$$

Where:

$\Delta C_{LG_{LB}}$ = annual change in carbon stocks in living biomass in land converted to grassland, tonnes C yr^{-1}

$A_{Conversion}$ = annual area of land converted to grassland from some initial use, ha yr^{-1}

$L_{Conversion}$ = carbon stock change per area for that type of conversion when land is converted to grassland, tonnes C ha^{-1}

ΔC_{Growth} = carbon stocks from one year of growth of grassland vegetation after conversion, tonnes C ha^{-1}

C_{After}= carbon stocks in biomass immediately after conversion to grassland, tonnes C ha^{-1}

C_{Before}= carbon stocks in biomass immediately before conversion to grassland, tonnes C ha^{-1}

Biomass stocks in newly established grassland tend to level out within a few years following conversion (e.g. 1-2 years for above-ground herbaceous biomass, 3-5 years for below-ground biomass), varying depending on the type of land conversion (for example, sown pastures can become quickly established whereas natural regeneration on abandoned cropland may take several years), climate and management conditions. Since under Tier 1 *Grassland Remaining Grassland* the default biomass stock change is zero, changes in biomass carbon stocks for grassland established following land use conversion are accounted for in the year of the conversion.

Tier 2: The Tier 2 calculations are structurally similar to Tier 1, with these distinctions. First, Tier 2 relies on at least some country-specific estimates of the carbon stocks in initial and final land uses rather than the defaults provided in Section 3.4.2.1.1.2. Area estimates for land converted to grassland are disaggregated at finer spatial scales to capture regional variations in country-specific carbon stocks values.

Second, Tier 2 may modify the assumption that carbon stocks immediately following conversion are zero. This enables countries to take into account land use transitions where some, but not all, vegetation from the original land use is removed. In addition, under Tier 2 it is possible to account for biomass accumulation following grassland establishment over a several year period (rather than accounting all biomass stock change in the year of conversion) if data are available to estimate the time to full biomass establishment and the annual stock changes.

Third, under Tier 2, it is *good practice* to apportion carbon losses to burning and decay processes if applicable. Emissions of carbon dioxide occur as a result of burning and decay in land-use conversions. In addition, non-CO_2 trace gas emissions occur as a result of burning. By partitioning losses to burning and decay, countries can calculate non-CO_2 trace gas emissions from burning. The *IPCC Guidelines* Workbook provides step-by-step instructions for estimating carbon removals from burning and decay of biomass on-site and off-site and for estimating non-CO_2 trace gas emissions from burning (pages 5.7-5.17). Below is guidance on estimating carbon removals from burning and decay and Section 3.2.1.4 of this chapter provides further guidance on estimating non-CO_2 trace gas emissions from burning.

The basic equations for estimating the amount of carbon burned or left to decay are provided in Equations 3.4.15 and 3.4.16 below, respectively. This methodology addresses burning for the purposes of land clearing. Non-CO_2 emissions from burning in Grassland Remaining Grassland are covered in Section 3.4.3 of this report. The default assumption in Equations 3.4.15 and 3.4.16 is that only aboveground biomass is burned or decays. Countries are encouraged to use additional information to assess this assumption, particularly for decaying belowground biomass. The basic approach can be modified to address other conversion activities as well as to meet the needs of national circumstances. Both equations use as an input the total amount of carbon in biomass removed during land clearing ($\Delta C_{conversion}$) (Equation 3.4.14), which is equivalent to area of land converted ($A_{Conversion}$) multiplied by the carbon stock change per area for that type of conversion ($L_{Conversion}$) in Equation 3.4.13).

The portion of woody biomass removed is sometimes used as wood products. In the case of wood products, countries may use the default assumption that carbon in wood products is oxidized in the year of removal. Alternatively, countries may refer to Appendix 3a.1 for estimation techniques for carbon storage in harvested wood products, which may be accounted provided carbon in the product pool is increasing.

EQUATION 3.4.14
CHANGE IN CARBON STOCKS AS A RESULT OF BIOMASS CLEARING DURING LAND USE CONVERSION

$$\Delta C_{conversion} = A_{conversion} \bullet (L_{conversion})$$

Where:

$\Delta C_{conversion}$ = change in carbon stocks as a result of a clearing biomass in a land use conversion, tonnes C

$A_{Conversion}$ = area of land converted to grassland, ha

$L_{Conversion}$ = carbon stock change per area for that type of conversion, tonnes C ha^{-1} (from Equation 3.4.13)

EQUATION 3.4.15
CARBON LOSSES FROM BIOMASS BURNING, ON-SITE AND OFF-SITE

$$L_{burn\ onsite} = \Delta C_{conversion} \bullet \rho_{burned\ on\ site} \bullet \rho_{oxid}$$

$$L_{burn\ offsite} = \Delta C_{conversion} \bullet \rho_{burned\ off\ site} \bullet \rho_{oxid}$$

Where:

L_{burn} = carbon losses from biomass burned, tonnes C

$\Delta C_{conversion}$ = change in carbon stocks as a result of a clearing biomass in a land use conversion, tonnes C

$\rho_{burned\ on\ site}$ = proportion of biomass that is burned on-site, dimensionless

ρ_{oxid} = proportion of biomass that oxidizes when burned, dimensionless

$\rho_{burned\ off\ site}$ = proportion of biomass that is burned off-site, dimensionless

EQUATION 3.4.16
CARBON LOSSES FROM BIOMASS DECAY

$$L_{decay} = \Delta C_{conversion} \bullet \rho_{decay}$$

$$\rho_{decay} = 1 - (\rho_{burned\ on\ site} + \rho_{burned\ off\ site})$$

Where:

L_{decay} = carbon losses from biomass decay, tonnes C

$\Delta C_{conversion}$ = change in carbon stocks as a result of a clearing biomass in a land use conversion, tonnes C

ρ_{decay} = proportion of biomass that is left on-site to decay, dimensionless

$\rho_{burned\ on\ site}$ = proportion of biomass that is burned on-site, dimensionless

$\rho_{burned\ off\ site}$ = proportion of biomass that is burned off-site, dimensionless

It is *good practice* for countries to use the terms $L_{burn\ on\ site}$ and $L_{burn\ off\ site}$ as inputs to estimate non-CO_2 trace gas emissions from burning following guidance provided in Section 3.2.1.4.

Tier 3: Tier 3 is similar to Tier 2, with the following distinctions: rather than relying on average annual rates of conversion, countries use direct estimates of spatially disaggregated areas converted annually for each initial and final land use; carbon stock changes are based on locally specific information. In addition, countries may use dynamic models, making it possible to spatially and temporally link biomass and soil carbon stock change estimates.

3.4.2.1.1.2 Choice of Emission/Removal Factors

Tier 1: The first step in this methodology requires parameters for carbon stocks before conversion for each initial land use (C_{Before}) and after conversion (C_{After}). It is assumed that all biomass is cleared when preparing a site for grassland use, thus, the default for C_{After} is 0 tonnes C ha^{-1}. Table 3.4.8 provides users with directions on where to find carbon stock values for C_{Before} in land uses prior to clearing. Table 3.4.9 provides default values for carbon stocks in grassland after conversion (ΔC_{Growth}). These values are based on the defaults aboveground biomass stocks (Table 3.4.2) and the root:shoot ratios (Table 3.4.3), provided in Section 3.4.1.1.1.2 under Grassland Remaining Grassland, and apply to herbaceous (i.e. non-woody) biomass only.

TABLE 3.4.8
DEFAULT BIOMASS CARBON STOCKS REMOVED DUE TO LAND CONVERSION TO GRASSLAND

Land-use category	Carbon stock in biomass before conversion (C_{Before}) (tonnes C ha^{-1})	Error Range [1]
Forest land	See Table 3A.1.2 for carbon stocks in a range of forest types by climate regions. Stocks are in terms of dry matter of carbon. *Multiply values by a carbon fraction (CF) 0.5 to convert dry matter to carbon.*	
Cropland: Perennial Woody Crops	See Table 3.3.2 for carbon stocks in a range of climate regions for generic perennial woody cropland. Use the term for aboveground biomass carbon stocks at harvest. Values are in units of tonnes C ha^{-1}.	± 75%
Cropland: Annual Crops	Use *IPCC Guidelines* default of 5 tonnes carbon ha^{-1} (or 10 tonnes dry matter ha^{-1})	± 75%

[1] Represents a nominal estimate of error, equivalent to two times standard deviation, as a percentage of the mean.

Tier 2: Tier 2 methods should include some country-specific estimates for biomass stocks and removals due to land conversion, and also include estimates of on- and off-site losses due to burning and decay following land conversion to grassland. These improvements can take the form of systematic studies of carbon content and emissions and removals associated with land uses and land-use conversions within the country and a re-examination of default assumptions in light of country-specific conditions.

Default parameters for emissions from burning and decay are provided, however countries are encouraged to develop country-specific coefficients to improve the accuracy of estimates. The *IPCC Guidelines* use a general default of 0.5 for the proportion of biomass burned on-site for forest conversions. Research studies suggests that the fraction is highly variable and could be as low as 0.2 (e.g. Fearnside, 2000; Barbosa and Fearnside, 1996; and Fearnside, 1990). Updated default proportions of biomass burned on site are provided here. Table 3A.1.12 provides defaults for proportion of biomass consumed in on-site burning by a range of forest vegetation classes. These defaults should be used for transitions from forest land to grassland. For non-forest initial land uses, the default proportion of biomass left on-site and burned is 0.35. This default takes into consideration research, which suggests the fraction should fall within the range 0.2 to 0.5 (Fearnside, 2000; Barbosa and Fearnside, 1996; and Fearnside, 1990). It is *good practice* for countries to use 0.35, or another value within this range provided the rationale for the choice is documented. There is no default value for the amount of biomass taken off-site and burned; countries will need to develop a proportion based on national data sources. In Equation 3.4.15., the default proportion of biomass oxidized as a result of burning is 0.9, as originally stated in the *IPCC Guidelines.*

The method for estimating emissions from decay assumes that all biomass decays over a period of 10 years. For reporting purposes countries have two options: to report all emissions from decay in one year, recognizing that in reality they occur over a 10 year period, or report all emission from decay on an annual basis, estimating the rate as one tenth of the totals in Equation 3.4.16. If countries choose the latter option, they should add a multiplication factor of 0.10 to Equations 3.4.16.

Tier 3: Under Tier 3, all parameters should be country-defined using more accurate values rather than the defaults.

TABLE 3.4.9
DEFAULT BIOMASS CARBON STOCKS PRESENT ON LAND CONVERTED TO GRASSLAND

IPCC Climate zone	Total (above- and belowground) non-woody biomass (tonnes d.m. ha^{-1})	Error [1]
Boreal - Dry & Wet [2]	8.5	± 75%
Cold Temperate - Dry	6.5	± 75%
Cold Temperate -Wet	13.6	± 75%
Warm Temperate – Dry	6.1	± 75%
Warm Temperate –Wet	13.5	± 75%
Tropical - Dry	8.7	± 75%
Tropical - Moist & Wet	16.1	± 75%

[1] Represents a nominal estimate of error, equivalent to two times standard deviation, as a percentage of the mean.

[2] Due to limited data, dry and moist zones for the boreal temperature regime and moist and wet zones for the tropical temperature regime were combined.

3.4.2.1.1.3 Choice of Activity Data

All tiers require estimates of land areas converted to grassland. The same area data should be used for biomass calculations and the soil estimates described in Section 3.4.2.2. If necessary, area data used in the soils analysis can be aggregated to match the spatial scale required for lower order estimates of biomass; however, at higher tiers, stratification should take account of major soil types. Area data should be obtained using the methods described in Chapter 2. Higher tiers require greater detail but the minimum requirement for inventories to be consistent with the *IPCC Guidelines* is that the areas of forest conversion can be identified separately. This is because forest will usually have higher carbon density before conversion. This implies that at least partial knowledge of the land-use change matrix and therefore, where Chapter 2 Approaches 1 and 2 are being used, supplementary surveys may be needed to identify how much of the land being converted to grassland came from forest. As pointed out in Chapter 2, where surveys are being set up, it will often be more accurate to seek to establish directly areas under conversion, than to estimate these from the differences in total land areas under particular uses at different times.

Tier 1: At this level, one type of activity data is needed: estimates of areas converted to grassland from initial land uses (i.e., forest land, cropland, settlements, etc.) to final grassland type ($A_{conversion}$). The methodology assumes that area estimates are based on a one-year time frame. If area estimates are assessed over longer time frames, they should be converted to average annual areas to match the default carbon stock values provided. If countries do not have these data, partial samples may be extrapolated to the entire land base or historic estimates of conversions may be extrapolated over time based on the judgement of country experts. At a minimum, countries can rely on information on average deforestation rates and land-use conversions to grassland from international sources, including the FAO. Tier 1 approaches may use average annual rates of conversion and estimated areas in place of direct estimates.

Tier 2: Countries should strive to use actual area estimates for all possible transitions from initial land use to final grassland type. Complete reporting can be accomplished either through analysis of periodic remotely sensed images of land use and land cover patterns, and/or periodic ground-based sampling of land use patterns, or hybrid inventory systems.

Tier 3: Activity data used in Tier 3 calculations should be a full accounting of all land use transitions to grassland and be disaggregate to account for different conditions within a country. Disaggregation can occur along political (county, province, etc.), biome, climate, or on a combination of these parameters. In many cases countries may have information on multi-year trends in land conversion (from periodic sample-based or remotely sensed inventories of land use and land cover).

3.4.2.1.1.4 Uncertainty Assessment

Tier 1: The sources of uncertainty in this method are from the use of global or national average rates of conversion and course estimates of land areas converted to grassland. In addition, reliance on default parameters for carbon stocks in initial and final conditions contributes to relatively high degrees of uncertainty. The default values in this method have corresponding error ranges associated with them and the values are included in default tables.

Tier 2: The use of actual area estimates rather than average rates of conversion will improve the accuracy of estimates. In addition, the tracking of each land area for all possible land-use transitions will enable more transparent accounting and allow experts to identify gaps and areas where land areas are accounted for multiple times. Finally, a Tier 2 method uses at least some country-defined defaults, which will improve the accuracy of estimates, provided they better represent conditions relevant to the country. Probability density functions (i.e. providing mean and variance estimates) can be derived for all country-defined parameters. Such data can be used in advanced uncertainty analyses such as Monte Carlo simulations. Refer to Chapter 5 (Section 5.2) of this report for guidance on developing estimates of sample-based uncertainties. At a minimum, Tier 2 methods should provide error ranges in the form of percent standard deviations for each country-defined parameter.

Tier 3: Activity data from a land use and management inventory system should provide a basis to assign estimates of uncertainty to areas associated with land-use changes by use of various methods, including Monte Carlo simulations.

3.4.2.2 CHANGE IN CARBON STOCKS IN SOILS

3.4.2.2.1 METHODOLOGICAL ISSUES

Land conversion to grassland can occur from unmanaged land, including native, relatively undisturbed ecosystems (e.g. forest land, wetlands) and from intensively managed cropland. With conversion from forest land, disturbance associated with land clearing will usually result in losses of C in dead organic matter (surface litter and coarse woody debris). Any litter and coarse woody debris pools (estimated using the methods described in Section 3.2.2.2) should be assumed oxidized following land conversion and changes in soil organic matter C stocks should be estimated as described below.

The total change in carbon stocks in soils on Lands Converted to Grassland is shown in Equation 3.4.17 below:

EQUATION 3.4.17
ANNUAL CHANGE IN CARBON STOCKS IN SOILS IN LAND CONVERTED TO GRASSLAND (LG)

$$\Delta C_{LG_{Soils}} = \Delta C_{LG_{Mineral}} - \Delta C_{LG_{Organic}} - \Delta C_{LG_{Lime}}$$

Where:

$\Delta C_{LG_{Soils}}$ = annual change in stocks in soils in land converted to grassland, tonnes C yr^{-1}

$\Delta C_{LG_{Mineral}}$ = change in carbon stocks in mineral soils in land converted to grassland, tonnes C yr^{-1}

$\Delta C_{LG_{Organic}}$ = annual C emissions from organic soils converted to grassland (estimated as net annual flux), tonnes C yr^{-1}

$\Delta C_{LG_{Lime}}$ = annual C emissions from agricultural lime application on land converted to grassland, tonnes C yr^{-1}

Criteria for selecting the most suitable estimation method depend on the type of land conversion and the longevity of the conversion, and availability of suitable country-specific information to estimate reference soil C stocks and stock change and emission factors. All countries should strive for improving inventory and reporting approaches by advancing to the highest tier possible given national circumstances. It is *good practice* for countries to use a Tier 2 or Tier 3 approach if carbon emissions and removals in land converted to grassland is a key category and if the sub-category of soil organic matter is considered significant based on principles outlined in Chapter 5. Countries should use the decision tree in Figure 3.1.2 to help with the choice of method.

3.4.2.2.1.1 Choice of Method

Mineral Soils

Tier 1: The Tier 1 method is fundamentally similar as for Grasslands Remaining Grasslands (Equation 3.4.8 in Section 3.4.1.2.1.1) except pre-conversion carbon stocks are dependent of parameters for other land use. Tier 1 methods rely on default values for reference C stocks and stock change factors and relatively aggregated data on the location and rates of land-use conversion.

For Tier 1, the initial (pre-conversion) soil C stock ($SOC_{(0-T)}$) is determined from the same reference soil C stocks (SOC_{REF}) used for all land uses (Table 3.4.4), together with stock change factors (F_{LU}, F_{MG}, F_I) appropriate for the previous land use as well as for grassland use. For native unmanaged land, as well as for managed forest, soil C stocks are assumed equal to the reference values (i.e. land use, management and input factors equal 1). Current (SOC_0) soil C stocks on land converted to grassland are estimated exactly as for permanent grassland, i.e., using the reference carbon stocks (Table 3.4.4) and stock change factors (Table 3.4.5). Thus, annual rates of emissions (source) or removals (sink) are calculated as the difference in stocks (over time) divided by the inventory time period (default is 20 years).

The calculation steps for determining SOC_0 and $SOC_{(0-T)}$ and net soil C stock change per ha of land area are as follows:

Step 1: Select the reference carbon stock value (SOC_{REF}), based on climate and soil type, for each area of land being inventoried.

Step 2: Calculate the pre-conversion C stock ($SOC_{(0-T)}$) of land being converted into grassland, based on the reference carbon stock and previous land use and management, which determine land use (F_{LU}), management (F_{MG}) and input (F_I) factors. Note that where the land being converted is forest the pre-conversion stocks will be equal to the native soil carbon reference stocks.

Step 3: Calculate SOC_0 by repeating step 2 using the same reference carbon stock (SOC_{REF})), but management and input factors that represent conditions in the land converted to grassland.

Step 4: Calculate the average annual change in soil C stock for the area over the inventory period ($\Delta C_{LG_{Mineral}}$).

Example 1: For a forest on volcanic soil in a tropical moist environment: SOC_{REF} = 70 tonnes C ha^{-1}. For all forest soils default values for stock change factors (F_{LU} , F_{MG} , F_I) are all 1; thus $SOC_{(0-T)}$ is 70 tonnes C ha^{-1}. If the land is converted into pasture that is moderately degraded/overgrazed then SOC_0 = 70 tonnes C ha^{-1} ● 1 ● 0.97 ● 1 = 67.9 tonnes C ha^{-1}. Thus the average annual change in soil C stock for the area over the inventory period is calculated as (67.9 tonnes C ha^{-1} – 70 tonnes C ha^{-1}) / 20 yrs = -0.01 tonnes C ha^{-1} yr^{-1}.

Example 2: For tropical moist, volcanic soil that has been under long-term annual cropland, with intensive tillage and where crop residues are removed from the field, carbon stocks at the beginning of the inventory period $SOC_{(0-T)}$ are 70 tonnes C ha^{-1} ● 0.58 ● 1 ● 0.91 = 36.9 tonnes C ha^{-1}. Following conversion to improved (e.g. fertilised) pasture, carbon stocks (SOC_0) are 70 tonnes C ha^{-1} ● 1● 1.17 ● 1 = 81.9 tonnes C ha^{-1}. Thus the average annual change in soil C stock for the area over the inventory period is calculated as (81.9 tonnes C ha^{-1} – 36.9 tonnes C ha^{-1}) / 20 yrs =2.25 tonnes C ha^{-1} yr^{-1}.

Tier 2: The Tier 2 method for mineral soils also uses Equation 3.4.8, but involves country or region-specific reference C stocks and/or stock change factors and more disaggregated land use activity data.

Organic Soils

Tier 1 and Tier 2 approaches for organic soils that are converted from other land uses to grassland within the inventory period are treated the same as long-term grassland on organic soils, i.e., they have a constant emission factor applied to them, based on climate regime (see Equation 3.4.10 and Table 3.4.6). In Tier 2, emission factors are derived from country or region-specific data.

Mineral and Organic soils

For both mineral and organic soils, Tier 3 methods will involve more detailed and country-specific models and/or measurement-based approaches along with highly disaggregated land use and management data. Tier 3 approaches for estimating soil C changes from land-use conversions to grassland should employ models and data sets that are capable of representing transitions over time between different land use and vegetation types, including forest, savanna, grassland and cropland. The Tier 3 method needs to be integrated with estimates of biomass removal and the post-clearance treatment of plant residues (including woody debris and litter), as variation in the removal and treatment of residues (e.g. burning, site preparation) will affect C inputs to soil organic matter formation and C losses through decomposition and combustion. It is critical that models be validated with independent observations from country or region-specific field locations that are representative of the interactions of climate, soil and vegetation type on post-conversion changes in soil C stocks.

Liming

If lime is applied to grassland converted from other land uses then the methods for estimating CO_2 emissions from liming are the same as described for *Grassland Remaining Grassland*, in Section 3.4.1.2.1.1.

3.4.2.2.1.2 Choice of Emission/Removal Factors

Mineral soils

The following variables are needed when using either the Tier 1 or Tier 2 method:

Reference carbon stocks (SOC_{REF})

Tier 1: Under Tier 1, it is *good practice* to use the default reference carbon stocks (SOC_{REF}) provided in Table 3.4.4. These are updated from those provided in the *IPCC Guidelines* with the following improvements: i) estimates are statistically-derived from recent compilations of soil profiles under native vegetation, ii) 'Spodic' soils (defined as boreal and temperate zone podzols in WRB classification, Spodosols in USDA classification) are included as a separate category, iii) soils within the boreal climate region have been included.

Tier 2: For the Tier 2 method, reference soil C stocks can be determined from measurements of soils, for example, as part of a country's soil survey and mapping activities. It is important that reliable taxonomic descriptions of measured soils be used to group soils into the classes defined in Table 3.4.4 or if a finer subdivision of reference soil C stocks is used definitions of soil groupings need to be consistently and well documented. Advantages to using country-specific data for estimating reference soil C stocks include more accurate and representative values for an individual country and the ability to better estimate probability distribution functions that can be used in a formal uncertainty analysis.

Stock change factors (F_{LU}, F_{MG}, F_I)

Tier 1: Under Tier 1, it is *good practice* to use default stock change factors (F_{LU}, F_{MG}, F_I) as referred to in Table 3.4.10. These are updated from the *IPCC Guidelines*, based on a statistical analysis of published research. Definitions guiding the selection of appropriate factor values are provided in the table. Stock change factors are used in estimating both post- (SOC_0) and pre-conversion ($SOC_{(0-T)}$) stocks; values will vary according to land use and management conditions before and after the conversion. Note that where forest is converted to grassland use, the stock change factors all have the value of one, such that the pre-conversion soil carbon stocks are equal to the native vegetation reference values (SOC_{REF}).

TABLE 3.4.10
RELATIVE SOIL STOCK CHANGE FACTORS FOR LAND-USE CONVERSIONS TO GRASSLAND

Factor value type	Level	*GPG* default
Land use, Management, & Input	Managed grassland	See default values in Table 3.4.5
Land use, Management, & Input	Cropland	See default values in Table 3.3.4
Land use, Management, & Input	Forest land	Default values for F_{LU}, F_{MG}, F_I = 1

Tier 2: For the Tier 2 method, estimation of country-specific stock change factors for land-use conversion to grassland will typically be based on paired-plot comparisons representing converted and unconverted lands, where all factors other than land-use history are as similar as possible (e.g. Davidson and Ackermann, 1993). Ideally several sample locations can be found that represent a given land use at different times since conversion – referred to as a chronosequence (e.g. Neill *et al.*, 1997). There are few replicated long-term experiments of

land- use conversions and thus stock change factors and emission factors for land-use conversions will have a relatively high uncertainty. In evaluating existing studies or conducting new measurements it is critical that the plots being compared have similar pre-conversion histories and management as well as similar topographic position, soil physical properties, and be located in close proximity. As for permanent grassland, required information includes C stock (i.e. mass per unit area to a specified depth) for each land use (and time point if a chronosequence). As previously described under Grassland Remaining Grassland, in the absence of specific information upon which to select an alternative depth interval, it is *good practice* to compare stock change factors at a depth of at least 30 cm (i.e. the depth used for Tier 1 calculations). Stock changes over a deeper depth may be desirable if a sufficient number of studies are available and if statistically significant differences in stocks due to land management are demonstrated at deeper depths. However, it is critical that the reference soil carbon stocks (SOC_{Ref}) and stock change factors (F_{LU}, F_{MG}, F_I) be determined to a common depth.

Organic soils

Tier 1 and Tier 2 choice of C emission factors from organic soils recently converted to managed grassland should observe the same procedures for deriving emission factors as described earlier under the Grassland Remaining Grassland section.

3.4.2.2.1.3 Choice of Activity Data

All tiers require estimates of land areas converted to grassland. The same area estimates should be used for both biomass and soil calculations on land converted to grassland. Higher tiers require greater specificity of areas. To be consistent with *IPCC Guidelines*, at a minimum, the area of land converted to grassland should be identified separately for all tiers. This implies at least some knowledge of the land uses prior to conversion; this may require expert judgment if Approach 1 in Chapter 2 is used for land area identification.

Tier 1: One type of activity data is needed for a Tier 1 approach: separate estimates of areas converted to grassland from initial land uses (i.e., forest land, cropland), by climate region. Distribution of land use conversion by soil type (i.e. within a climate region) needs to be estimated, either by spatially explicit methods (e.g. overlays between maps of land use conversion and soils maps) or by knowledge of the distribution of major soil types within areas subject to land use conversion by country experts. The determination of the area of land converted to grassland needs to be consistent with the time period (T in Equation 3.4.8) used in the stock change calculations. If countries do not have these data, partial samples may be extrapolated to the entire land base or historic estimates of conversions may be extrapolated in time based on the judgement of country experts. Under Tier 1 calculations, international statistics such as FAO databases, *IPCC Guidelines*, and other sources, supplemented with sound assumptions by country experts, can be used to estimate the area of land converted to grassland from each initial land use. For higher tier calculations, country-specific data sources are used to estimate all transitions from initial land use to grassland.

Tier 2: Countries should strive to use actual area estimates for all possible transitions from initial land use to grassland, stratified by management condition. Full coverage of land areas can be accomplished through analysis of periodic remotely sensed images of land use and land cover patterns, through periodic ground-based sampling of land use patterns, or hybrid inventory systems. If such finer resolution country-specific data are partially available, countries are encouraged to use sound assumptions from best available knowledge to extrapolate to the entire land base. Historical estimates of conversions may be extrapolated in time based on the judgment of country experts.

Tier 3: Activity data used in Tier 3 calculations should be a full accounting of all land use transitions to grassland and be disaggregated to account for different conditions within a country. Disaggregation can occur along political (county, province, etc.), biome, climate, or on a combination of these parameters. In many cases countries may have information on multi-year trends in land conversion (from periodic sample-based or remotely sensed inventories of land use and land cover).

3.4.2.2.1.4 Uncertainty Assessment

Tier 1: The sources of uncertainty in this method are from the use of global or national average rates of conversion and course estimates of land areas converted to grassland. In addition, reliance on default parameters for carbon stocks in initial and final conditions contributes to relatively high degrees of uncertainty. The default values in this method have corresponding error ranges associated with them.

Tier 2: Actual area estimates for different land use transitions will enable more transparent accounting and allow experts to identify gaps and double counting of land areas. The Tier 2 method uses at least some country-defined defaults, which will improve the accuracy of estimates, because they better represent conditions relevant to the country. Use of country-specific values should entail sufficient sample sizes and or use of expert judgment to estimate uncertainties, which, together with uncertainty estimates on activity data derived using the advice in Chapter 2 should be used in the approaches to uncertainty analysis described in Chapter 5 of this report.

Tier 3: Activity data from a land use and management inventory system should provide a basis to assign estimates of uncertainty to areas associated with land-use changes. Combining emission and activity data and their associated uncertainties can be done using Monte-Carlo procedures to estimate means and confidence intervals for the overall inventory.

3.4.2.3 NON-CO_2 GREENHOUSE GASES

As for all grasslands, sources of CH_4 and N_2O emissions associated with grassland that have recently undergone a change in land use are likely to be:

- Emissions from vegetation fires;
- N_2O emissions from mineralisation of soil organic matter;
- N_2O from fertiliser use;
- Increase in N_2O emissions and reduction in CH_4 emissions from drainage of organic soils; and
- Reduced CH_4 sink in aerobic soils due to fertiliser use.

Emissions of methane from grazing livestock (enteric fermentation) and nitrous oxide from fertiliser use and animal waste should be calculated and reported using the methods set out in Chapter 4 (the Agriculture chapter) of the *IPCC Guidelines* and the corresponding parts (Section 4.2 and 4.7) of *GPG2000*.

Fire related emissions should be calculated using the methods set out in Section 3.2.1.4, taking account, where data are available to do so, of the fact that the fuel load will often be higher during the transition period if the previous land use was forest.

Land-use conversion may lead to mineralisation of soil organic matter nitrogen, which can increase N_2O emissions. However, depending on the previous land use, climate and soil type, land-use conversion to grassland can also increase soil organic matter (Guo and Gifford, 2002).

Fertilization of grassland will tend to reduce the soil methane uptake, and, where wetland soils have been drained nitrous oxide emissions may increase and countries reporting Agricultural emissions at Tier 3 may wish to take these effects into account as described in Section 3.4.1.3. Additional effects of the transition to grassland that may influence non-CO_2 emissions, for example soil disturbance due to ploughing, or compaction where mechanical equipment is used for clearance, but the effects are unlikely to be large, and no default methods exist to account for them. Changes in the rate of removal CH_4 from the atmosphere by aerated topsoil arising from the conversion is not addressed in this guidance, though a fuller consideration of various activities on methane oxidation may be possible in future.

3.4.3 Completeness

A complete data series for land area estimates contains, at a minimum, the area of land within country boundaries that is considered grassland during the time period covered by land use surveys or other data sources and for which greenhouse gas emission and removals are estimated in the LULUCF sector. The total area covered by the grassland inventory methodology is the sum of land remaining in grassland and land converted to grassland during the time period. This inventory methodology may not include some grassland areas where greenhouse gas emissions and removals are believed to be insignificant or constant through time, such as native grassland with moderate grazing and no significant management inputs. Therefore, it is possible for the total grassland area for which estimates are prepared to be less than the total area of grassland within country boundaries. In this case, it is *good practice* for countries to document and explain the difference in grassland area in the inventory and total grassland within their boundaries. Countries are encouraged to track through time the total area of land in grassland within country boundaries, keeping transparent records on which portions are used to estimate carbon dioxide emissions and removals. As addressed in Chapter 2, all grassland areas, including those not covered by the emissions inventory, should be part of the consistency checks to help avoid double counting or omission. When summed with area estimates for other land uses, the grassland area data series will enable a complete assessment of the land base included in a countries' LULUCF sector inventory report.

Countries that use Tier 2 or 3 methods for grassland biomass and soil pools should include more detail in their inventory on the grassland area data series. For example, countries may need to stratify the grassland area by major climate and soil types, including both the inventoried and non-inventoried grassland areas. When stratified land areas are used in the inventory, it is *good practice* for countries to use the same area classifications for both the biomass and soils pools. This will ensure consistency and transparency, allow for efficient use of land surveys and other data collection tools, and enable the explicit linking between carbon dioxide emissions and removals in biomass and soil pools.

3.4.4 Developing a Consistent Time Series

To maintain a consistent time series, it is *good practice* for countries to maintain records on the grassland areas used in inventory reports over time. These records should track the total grassland area included in the inventory, subdivided by lands remaining in grassland and land converted to grassland. Countries are encouraged to include an estimate of the total grassland area within country boundaries. To ensure that area estimates are treated consistently through time, land use definitions should be clearly defined and kept constant. If changes are made to land use definitions, it is *good practice* to keep transparent records of how the definition changed. Consistent definitions should also be used for each of the grassland types and management systems included in the inventory. In addition, to facilitate the proper accounting of carbon emissions and removals over several periods, information on historic land conversions can be utilized. Even if a country cannot rely on historic data for current inventories, improvements to current inventory practices to provide the ability to track land conversions across time will have benefits in future inventories.

Consistent estimation and reporting requires common definitions of activities, climate and soil types during the period of the inventory, which may require work to relate definitions used by national agencies involved in data collection, as set out in Chapter 2.

3.4.5 Reporting and Documentation

The categories described in Section 3.4 can be reported using the reporting tables in Annex 3A.2. The estimates under the grassland category can be compared with the reporting categories in the *IPCC Guidelines* as follows:

- Carbon dioxide emissions and removals in woody biomass in grassland remaining grassland to IPCC Reporting Category 5A, Changes in woody biomass;
- Carbon dioxide emissions and removals in soils in grassland remaining grassland to IPCC Reporting Category 5D, Changes in soil carbon; and
- Carbon dioxide emissions and removals resulting from land-use conversions to grassland to IPCC Reporting Category 5B for biomass, IPCC Reporting category 5D for soils, and IPCC Reporting Category 5E for non-CO_2 gases.

It is *good practice* to maintain and archive all information used to produce national inventory estimates. Metadata and data sources for information used to estimate country-specific factors should be documented and both mean and variance estimates provided. Actual databases and procedures used to process the data (e.g. statistical programs) to estimate country-specific factors should be archived. Activity data and definitions used to categorize or aggregate the activity data must be documented and archived. Procedures used to categorize activity data by climate and soil types (for Tier 1 and Tier 2) must be clearly documented. For Tier 3 approaches that use modelling, the model version and identification must be documented. Use of dynamic models requires that copies of all model input files as well as copies of model source code and executable programs be permanently archived.

3.4.6 Inventory Quality Assurance/Quality Control (QA/QC)

It is *good practice* to implement quality control checks and external expert review of inventory estimates and data. Specific attention should be paid to country-specific estimates of stock change and emission factors to ensure that they are based on high quality data and verifiable expert opinion.

Specific QA/QC checks across the grassland methodology include:

Grassland remaining grassland: Areas reporting of grassland biomass stock changes and grassland soil stock changes should be the same. Grassland may include areas where soil stock changes are accounted for but biomass changes are assumed to be zero (e.g. where non-woody biomass is largely absent), areas where both biomass and soil stocks are changing (e.g. areas with woody biomass encroachment), and areas where neither biomass nor soil stocks are changing (e.g. extensively managed native grassland). To increase transparency and eliminate errors, the total grassland area where any stock changes are estimated should be reported, and where biomass stock changes equal zero these should still be reported if soil carbon stock changes are reported for the same area.

Lands converted to grassland: Aggregate area totals for land converted to grassland should be the same in the biomass and soils estimations. While biomass and soil pools may be disaggregated to different levels of detail, the same general categories should be used to disaggregate the area data.

For all soil carbon stock change estimates using Tier 1 or Tier 2 methods, total areas for each climate-soil type combination must be the same for the start ($year_{(0-T)}$) and the end ($year_{(0)}$) of the inventory period (see Equation 3.4.9).

3.4.7 Estimation of Revised GPG Tier 1 Defaults for Grassland Management (see Table 3.4.5)

Grassland C stock change factors were calculated for three general types of grassland condition: degraded, nominally managed, and improved grassland. An additional input factor was included for application to improved grassland. The management improvements considered here were limited to fertilization (organic or inorganic), sowing legumes or more grass species, and irrigation. Overgrazed grassland and poorly managed (i.e., none of the management improvements were applied) tropical pastures were classified as degraded grassland. Native or introduced grasslands that were unimproved were grouped into the nominal grassland classification. Grasslands with any single type of management improvement were classified as improved grassland with medium C input rates. For improved grassland in which multiple management improvements were implemented, C input rates were considered high. The data were synthesized in linear mixed-effects models, accounting for both fixed and random effects. Fixed effects included depth, number of years since the management change, and the type of management change (e.g., reduced tillage vs. no-till). For depth, we did not aggregate data but included C stocks measured for each depth increment (e.g., 0-5 cm, 5-10 cm, and 10-30 cm) as a separate point in the dataset. Similarly, we did not aggregate data collected at different points in time from the same study. Consequently, random effects were used to account for the interdependence in times series data and the interdependence among data points representing different depths from the same study. We estimated factors for the effect of the management practice at 20 years for the top 30 cm of the soil. Variance was calculated for each of the factor values, and used to construct probability distribution functions with a normal density.

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