CHAPTER 6

GRASSLAND

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This section deals with the impacts of grassland management on soil organic C stocks, primarily by influencing C inputs to the soil, and thus soil C storage, by affecting net primary production, root turnover, and allocation of C between roots and shoots. Soil C stocks in grassland are influenced by fire, grazing intensity, fertilizer management, liming, irrigation, re-seeding with more or less productive grass species and mixed swards with N-fixing legumes (Conant *et al*., 2001; Follett *et al*., 2001; Ogle *et al*., 2004). In addition, drainage of organic soils for grassland management causes losses of soil organic C (Armentano and Menges, 1986).

General information and guidance for estimating changes in soil C stocks are provided in Chapter 2, Section 2.3.3 (including equations), and this section needs to be read before proceeding with a consideration of specific guidelines dealing with grassland soil C stocks. The total change in soil C stocks for grassland is estimated using Equation 2.24 (Chapter 2), which combines the change in soil organic C stocks for mineral soils and organic soils; and stock changes associated with soil inorganic C pools (if estimated at Tier 3). This section provides specific guidance for estimating soil organic C stocks. There is a general discussion in Section 2.3.3.1 on soil inorganic C and no additional information on this is provided here.

To account for changes in soil C stocks associated with *Grassland Remaining Grassland*, countries need to have, at a minimum, estimates of grassland areas at the beginning and end of the inventory time period. If land-use and management data are limited, aggregate data, such as FAO statistics on grassland, can be used as a starting point, along with knowledge of country experts about the approximate distribution of land management systems (e.g., degraded, nominal and improved grassland/grazing systems). Grassland management classes must be stratified according to climate regions and major soil types, which could either be based on default or country-specific classifications. This can be accomplished with overlays of land use on suitable climate and soil maps.

6.2.3.1 CHOICE OF METHOD

This section contains further elaboration on methods, updates and new guidance.

Inventories can be developed using a Tier 1, 2 or 3 approach, with each successive Tier requiring more details and resources than the previous one. It is also possible that countries will use different tiers to prepare estimates for the separate sub-categories of soil C (i.e., soil organic C stocks changes in mineral and organic soils; and stock changes associated with soil inorganic C pools). Decision trees are provided for mineral (Figure 2.4) and organic soils (Figure 2.5) in Section 2.3.3.1 (Chapter 2) to assist inventory compilers with the selection of the appropriate tier for their soil C inventory.

Mineral soils

Tier 1

For mineral soils, the estimation method is based on changes in soil organic C stocks over a finite period following changes in management that impact soil organic C storage. After a finite transition period, one can assume a steady state for this stock. Equation 2.25 (Chapter 2) is used to estimate change in soil organic C stocks in mineral soils by subtracting the C stock in the last year of an inventory time period (SOC_0) from the C stock at the beginning of the inventory time period ($SOC_{(0-T)}$) and dividing by the time dependence of the stock change factors (D). Note that area of exposed bedrock in grasslands are not included in the soil C stock calculation (assume a stock of 0). In practice, country-specific data on grassland management activity should be obtained and classified into appropriate land management systems, and then stratified by IPCC climate regions and soil types (see Chapter 3). Soil organic C stocks (SOC) are estimated for each time period in the inventory using default reference carbon stocks (SOC_{ref}) and default stock change factors (F_{LU}, F_{MG}, F_I).

Tier 2

Refining Application of Default Equations

The Tier 2 method for mineral soils also uses Equation 2.25 (Chapter 2), but the inventory approach is further developed with country-specific information to better specify stock change factors, reference C stocks, climate regions, soil types, and/or the land management classification system.

Three-Pool Steady-State C Model

The three-pool steady-state soil C model is based on estimating C inputs to soils and applying soil carbon pool specific decomposition rates that are modified given environmental conditions and management practices. This model embraces more of the heterogeneity in soils, by subdividing soil C pool into different rates of turnover, i.e., fast (Active Pool), intermediate (Slow Pool) , and long turnover times (Passive Pool).

Tier 3

Tier 3 approaches do not employ simple stock change factor *per se*, but rather use dynamic models and/or detailed soil C inventory measurements as the basis for estimating annual stock changes.

Estimates of stock changes using model-based approaches are computed from the coupled equations that estimate the net change of soil carbon. A variety of models designed to simulate soil carbon dynamics exist (for example, see reviews by McGill *et al.*, 1996; Smith *et al.*, 1997). Key criteria in selecting an appropriate model include its capability of representing all of the relevant management practices/systems for grasslands; model inputs (i.e., driving variables) are compatible with the availability of country-wide input data; and the model sufficiently represents stock changes based on comparisons with experimental data.

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

Organic soils

No Refinement. See 2013 Wetlands Supplement.

Biochar C Amendments to Mineral Soils

Tier 1

This methodology utilizes a top-down approach in which the total amount of biochar generated and added to mineral soil is used to estimate the change in soil organic C stocks. Use Equation 2.27 to estimate the change in C stock from biochar amendments in Chapter 2, Section 2.3.3.1, Volume IV.

Tier 2

Tier 2 methods use the same definitions and equations as Tier 1, but with country-specific factors. See Section 2.3.3.1, Chapter 2, Volume IV for more information.

Tier 3

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

6.2.3.2 CHOICE OF STOCK CHANGE AND EMISSION FACTOR

Mineral soils

This section contains further elaboration on methods, updates and new guidance.

Tier 1

For the Tier 1 approach, default stock change factors are provided in Table 6.2, which includes values for land use factor (F_{LU}), input factor (F_I), and management factor (F_{MG}). The method and studies that were used to derive the default stock change factors are provided in Annex 6A.1. The time dependence (D) is 20 years for default stock change factors in grasslands, and they represent the influence of management to a depth of 30cm. Default reference soil organic C stocks are found in Table 2.3 of Chapter 2. The reference stock estimates are for the top 30cm of the soil profile, to be consistent with the depth increment for default stock change factors.

Tier 2

Refining Application of Default Equations

Estimation of country-specific stock change factors is an important advancement for improving an inventory that can be developed in the Tier 2 approach. Derivation of management factor (F_{MG}) and input factor (F_I) factor are based on experimental comparisons to nominally-managed grasslands with medium input, respectively, because these classes are considered the nominal practices in the IPCC default classification scheme for management systems (see Choice of Activity Data). It is considered *good practice* to derive values for more detailed classification schemes of management, climate and soil types, if there are significant differences in the stock change factors among finer categories based on an empirical analysis. Reference C stocks can also be derived from country-specific data in a Tier 2 approach.

The depth for evaluating soil C stock changes can also be extended with the Tier 2 method. However, this will require extending the depth of the reference C stocks (SOC_{REF}) and stock change factors for all land uses (i.e., F_{LU}, F_I, and F_{MG}) to ensure consistency. Variable depths between reference stocks and stock change factors are likely to introduce biases into the inventory estimates that are computed using Equation 2.25. Additional guidance is provided in Section 2.3.3.1 (Chapter 2). For the cases of "reverse" land use changes, such as Croplands converted to Grasslands, a Tier 2 method may be a more accurate way to estimate the increase of soil C stocks to native levels. The Tier 1 method may overestimate soil C stock increases on annual basis (e.g., Villarino et al., 2014. Furthermore, it is good practice to estimate carbon stocks on a mass equivalency basis if developing country-specific factors for F_{LU},. This is because the soil weight in a certain soil depth changes with the various operation associated with land use change, for example uprooting, land leveling, and rain compaction due to the disappearance of the cover of tree canopy. In addition, cropland soils usually tend to have relatively high density than the soils in forest land and possibly grasslands or wetlands. Settlement management may also impact the soil bulk density. In such case, the comparison of the soil carbon stocks between the cropland, settlement, grassland, wetland, or forest land within the same depth is not appropriate. It is more robust to compare the carbon stock on an equivalent mass basis, with the stock change calculated on the same weight soil. This method is also recommended when the bulk density between cropland, grassland, wetland, settlement and forest land is remarkably different even if the site is within close proximity.

Three-Pool Steady-State C Model

Default parameters are provided for the three-pool steady-state C pool equations (Chapter 2, Section 2.3.3.1, Table 2), but parameters may be revised if experimental data are available to test the model. The average lignin and nitrogen contents of the C input is also required to estimate the size of the three C pools (See Table 6.3).

Tier 3

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

UPDATED - TABLE 6.2
RELATIVE STOCK CHANGE FACTORS FOR GRASSLAND MANAGEMENT

Factor	Level	Climate regime	IPCC default	Error [1,2]	Definition
Land use (FLU)	All	All	1.0	NA	All native and/or permanent grassland in a nominal condition is assigned a land-use factor of 1.
Management (FMG)	Nominally managed (non –degraded)	All	1.0	NA	Represents non-degraded and sustainably managed grassland, but without significant management improvements.
Management (FMG)	Moderately degraded grassland	Temperate /Boreal	TBD	TBD	Represents overgrazed or moderately degraded grassland, with somewhat reduced productivity (relative to the native or nominally managed grassland) and receiving no management inputs.
		Tropical	TBD	TBD	
		Tropical Montane3	TBD	TBD	
Management (FMG)	Severely degraded	All	TBD	TBD	Implies major long-term loss of productivity and vegetation cover, due to severe mechanical damage to the vegetation and/or severe soil erosion.
Management (FMG)	Improved grassland	Temperate /Boreal	TBD	TBD	Represents grassland which is sustainably managed with moderate grazing pressure and that receive at least one improvement (e.g., fertilization, species improvement, irrigation).
		Tropical	TBD	TBD	
		Tropical Montane3	TBD	TBD	
Input (applied only to improved grassland) (FI)	Medium	All	1.0	NA	Applies to improved grassland where no additional management inputs have been used.
Input (applied only to improved grassland) (FI)	High	All	TBD	TBD	Applies to improved grassland where one or more additional management inputs/improvements have been used (beyond that is required to be classified as improved grassland).

TBD – To be determined based on literature review for second order draft. These updates to may also require some changes to the descriptions of practices. See Annex 6A1 for more information.

[1] $\pm$ 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 $\pm$ 40% is used as a measure of the error. NA denotes 'Not Applicable', for factor values that constitute reference values or nominal practices for the input or management classes.

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

[3] There were not enough studies to estimate stock change factors for mineral soils in the tropical montane climate region. As an approximation, the average stock change between the temperate and tropical regions was used to approximate the stock change for the tropical montane climate.

NEW GUIDANCE - TABLE 6.3
DEFAULT VALUES FOR NITROGEN AND LIGNIN CONTENTS IN CROPS FOR THREE-POOL STEADY-STATE C MODEL

Grass	N content of above-ground residues	N content of below-ground residues	Lignin content of above-ground residues	Lignin content of below-ground residues
N-fixing forages	0.027	0.022	TBD	TBD
Non-N-fixing forages	0.015	0.012	TBD	TBD
Perennial Grasses	0.015	0.012	TBD	TBD
Grass-Clover Mixtures	0.025	0.016[c]	TBD	TBD

TBD – To be determined based on literature review for second order draft. These updates to may also require some changes to the descriptions of practices.

Organic soils

No Refinement. See 2013 Wetlands Supplement.

Biochar C Amendments to Mineral Soils

Tier 1

Default emission factors are provided in Section 2.3.3.1, Chapter 2, Volume IV.

Tier 2

Tier 2 emission factors may be further disaggregated relative to the default factors based on variation in environmental conditions, such as the climate and soil types, in addition to variation associated with the biochar production methods. See Section 2.3.3.1, Chapter 2, Volume IV for more information.

Tier 3

Tier 3 methods are country-specific and may involve empirical or process-based models to account for a broader set of impacts of biochar amendments. More information on Tier 3 methods is provided in Section 2.3.3.1, Chapter 2, Volume IV.

6.2.3.3 CHOICE OF ACTIVITY DATA

This section contains further elaboration on methods, updates and new guidance.

Mineral soils

Tier 1

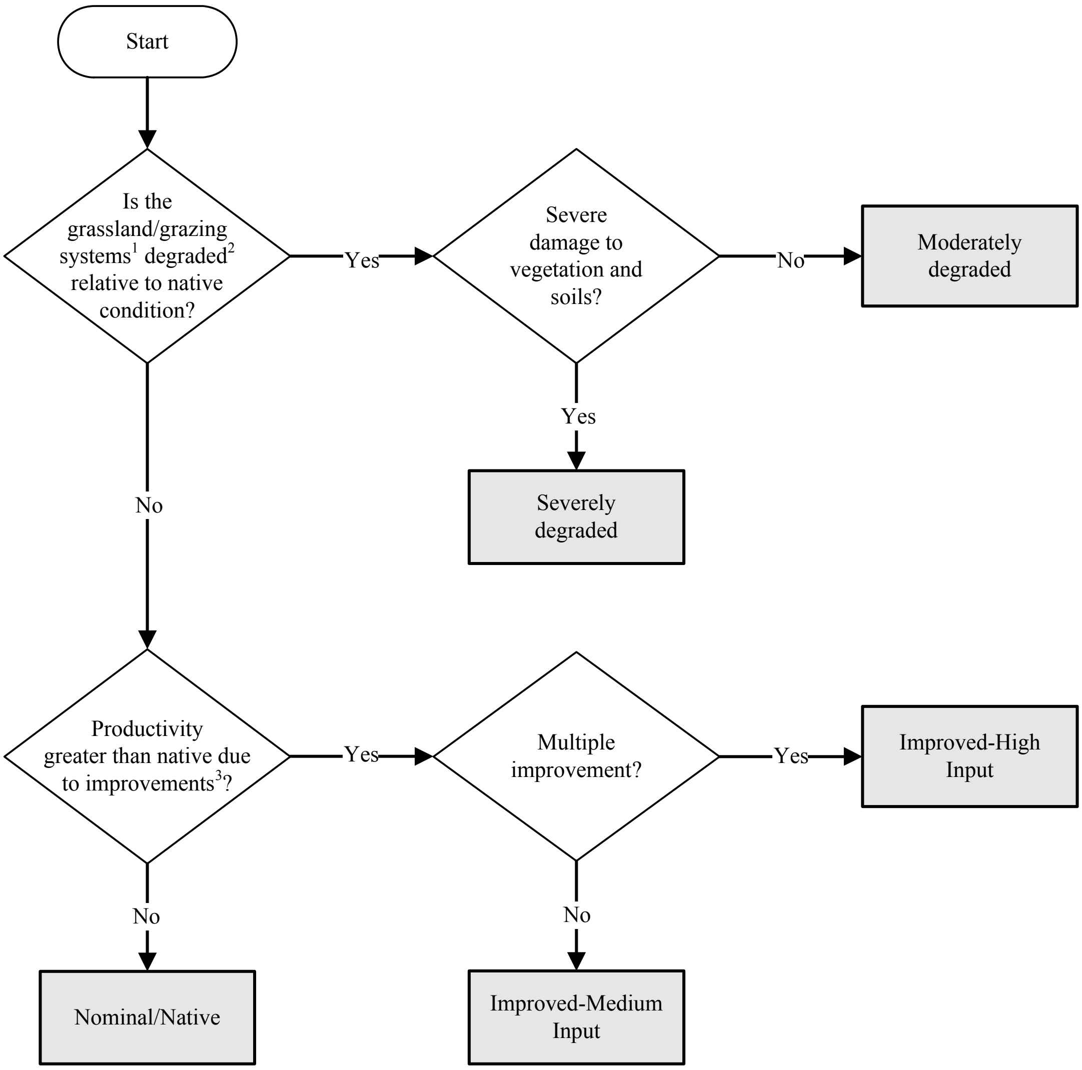
Grassland systems are classified by practices that influence soil C storage. In general, practices that are known to increase C input to the soil and thus soil organic C stocks, such as irrigation, fertilization, liming, organic amendments, more productive grass varieties, are given an improved status, with medium or high inputs depending on the level of improvement. Practices that decrease C input and soil organic C storage, such as long-term heavy grazing, are given a degraded status relative to nominally-managed seeded pastures or native grassland that are neither improved nor degraded. These practices are used to categorize management systems and then estimate the change in soil organic C stocks. A classification system is provided in Figure 6.1, which forms the basis for a Tier 1 inventory. Inventory compilers should use this classification to categorize management systems in a manner consistent with the default Tier 1 stock change factors. This classification may be further developed for Tiers 2 and 3 approaches.

The main types of land-use activity data include: i) aggregate statistics (Approach 1), ii) data with explicit information on land-use conversions but without specific geo-referencing (Approach 2), or iii) data with information on land-use conversion and explicit geo-referencing (Approach 3), such as point-based land-use and management inventories making up a statistically-based sample of a country's land area. (See Chapter 3 for discussion of Approaches). At a minimum, globally available land-use statistics, such as FAO's databases (http://www.fao.org/waicent/portal/glossary_en.asp), provide annual compilations of total land area by major land-use types. This would be an example of aggregate data (Approach 1).

Management activity data supplement the land-use data, providing information to classify management systems, such as stocking rates, fertilizer use, irrigation, etc. These data can also be aggregate statistics (Approach 1) or provide information on explicit management changes (Approach 2 or 3). It is *good practice* where possible for grassland areas to be assigned appropriate general management activities (i.e., degraded, native, or improved) or specific management activities (e.g., fertilization or grazing intensity). Soil degradation maps may be a useful source of information for stratifying grassland according to management (e.g., Conant and Paustian, 2002; McKeon *et al*., 2004). Expert knowledge is another source of information for management practices. It is *good* *practice* to elicit expert knowledge, where appropriate, using methods provided in Volume 1, Chapter 2 (Annex 2A.1, A protocol for expert elicitation).

National land-use and resource inventories based on repeated surveys of the same locations constitute activity data gathered using Approach 2 or 3, and have some advantages over aggregated pastoral and land-use statistics (Approach 1). Time series data can be more readily associated with a particular grassland management system and the soil type associated with the particular location can be determined by sampling or by referencing the location to a suitable soil map. Inventory points that are selected based on an appropriate statistical design also enable estimates of the variability associated with activity data, which can be used as part of a formal uncertainty analysis. An example of a survey using Approach 3 is the National Resource Inventory in the U.S. (Nusser and Goebel, 1997).

Figure 6.1 Classification scheme for grassland/grazing systems. In order to classify grassland management systems, the inventory compiler should start at the top and proceed through the diagram answering questions (move across branches if answer is yes) until reaching a terminal point on the diagram. The classification diagram is consistent with default stock change factors in Table 6.2.



Note:
1: Includes continuous pasture, hay lands and rangelands.
2: Degradation is equated with C input to the soil relative to native conditions, which may be caused by long-term heavy grazing or planting less productive plants relative to native vegetation.
3: Productivity refers explicitly to C input to soil (management improvements that increase input e.g., fertilization, organic amendment, irrigation, planting more productive varieties, liming, and seeding legumes).

Activity data require additional in-country information to stratify areas by climate and soil types. If such information has not already been compiled, an initial approach would be to overlay available land cover/land-use maps (of national origin or from global datasets such as IGBP_DIS) with soil maps of national origin or global sources, such as the FAO Soils Map of the World and climate data from the United Nations Environmental Program. A detailed description of the default climate and soil classification schemes is provided in Chapter 3, Annex 3A.5. The soil classification is based on soil taxonomic description and textural data, while climate regions are based on mean annual temperatures and precipitation, elevation, occurrence of frost, and potential evapotranspiration.

Tier 2

Refining Application of Default Equations

Tier 2 approaches are likely to involve a more detailed stratification of management systems (Figure 6.1) than in Tier 1, if sufficient data are available. This could include further subdivisions of grassland systems (i.e., moderately degraded, severely degraded, nominal and improved), and the input classes (medium and high input). It is *good practice* to further subdivide default classes based on empirical data that demonstrates significant differences in soil organic C storage among the proposed categories. In addition, Tier 2 approaches could involve a finer stratification of climate regions and soil types. The resolution of activity data, such as that determined by intensity of survey data, often determines the finest feasible resolutions for spatial stratification.

For Tier 2, the specific definitions of management and input factors are typically made to match available activity data on how activities affects C stocks. For example, if a country has management factors related to levels of grazing intensity, then the country will also need activity data on grazing intensity to apply the country-specific factors.

Three-Pool Steady-State C Model

This method requires soil C input data based on the amount of biomass that is converted to dead organic matter annually. This rate will vary depending on the crop production, management activity, and other environmental variables. Removals or reductions in dead organic matter are subtracted from the C input amount, which could occur with livestock grazing, grassland burning, or harvesting of grass for feed or bioenergy. Additions of C, particularly organic amendments such as manure, are included in the estimate of C input.

It is good practice to estimate C input using country-specific methods in order to produce more accurate estimates, but Equation 6.1 can be used to estimate the C input if country-specific methods are not available. This method assumes that plants are not accumulating much C from year to year, and so the balance of the NPP represents C input to soils. This method is adapted from Del Grosso et al. (2008).

EQUATION 6.1

GRASSLAND LITTER CARBON INPUT FOR THREE-POOL Steady-STATE C MODEL

$$C_{input} = 0.7933 * sqrt(precip) - 5.4196$$

Where:

C_{input} = Carbon input, which is based on Net primary production, g C m^{-2} $year^{-1}$

sqrt(precip) = square-root of the long-term mean annual precipitation

precip = long-term average annual precipitation, mm

Organic soils

No Refinement. See 2013 Wetlands Supplement.

Biochar C Amendments to Mineral Soils

Tier 1

The activity data required for the Tier 1 method includes the total quantities of biochar distributed for amendment to mineral soils. These data must be disaggregated by production type, where production type is defined as a process utilizing a specific feedstock type, and a specific conversion process (gasification, or high-, medium-, or low-temperature pyrolysis; Tables 2.4 and 2.5). In case data on the temperature of pyrolysis are unavailable, default factors for uncontrolled or unspecified pyrolysis temperatures are provided in Section 2.3.3.1 of Chapter 2, Volume IV. Changes in soil C associated with biochar amendments is considered to occur where it is incorporated into soil. However, due to the distributed nature of the land sector in which this can take place, inventory compilers may not have access to data on when or where biochar C amendments occur. Therefore, for the purposes of Tier 1 method, inventory compilers can rely on centralized records from biochar producers, importers, exporters or distributors, recording the quantity of biochar that has been provided to the land use sector for use as a soil amendment in the country. Note that exported biochar is not included in the total amount of biochar amended to soils in the country. Inventory compilers may further disaggregate amendments by land use if the data are available.

Tier 2

Tier 2 methods have the same activity data requirements as Tier 1 (quantities of biochar distributed for incorporation into mineral soils, disaggregated by production type). Additionally, activity data on the amount of biochar amendments may be disaggregated by climate zones and/or soil types if country-specific factors are disaggregated by these environmental variables. The additional climate and soil activity data may be obtained with a survey of biochar distributors and land managers.

Tier 3

The additional activity data required to support a Tier 3 method will depend on which processes are represented and environmental variables that are required as input to the model. Priming, soil GHG emissions, and plant production responses to biochar all vary with biochar type, climate, and soil type. Furthermore, soil GHG emissions and plant production responses also vary with grass type and management. Therefore, Tier 3 methods may require environmental data on climate zones, soil types, grass types and management systems (such as nitrogen fertilizer application rates), in addition to the amount of biochar amendments in each of the individual combinations of strata for the environmental variables. More detailed activity data specifying the process conditions for biochar production or the physical and chemical characteristics of the biochar may also be required (such as surface area, cation exchange capacity, pH, and ash content).

6.2.3.4 CALCULATION STEPS FOR TIER 1

This section will be updated for the second order draft based on new factors, and also will provide new guidance.

Mineral soils

The steps for estimating SOC_0 and $SOC_{(0-T)}$ and net soil C stock change from *Grassland Remaining Grassland* are as follows:

Step 1: Organize data into inventory time periods based on the years in which activity data were collected (e.g., 1990 and 1995, 1995 and 2000, etc.)

Step 2: Determine the land-use and management by mineral soil type and climate region for land at the beginning of the inventory period, which can vary depending on the time step of the activity data (0-T; e.g., 5, 10 or 20 years ago).

Step 3: Select the native reference C stock value (SOC_{REF}), based on climate and soil type from Table 2.3, for each area of land being inventoried. The reference C stocks are the same for all land-use categories to ensure that erroneous changes in the C stocks are not computed due to differences in reference stock values among sectors.

Step 4: Select the land-use factor (F_{LU}), management factor (F_{MG}) and C input levels (F_I) representing the land-use and management system present at the beginning of the inventory period. Values for F_{LU}, F_{MG} and F_I are provided in Table 6.2.

Step 5: Multiply these values by the reference soil C stock to estimate the 'initial' soil organic C stock ($SOC_{(0-T)}$) for the inventory time period.

Step 6: Estimate SOC_0 by repeating Step 1 to 4 using the same native reference C stock (SOC_{REF}), but with land-use, management and input factors that represent conditions in the last (year 0) inventory year.

Step 7: Estimate the average annual change in soil organic C stock for the area over the inventory time period ($\Delta C_{Mineral}$).

Step 8: Repeat Steps 1 to 6 if there are additional inventory time periods (e.g., 1995 to 2000, 2001 to 2005, etc.).

A case example is given below for computing a change in grassland soil organic C stocks using Equation 2.25 (Chapter 2), default stock change factors and reference C stocks.

Updated Example: The following example shows calculations for aggregate areas of grassland soil carbon stock change to a 30 cm depth. In a tropical moist climate on Ultisol soils, there are 1Mha of permanent grassland. The native reference carbon stock (SOC_{Ref}) for the climate/soil type is 47 tonnes C ha^{-1}. At the beginning of the inventory time period (1990 in this example) the distribution of grassland systems was 500,000 ha of unmanaged native grassland; 400,000 ha of unimproved, moderately degraded grazing land; and 100,000 ha of heavily degraded grassland. Thus, initial soil carbon stocks for the area were: 500,000 ha ● (47 tonnes C ha^{-1} ● 1 ● 1 ● 1) + 400,000 ha ● (47 tonnes C ha^{-1} ● 1 ● 0.97 ● 1) + 100,000 ● (47 tonnes C ha^{-1} ● 1 ● 0.7 ● 1) = 45,026,000 tonnes C. In the last year of inventory time period (2010 in this example), there are: 300,000 ha of unmanaged native grassland; 300,000 ha of unimproved, moderately degraded grazing land; 200,000 ha of heavily degraded grassland; 100,000 ha of improved pasture receiving fertilizer; and 100,000 of highly improved pasture receiving fertiliser together with irrigation. Thus, total soil carbon stocks in the inventory year are: 300,000 ha • (47 tonnes C ha^{-1} ● 1 ● 1 ● 1) + 300,000 ha ● (47 tonnes C ha^{-1} ● 1 ● 0.97 ● 1) + 200,000 ● (47 tonnes C ha^{-1} 1 ● 0.7 ● 1) + 100,000 ● (47 tonnes C ha^{-1} 1 ● 1.17 ● 1) + 100,000 ● (47 tonnes C ha^{-1} ● 1 ● 1.17 ● 1.11) = 45,959,890 tonnes C. The average annual stock change over the period for the entire area is: 45,959,890 – 45,026,000 = 933,890 tonnes/20 yr = 46,694.5 tonnes per year soil C stock increase. (Note: 20 years is the time dependence of the stock change factor, i.e., factor represents annual rate of change over 20 years).

Organic soils

No Refinement. See 2013 Wetlands Supplement.

Biochar C Amendments to Mineral Soils

Will be provided in second order draft after factors are derived.

6.2.3.5 UNCERTAINTY ASSESSMENT

No Refinement

6.2.4 Non-CO_2 greenhouse gas emissions from biomass burning

No Refinement

6.3 LAND CONVERTED TO GRASSLAND

No Refinement in the Introduction

6.3.1 Biomass

No Refinement in First Order Draft (Lead Authors are reviewing the literature with objective of updating factors in the Second Order Draft)

6.3.2 Dead organic matter

No Refinement

6.3.3 Soil carbon

No Refinement in the Introduction

Grassland management involving drainage will generate emissions from organic soil, regardless of the previous land use. However, the impact on mineral soils is less clear-cut for lands converted to Grassland. Literature on one of the dominant conversion types globally (from Forest Land to Grassland in the tropics) provides evidence for net gains as well as net losses in soil C, and it is known that the specific management of the grassland after conversion is critical (e.g., Veldkamp, 2001).

General information and guidance for estimating changes in soil C stocks are provided in Chapter 2, Section 2.3.3 (including equations), and this section needs to be read before proceeding with a consideration of specific guidelines dealing with grassland soil C stocks. The total change in soil C stocks for *Land Converted to Grassland* is estimated using Equation 2.24 for the change in soil organic C stocks for mineral soils and organic soils; and stock changes associated with soil inorganic C pools (if estimated at Tier 3). This section provides specific guidance for estimating soil organic C stock changes. There is a general discussion in Section 2.3.3 in Chapter 2 on soil inorganic C and no additional information is provided here.

To account for changes in soil C stocks associated with *Land Converted to Grassland*, countries need to have, at a minimum, estimates of the areas of *Land Converted to Grassland* during the inventory time period, stratified by climate region and soil type. If land-use and management data are limited, aggregate data, such as FAO statistics, can be used as a starting point, along with country expert knowledge of the approximate distribution of land-use types being converted and the management of those lands. If the previous land uses and conversions are unknown, SOC stocks changes can still be estimated using the methods provided in *Grassland Remaining Grassland*, but the land base area will likely be different for grasslands in the current year relative to the initial year in the inventory. It is critical, however, that the total land area accounted across all land-use sectors be equal over the inventory time period (e.g., if 3 Million ha of Forest Land and Cropland are converted to Grassland during the inventory time period, then Grassland will have an additional 3 Million ha in the last year of the inventory, while Cropland and Forest Land will have a corresponding loss of 3 Million ha in the last year). *Land Converted to Grassland* is stratified according to climate regions, management, and major soil types, which could either be based on default or country-specific classifications. This can be accomplished with overlays of suitable climate and soil maps, coupled with spatially-explicit data on the location of land conversions.

6.3.3.1 CHOICE OF METHOD

This section contains elaboration on methods and new guidance.

Inventories can be developed using a Tier 1, 2 or 3 method, with each successive Tier requiring more details and resources than the previous one. It is possible that countries will use different tiers to prepare estimates for the separate sub-categories of soil C (i.e., soil organic C stocks changes in mineral soils and organic soils; and stock changes associated with soil inorganic C pools). Decision trees are provided for mineral soils (Figure 2.4) and organic soils (Figure 2.5) in Section 2.3.3.1 Chapter 2 to assist inventory compilers with selection of the appropriate tier for their soil C inventory.

Mineral soils

Tier 1

Using Equation 2.25 (Chapter 2), the change in soil organic C stocks can be estimated for mineral soils accounting for the impact of land-use conversion to Grassland. The method is fundamentally the same as the one used for *Grassland Remaining Grassland*, except pre-conversion C stocks are dependent on stock change factors for another land use. Specifically, the initial (pre-conversion) soil organic C stock ($SOC_{(0-T)}$) and stock in the last year of inventory time period (SOC_0) are computed from the default reference soil organic C stocks (SOC_{REF}) stock change factors (F_{LU}, F_{MG}, F_I). Note that area of exposed bedrock in Forest Land or the previous land use are not included in the soil C stock calculation (assume a stock of 0). Annual rates of stock changes are estimated based on the difference in stocks (over time) for the first and last year in the inventory time period divided by the time dependence of the stock change factors (D, default is 20 years).

Tier 2

Refining Application of Default Equations

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

Three-Pool Steady-State C Model

The three-pool steady-state soil C model is based on estimating C inputs to soils and applying soil carbon pool specific decomposition rates that are modified by given environmental conditions and management practices. This model embraces more of the heterogeneity in soils, by subdividing soil C pool into different rates of turnover, i.e., fast (Active Pool), intermediate (Slow Pool) , and long turnover times (Passive Pool).

Tier 3

Tier 3 methods will involve more detailed and country-specific models and/or measurement-based approaches along with highly disaggregated land-use and management data. It is *good practice* that Tier 3 approaches, estimating soil C change from land-use conversions to Grassland, employ models, data sets and/or monitoring networks that are capable of representing transitions over time from other land uses, including Forest Land, Cropland, and possibly Settlements or other lands. If possible, it is also recommended for Tier 3 methods to be integrated with estimates of biomass removal and the post-clearance treatment of plant residues (including woody debris and litter), as variation in the removal and treatment of residues (e.g., burning, site preparation) will affect C inputs to soil organic matter formation and C losses through decomposition and combustion. It is important that models be evaluated with independent observations from country-specific or region-specific field locations that are representative of the interactions of climate, soil, and grassland management on post-conversion change in soil C stocks.

Organic soils

No Refinement. See 2013 Wetlands Supplement.

Biochar C Amendments to Mineral Soils

Tier 1

This methodology utilizes a top-down approach in which the total amount of biochar generated and added to mineral soil is used to estimate the change in soil organic C stocks. Use Equation 2.27 to estimate the change in C stock from biochar amendments in Chapter 2, Section 2.3.3.1, Volume IV.

Tier 2

Tier 2 methods use the same definitions and equations as Tier 1, but with country-specific factors. See Section 2.3.3.1, Chapter 2, Volume IV for more information.

Tier 3

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

6.3.3.2 CHOICE OF STOCK CHANGE AND EMISSION FACTORS

This section contains elaboration on methods and new guidance.

Mineral soils

Tier 1

For unmanaged land, as well as for managed Forest Land, Settlements and nominally managed Grassland with low disturbance regimes, soil C stocks are assumed equal to the reference values (i.e., land use, disturbance (forests only), management and input factors equal 1), while it will be necessary to apply the appropriate stock change factors to represent other systems such as improved and degraded grasslands, as well as all cropland systems. Default reference C stocks are given in Chapter 2, Table 2.3. See the *Choice of Stock Change and Emission Factors* in the appropriate land-use chapter for default stock change factors (Forest Land in Section 4.2.3.2, Cropland in 5.2.3.2, Grassland in 6.2.3.2, Settlements in 8.2.3.2, and Other land in 9.3.3.2).

Note that it is *good practice* to use the management factor (F_{LU}) for set-asides (Table 5.5) if dealing with cultivated annual Cropland converted into Grassland (i.e., until the land is re-classified as *Grassland Remaining Grassland*) because recently converted annual cropland systems will typically gain C at a rate similar to set-aside lands. Moreover, the Tier 1 set-aside factors were derived from empirical data to explicitly represent the expected gain during the first 20 years for lands removed from cultivation. If countries decide to assume a faster increase in C that raises levels to native conditions within 20 years, a justification should be provided in the documentation.

Tier 2

Refining Application of Default Equations

Estimation of country-specific stock change factors is probably the most important development for the Tier 2 approach. Differences in soil organic C stocks among land uses are computed relative to a reference condition, using land-use factor (F_{LU}). Input factor (F_I) and management factor (F_{MG}) are then used to further refine the C stocks of the new grassland system. Additional guidance on how to derive these stock change factors is given in *Grassland Remaining Grassland*, Section 6.2.3.2 as well as other general guidance in Section 2.3.3.1 (Chapter 2). See the appropriate section for specific information regarding the derivation of stock change factors for other land-use sectors (Forest Land in Section 4.2.3.2, Cropland in 5.2.3.2, Wetlands in 7.2.3.3, Settlements in 8.2.3.2, and Other Land in 9.3.3.2).

Reference C stocks can also be derived from country-specific data in a Tier 2 approach. However, reference values must be consistent across land-use sectors (i.e., Forest Land, Cropland, Grassland, Settlements, Other land), which requires coordination among the various teams conducting soil C inventories for AFOLU.

The depth for evaluating soil C stock changes can also be extended with the Tier 2 method. This will require extending the depth of the reference C stocks (SOC_{REF}) and stock change factors for all land uses (i.e., F_{LU}, F_I, and F_{MG}) to ensure consistency. Variable depths between reference stocks and stock change factors are likely to introduce biases into the inventory estimates that are computed using Equation 2.25.

For the case of land use change to a system that is increasing in C, such as Croplands converted to Grasslands, a Tier 2 method may be a more accurate way to estimate the increase of soil C stocks to native levels. The Tier 1 method may overestimate soil C stock increases on an annual basis (e.g., Villarino et al., 2014).

Furthermore, inventories may be improved by estimating carbon stocks on a mass equivalency basis when deriving country-specific factors for F_{LU},. This is because the soil weight in a certain soil depth changes with the various operations associated with land use change, for example uprooting, land levelling, and rain compaction due to the disappearance of the cover of tree canopy. In addition, cropland soils usually tend to have relatively higher density than the soils in forest land and possibly grasslands or wetlands. Settlement management may also impact the soil bulk density. In such case, the comparison of the soil carbon stocks between the cropland, settlement, grassland, wetland, or forest land within the same depth is not appropriate. It is more robust to compare the carbon stock on an equivalent mass basis, with the stock change calculated on the same weight soil. This method is also recommended when the bulk density between cropland, grassland, wetland, settlement and forest land is remarkably different even if the site is within close proximity. However, it is important to realize that all measurements and associated stock change factors across all land uses must be on an equivalent mass basis if this method is applied. This will be challenging and possibly not even practical unless done comprehensively for all land uses.

Three-Pool Steady-State C Model

Default parameters are provided for the three-pool steady-state C pool equations (Chapter 2, Section 2.3.3.1, Table 2), but parameters may be revised if experimental data are available to test the model. Lignin and nitrogen contents are also needed for the C input data (See Section 5.2.3.2 for crop data, and Section 6.2.3.2 for grass data).

Tier 3

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

Organic soils

No Refinement. See 2013 Wetlands Supplement.

Biochar C Amendments to Mineral Soils

Tier 1

Default emission factors are provided in Chapter 2, Section 2.3.3.1, Volume IV.

Tier 2

Tier 2 emission factors may be further disaggregated relative to the default factors based on variation in environmental conditions, such as the climate and soil types, in addition to variation associated with the biochar production methods. See Section 2.3.3.1, Chapter 2, Volume IV for more information.

Tier 3

Tier 3 methods are country-specific and may involve empirical or process-based models to account for a broader set of impacts of biochar amendments. More information on Tier 3 methods is provided in Section 2.3.3.1, Chapter 2, Volume IV.

6.3.3.3 CHOICE OF ACTIVITY DATA

This section contains elaboration on methods and new guidance.

Mineral soils

Tier 1 and Tier 2 – Refinement of Default Equations

For purposes of estimating soil carbon stock change, area estimates of *Land Converted to Grassland* should be stratified according to major climate regions and soil types. This can be based on overlays with suitable climate and soil maps and spatially-explicit data of the location of land conversions. A detailed description of the default climate and soil classification schemes is provided in Chapter 3. See corresponding sections dealing with each land-use category for sector-specific information regarding the representation of land-use/management activity data (Forest Land in Section 4.2.3.3, Cropland in 5.2.3.3, Grassland in 6.2.3.3, Wetlands in 7.2.3.3, Settlements in 8.2.3.3, and Other land in 9.3.3.3).

An important issue in evaluating the impact of *Land Converted to Grassland* on soil organic C stocks is the type of land-use and management activity data. Activity data gathered using Approach 2 or 3 (see Chapter 3 for discussion about Approaches) provide the underlying basis for determining the previous land use for land categorized as *Land Converted to Grassland*. In contrast, aggregate data (Approach 1) only provide the total amount of area in each land use at the beginning and end of the inventory period (e.g., 1985 and 2005). Thus, unless supplementary information can be gathered to infer the pattern of land-use change (as suggested in Chapter 3) Approach 1 data are insufficient to determine specific transitions between land-use categories. Therefore, the previous land use before conversion to grasslands will be unknown. Fortunately, this is not problematic using a Tier 1 or 2 method because the calculation is not dynamic and assumes a step change from one equilibrium state to another. Therefore, with aggregated data (Approach 1), changes in soil organic C stocks may be computed separately for each land-use category and then combined to obtain the total stock change for all land uses combined. The soil C stock change estimate will be equivalent to results using Approach 2 (or 3) activity data (i.e., a full land-use change matrix), but evaluation of C stock trends will only be relevant after combining the stock estimates for all land uses (i.e., stocks will increase or decrease with the changes in land area within individual land uses, but this will offset by gains or losses in other land uses, and thus not an actual stock change in the soil pool for a country. Thus, with aggregate (Approach 1 data) it is important to achieve coordination among all land sector to ensure the total land base is remaining constant over time, given that some land area will be lost and gained within individual sectors during each inventory year due to land-use change.

Note that it will not be possible to determine the amount of cultivated annual croplands converted to grasslands with aggregated activity data (Approach 1). Therefore, grassland stock change factors will be applied, without consideration for the slower rate of C gain in recently converted annual croplands, which may lead to an over-estimation of C gain over a 20-year time period, particularly using the Tier 1 method (see Choice of Stock Change and Emission Factors for additional discussion). This caveat should be acknowledged in the reporting documentation, and it is *good practice* for future inventories to gather additional information needed to estimate the area of grassland recently converted from croplands, particularly if soil C is a key source category.

Tier 2 – Three-Pool Steady-State C Model

This method requires soil C input data based on the amount of biomass that is converted to dead organic matter annually. This rate will vary depending on plant production, management activity, natural disturbances, and other environmental variables. Removals or reductions in dead organic matter are subtracted from the C input, which could occur with practices such as collection of coarse woody debris or crop residues, burning of grasslands, field burning of agricultural residues, livestock grazing, and other practices. Disturbance events, such as pest outbreaks, may increase the dead organic matter, and therefore the C input to soils. It is good practice to use country-specific methods for estimating C input to soils, but defaults approaches are provided for cropland (Section 5.2.3.3) and grassland (Section 6.2.3.3). Tillage management data are also required for croplands (proportion of full tillage, reduced tillage and no-till), and irrigation data for any lands that are provided supplement water.

Additional ancillary data for this method include monthly weather data and soil texture (i.e., sand content), which are available from global weather and soils datasets if country-specific data are not available, such as the CRU climate dataset (https://crudata.uea.ac.uk/cru/data/hrg/), and the Harmonized World Soil Database (http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/), respectively.

Tier 3

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

Organic soils

No Refinement. See 2013 Wetlands Supplement.

Biochar C Amendments to Mineral Soils

Tier 1

The activity data required for the Tier 1 method includes the total quantities of biochar distributed for amendment to mineral soils. These data must be disaggregated by production type, where production type is defined as a process utilizing a specific feedstock type, and a specific conversion process (gasification, or high-, medium-, or low-temperature pyrolysis; Tables 2.4 and 2.5). In case data on the temperature of pyrolysis are unavailable, default factors for uncontrolled or unspecified pyrolysis temperatures are provided in Section 2.3.3.1 of Chapter 2, Volume IV. Changes in soil C associated with biochar amendments is considered to occur where it is incorporated into soil. However, due to the distributed nature of the land sector in which this can take place, inventory compilers may not have access to data on when or where biochar C amendments occur. Therefore, for the purposes of Tier 1 method, inventory compilers can rely on centralized records from biochar producers, importers, exporters or distributors, recording the quantity of biochar that has been provided to the land use sector for use as a soil amendment in the country. Note that exported biochar is not included in the total amount of biochar amended to soils in the country. Inventory compilers may further disaggregate amendments by land use if the data are available.

Tier 2

Tier 2 methods have the same activity data requirements as Tier 1 (quantities of biochar distributed for incorporation into mineral soils, disaggregated by production type). Additionally, activity data on the amount of biochar amendments may be disaggregated by climate zones and/or soil types if country-specific factors are disaggregated by these environmental variables. The additional climate and soil activity data may be obtained with a survey of biochar distributors and land managers.

Tier 3

The additional activity data required to support a Tier 3 method will depend on which processes are represented and environmental variables that are required as input to the model. Priming, soil GHG emissions, and plant production responses to biochar all vary with biochar type, climate, and soil type. Furthermore, soil GHG emissions and plant production responses also vary with grass type and management. Therefore, Tier 3 methods may require environmental data on climate zones, soil types, grass types and management systems (such as nitrogen fertilizer application rates), in addition to the amount of biochar amendments in each of the individual combinations of strata for the environmental variables. More detailed activity data specifying the process conditions for biochar production or the physical and chemical characteristics of the biochar may also be required (such as surface area, cation exchange capacity, pH, and ash content).

6.3.3.4 CALCULATION STEPS FOR TIER 1

This section will be updated for the second order draft based on new factors, and also will provide new guidance.

Mineral soils

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

Step 1: Organize data into inventory time periods based on the years in which activity data were collected (e.g., 1990 and 1995, 1995 and 2000, etc.)

Step 2: Determine the land-use and management by mineral soil types and climate regions for land at the beginning of the inventory period, which can vary depending on the time step of the activity data (0-T; e.g., 5, 10 or 20 years ago).

Step 3: Select the native reference C stock value (SOC_{REF}), based on climate and soil type from Table 2.3, for each area of land being inventoried. The reference C stocks are the same for all land-use categories to ensure that erroneous changes in the C stocks are not computed due to differences in reference stock values among sectors.

Step 4: Select the land-use factor (F_{LU}), management factor (F_{MG}) and C input levels (F_I) representing the land-use and management system present before conversion to grassland. Values for F_{LU}, F_{MG} and F_I are given in the respective section for the land-use sector (Cropland in Chapter 5, Grassland in Chapter 6, Settlements in Chapter 8, and Other land in Chapter 9).

Step 5: Multiply these values by the reference soil C stock to estimate 'initial' soil organic C stock ($SOC_{(0-T)}$) for the inventory time period.

Step 6: Estimate SOC_0 by repeating Steps 1 to 4 using the same native reference C stock (SOC_{REF}), but with land-use, management and input factors that represent conditions (after conversion to grassland) in the last (year 0) inventory year.

Step 7: Estimate the average annual change in soil organic C stock for the area over the inventory time period ($\Delta C_{Mineral}$)

Step 8: Repeat Steps 1 to 6 if there are additional inventory time periods (e.g., 1995 to 2000, 2001 to 2005, etc.).

A numerical example is given below for land conversion of cropland.

Using Equation 2.25 (Chapter 2), default stock change factors and reference C stocks, a case example is given below for estimating changes in soil organic C stocks associated with *Land Converted to Grassland*.

Updated Example: For tropical moist, volcanic soil that has been under long-term annual Cropland, with intensive tillage and where crop residues are removed from the field, carbon stocks at the beginning of the inventory time period (1990 in this example), $SOC_{(0-T)}$ are 70 tonnes C ha^{-1} ● 0.48 ● 1 ● 0.92 = 30.9 tonnes C ha^{-1}. Following conversion to improved (e.g., fertilised) pasture, carbon stocks in the last year of inventory (2010 in this example) (SOC_0) are 70 tonnes C ha^{-1} ● 0.82 ● 1.17 ● 1 = 67.2 tonnes C ha^{-1}. Thus the average annual change in soil C stock for the area over the inventory time period is calculated as (67.2 tonnes C ha^{-1} – 36.9 tonnes C ha^{-1}) / 20 yrs =1.5 tonnes C ha^{-1} yr^{-1}. Note that the set-aside factor (0.82) from croplands was used for the F_{LU} because grasslands do not gain the full complement of the native C stock in 20 years. After the first 20 years, a factor of 1 would be used for F_{LU} in the Tier 1 approach.

Organic soils

No Refinement. See 2013 Wetlands Supplement.

Biochar C Amendments to Mineral Soils

Will be provided in second order draft after factors are derived.

6.3.3.5 6.3.3.5 UNCERTAINTY ASSESSMENT

Uncertainty analyses for *Land Converted to Grassland* are fundamentally the same as *Grassland Remaining Grassland*. Three broad sources of uncertainty exist: 1) uncertainties in land-use and management activity and environmental data; 2) uncertainties in reference soil C stocks if using a Tier 1 or 2 approach (mineral soils only); and 3) uncertainties in the stock change/emission factors for Tier 1 or 2 approaches, model structure/parameter error for Tier 3 model-based approaches, or measurement error/sampling variability associated with a Tier 3 measurement-based inventories. See the uncertainty section in *Grassland Remaining Grassland* for additional discussion (Section 6.2.3.5).

6.3.4 Non-CO_2 greenhouse gas emissions from biomass burning

No Refinement

6.4 COMPLETENESS, TIME SERIES, QA/QC, AND REPORTING

No Refinement

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Annex 6A.1 Estimation of default stock change factors for mineral soil C emissions/removals for Grassland

Default stock change factors will be updated in Table 6.2 based on an analysis of a global dataset of experimental results for tillage, input, set-aside, and land use to a 30cm depth. Management and input factors represent the effect on C stocks after 20 years following the management change.

Semi-parametric mixed effect models are being derived to estimate the new factors. Variables included depth, number of years since the management change, and the type of management change (e.g., non-degraded, moderately degraded and severely degraded). For depth, data are not aggregated to a standardized set of depths but rather each of the original depth increments are used in the analysis (e.g., 0-5 cm, 5-10 cm, and 10-30 cm) as separate observations of C stock changes. Similarly, time series data are not aggregated, even though those measurements are taken from the same plots. Consequently, random effects are used to account for the dependencies in times series data and among data points representing different depths from the same study.

Special consideration is given to representing depth increments in order to avoid aggregating data across increments in the original dataset. Consider a field in which the soil has a characteristic $Y(s)$, such as soil organic C, that changes in value with depth, from $s = 0$ decimeters (surface) to $s = 8$ dm. For simplicity, suppose this field is perfectly uniform (no spatial variation) and we have no measurement error, so that a single soil core will be sufficient to describe the soil. We extract a 0-8dm core and measure the average value of Y in the core (averaging over decimeters), to obtain the true average value over $[0,8]$ as $\mu_{[0,8]} = 1/3$. Now suppose instead that we measured the core in increments: 0-1dm, 1-3dm, and 3-8dm. Again, we measure the average value of Y in each core increment, obtaining

$\mu_{[0,1]} = 0.8802083$, $\mu_{[1,3]} = 0.5677083$, and $\mu_{[3,8]} = 0.1302083$.

The simple average of these three values is 0.5260417, much larger than the true value of $1/3$. The simple average is wrong. Instead, we should take a weighted average that reflects the differently-sized increments:

$$\frac{(1-0)\mu_{[0,1]} + (3-1)\mu_{[1,3]} + (8-3)\mu_{[3,8]}}{8} = \frac{2.6666667}{8} = \frac{1}{3}.$$

Next, suppose that instead of one soil core, we took two sets of soil cores. The first core uses 0-1dm, 1-3dm, and 3-8dm as before, but the second uses only 0-4dm and 4-8dm. Using the same weighting scheme as before, we can compute weighted averages within each core. Then using the fact that both cores have the same amount of information about 0-8dm, we would take a simple average of the two weighted averages:

$$\frac{(1-0)\mu_{[0,1]} + (3-1)\mu_{[1,3]} + (8-3)\mu_{[3,8]}}{(2)(8)} + \frac{(4-0)\mu_{[0,4]} + (8-4)\mu_{[4,8]}}{(2)(8)} = \frac{2.6666667}{16} + \frac{2.6666667}{16} = \frac{1}{3}.$$

Now suppose we wanted to use those data to estimate the average characteristic in the increment 2-4dm, an increment which is not used in either core. Instead, it is partially contained in the first core's increments [1, 3] and [3, 8], and fully contained in the second core's increment [0,4]. We might try using a fraction of each increment, one-half of [1, 3], one-fifth of [3, 8], and one-half of [0, 4]:

$$\frac{(1/2)(3-1)\mu_{[1,3]} + (1/5)(8-3)\mu_{[3,8]}}{(2)(2)} + \frac{(1/2)(4-0)\mu_{[0,4]}}{(2)(2)} = \frac{0.6979167}{4} + \frac{1.1666667}{4} = 0.4661458.$$

In fact, the correct value is $\mu_{[2,4]} = 0.3958333$, so we are way off target with this ad hoc approach.

Suppose we took a different approach, by trying to reconstruct the true $Y(s)$. These points are highly suggestive of a quadratic relationship. In fact, unknown to the scientist, the true relationship is exactly quadratic,

$$Y(s) = \frac{1}{64}(s-8)^2 = 1 - 0.25s + 0.015625s^2.$$

We fit the following quadratic model to the data using the midpoints x of the increments.

$$\beta_0 + \beta_1 x + \beta_2 x^2$$

The problem is using the midpoints of the increment ranges and ignoring the fact that these are increment data, not point data. To do this properly, we need to create a custom set of covariates, which are functions of the increment endpoints. These functions come from integrating the underlying quadratic function over the increments. We have centered at the maximum depth, 8dm, for convenience. This means that the true quadratic relationship is

$$\alpha_0 + \alpha_1(s-8) + \alpha_2(s-8)^2 = 0 + 0(s-8) + \frac{1}{64}(s-8)^2.$$

Because we now have the quadratic model exactly right, we can go back to the problem of estimating $\mu_{[2,4]}$ and we are able to calculate exactly the right answer, 0.3958333. More generally, when combining increment data for statistical analysis, we have to take into account the increment nature of the data or we will have statistically invalid inferences, particularly for regression relationships. In general, we will not know the true relationship and will need to model it flexibly. Any model (like the quadratic in our example) needs to be converted into a set of custom covariates by integrating, just as we did here.

Using this customized approach, we are in the process of estimating management and input factors to a 30 cm depth over a 20 year time period. Variance will be calculated for each of the factor values, and can be used with simple error propagation methods or to construct probability distribution functions with a normal density.

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