CHAPTER 6

GRASSLAND

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No refinement.

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No refinement.

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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 Food and Agriculture Organization (FAO) statistics on grassland, can be used as a starting point, along with knowledge of country experts about the approximate distribution of land management systems (e.g., degraded, nominal and improved grassland/grazing systems). Grassland management classes must be stratified according to climate regions and major soil types, which could either be based on default or country-specific classifications. This can be accomplished with overlays of land use on suitable climate and soil maps.

6.2.3.1 CHOICE OF METHOD

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

Mineral soils

Tier 1

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

Tier 2

The Tier 2 method for mineral soils also uses Equation 2.25 (Chapter 2), but the inventory approach is further developed with country-specific information to better specify stock change factors, reference C stocks, climate regions, soil types, and/or the land management classification system. For biochar C amendments, Tier 2 methods utilize a top-down approach in which the total amount of biochar generated and added to mineral soil is used to estimate the change in soil organic C stocks with country-specific factors. See Section 2.3.3.1, Chapter 2, Volume IV for more information.

Tier 3

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

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

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

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

Organic soils

No refinement.

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

6.2.3.2 CHOICE OF STOCK CHANGE AND EMISSION FACTOR

Mineral soils

Tier 1

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

TABLE 6.2 (UPDATED)
RELATIVE STOCK CHANGE FACTORS FOR GRASSLAND MANAGEMENT

Factor	Level	Climate regime	IPCC default	Error [1,2]	Definition
Land use (F_{LU})	All	All	1.0	NA	All native and/or permanent grassland in a nominal condition is assigned a land-use factor of 1.
Management (F_{MG})	Nominally managed (non – degraded)	All	1.0	NA	Represents low or medium intensity grazing regimes, in addition to periodic cutting and removal of above-ground vegetation, without significant management improvements.
Management (F_{MG})	High Intensity Grazing[3]	All	0.90	±8%	Represents high intensity grazing systems (or cutting and removal of vegetation) with shifts in vegetation composition and possibly productivity but is not severely degraded[4].
Management (F_{MG})	Severely degraded	All	0.7	±40%	Implies major long-term loss of productivity and vegetation cover, due to severe mechanical damage to the vegetation and/or severe soil erosion.
Management (F_{MG})	Improved grassland	Temperate/ Boreal	1.14	±11%	Represents grassland which is sustainably managed with light to moderate grazing pressure (or cutting and removal of vegetation) and that receive at least one improvement (e.g., fertilization, species improvement, irrigation).
		Tropical	1.17	±9%	
		Tropical Montane[5]	1.16	±40%	
Input (applied only to improved grassland) (F_I)	Medium	All	1.0	NA	Applies to improved grassland where no additional management inputs have been used.
Input (applied only to improved grassland) (F_I)	High	All	1.11	±7%	Applies to improved grassland where one or more additional management inputs/improvements have been used (beyond that required to be classified as improved grassland).

Management factors were derived using methods and studies provided in Annex 6A1. The basis for the other factors is described in the *2006 IPCC Guidelines*.

Source:

[3] The bibliography for the following references used for management factor can be found in Annex 6A.1:

Cao *et al.*, 2013; Ding *et al.*, 2014; Du *et al.*, 2017; Frank *et al.*, 1995; Franzluebbers and Stuedemann, 2009; Gao *et al.*, 2018; Gao *et al.*, 2007; Gillard, 1969; Han *et al.*, 2008; He *et al.*, 2008; Ingram *et al.*, 2008; Kioko *et al.*, 2012; Kölbl *et al.*, 2011; Li *et al.*, 2008; Liu *et al.*, 2012; Manley *et al.*, 1995; Martinsen *et al.*, 2011; Potter *et al.*, 2001; Qi *et al.*, 2010; Rutherford and Powrie, 2011; Schulz *et al.*, 2016; Schuman *et al.*, 1999; Segoli *et al.*, 2015; Smoliak *et al.*, 1972; Sun *et al.*, 2011; Talore *et al.*, 2016; Teague *et al.*, 2011; Wang *et al.*, 2017; Wei *et al.*, 2011; Xu *et al.*, 2014; Yanfen *et al.*, 1998; Zhang *et al.*, 2018; Zhou *et al.*, 2010; Zou *et al.*, 2015

Notes:

[1] ± two standard deviations, expressed as a percent of the mean; where sufficient studies were not available for a statistical analysis a default, based on expert judgement, of ± 40% is used as a measure of the error. NA denotes 'Not Applicable', for factor values that constitute reference values or nominal practices for the input or management classes.

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

[4] High intensity grazing may be moderately degraded, but do not represent excessive grazing intensity that leads to severe grassland degradation.

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

Tier 2

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

Reference C stocks can be derived from country-specific data in a Tier 2 approach. Reference values in Tier 1 correspond to non-degraded, unimproved lands under native vegetation, but other reference conditions can also be chosen for Tier 2. In addition, the depth for evaluating soil C stock changes can be different with the Tier 2 method. However, this will require consistency with the depth of the reference C stocks (SOC_{REF}) and stock change factors for all land uses (i.e., F_{LU}, F_{MG}, and F_I) to ensure consistent application of methods for determining the impact of land use change on soil C stocks.

The carbon stock estimates may be improved when deriving country-specific factors for F_{LU} and F_{MG}, by expressing carbon stocks on a soil-mass equivalent basis rather than a soil-volume equivalent (i.e. fixed depth) basis. This is because the soil mass in a certain soil depth changes with the various operations associated with land use that affect the density of the soil, such as uprooting, land levelling, tillage, and rain compaction due to the disappearance of the cover of tree canopy. However, it is important to realize that all data used to derive stock change factors across all land uses must be on an equivalent mass basis if this method is applied. This will be challenging to do comprehensively for all land uses. See Box 2.2C in Chapter2, Section 2.3.3.1 for more information.

For biochar C amendments to soils, the parameter F_{perm_p} can be based on H/Corg or O/Corg measured directly from representative samples of biochar, or from published data for biochar produced using similar process conditions as the biochar that is applied to soils in the country. Tier 2 emission factors may be disaggregated based on variation in environmental conditions, such as the climate and soil types, in addition to variation associated with the biochar production methods that generate production types defined by a specific feedstock type and conversion process. See Section 2.3.3.1, Chapter 2, Volume IV for more information.

Tier 3

Constant stock change rate factors *per se* are less likely to be estimated in favor of variable rates that more accurately capture land-use and management effects. See Section 2.3.3.1 (Chapter 2) for further discussion. Tier 3 methods for biochar C amendments to soils are country-specific and may involve empirical or process-based models to account for a broader set of impacts of biochar amendments. More information on Tier 3 methods is provided in Section 2.3.3.1, Chapter 2, Volume IV.

Organic soils

No refinement.

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

6.2.3.3 CHOICE OF ACTIVITY DATA

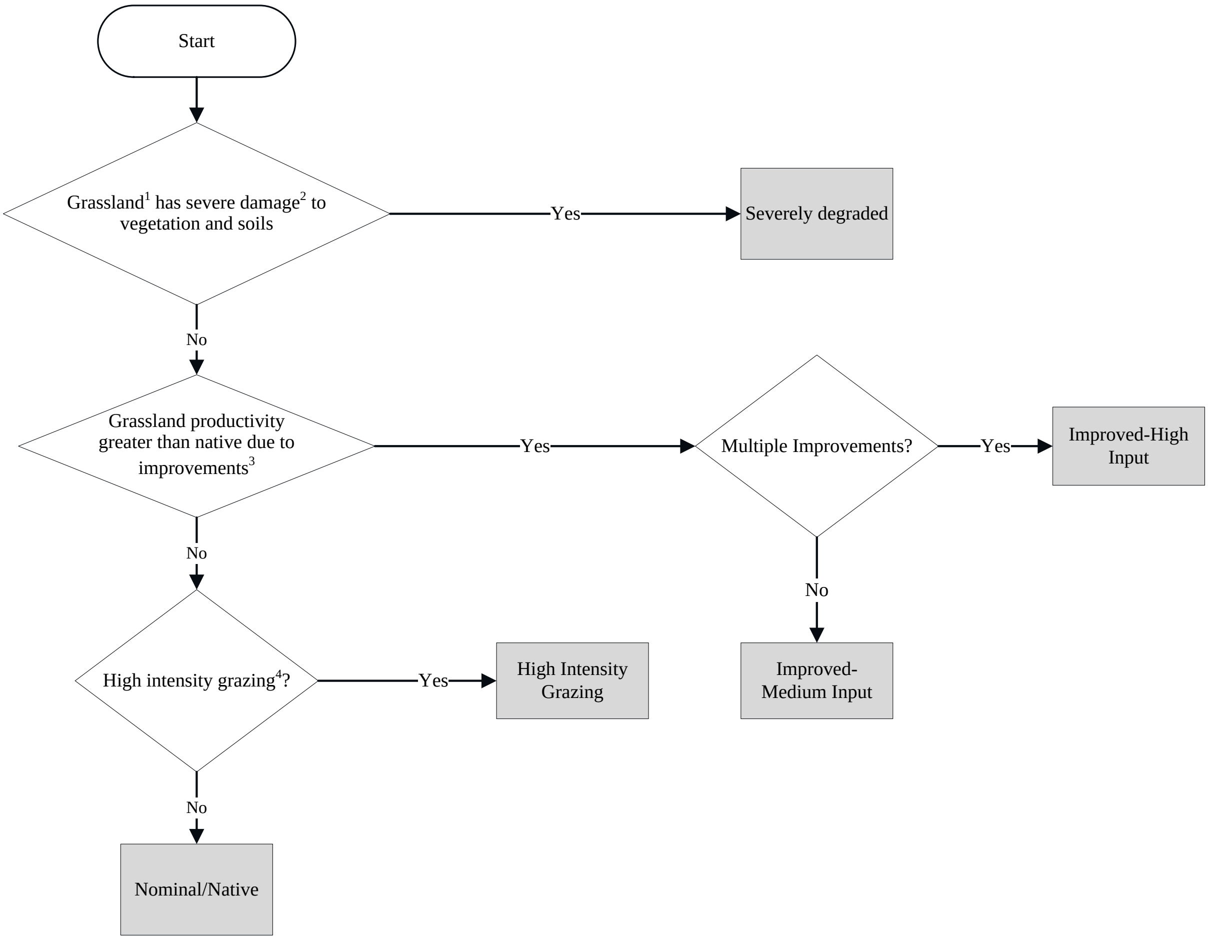
Mineral soils

Tier 1

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

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

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



Notes:

1: Includes continuous pasture, hay lands and rangelands

2: Large loss in vegetation cover and productivity due to continual overgrazing and/or high rates of erosion.

3: Productivity refers explicitly to C input to soil (management improvements that increase input e.g., fertilization, organic amendment, irrigation, planting more productive varieties, liming, and seeding legumes).

4: High intensity grazing is defined as grazing that deteriorates the condition and/or long-term recovery capacity of the vegetation compared with the vegetation state under nominal to moderate grazing intensity. High intensity grazing does not refer to stocking rate and duration only, but to the stocking rate and duration in relation to grassland productivity and resilience. This may be called a moderately degraded condition but high intensity grazing does not lead to the severe degradation such as is caused by relentless overgrazing. High intensity grazing also includes land where vegetation is frequently cut and removed equivalent to high intensity grazing and without application of any animal manure.

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

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

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

Tier 2

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

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

For biochar C amendments, the activity data for the Tier 2 method includes the total quantities of biochar distributed for amendment to mineral soils. These data must be disaggregated by production type, where production type is defined as a process utilizing a specific feedstock type, and a specific conversion process). Changes in soil C associated with biochar amendments are considered to occur where it is incorporated into soil. However, due to the distributed nature of the land sector in which this can take place, inventory compilers may not have access to data on when or where biochar C amendments occur. Inventory compilers may be able to compile data on the total amount of biochar applied to grassland mineral soils from biochar producers, importers, exporters or distributors, and/or from those applying biochar to grassland in the country. Note that exported biochar is not included in the total amount of biochar amended to soils in the country. Additionally, activity data on the amount of biochar amendments may be disaggregated by climate zones and/or soil types if country-specific factors are disaggregated by these environmental variables. The additional climate and soil activity data may be obtained with a survey of biochar distributors and land managers.

Tier 3

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

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

Organic soils

No refinement.

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

6.2.3.4 CALCULATION STEPS FOR TIER 1

Mineral soils

The steps for estimating SOC_0 and $SOC_{(0-T)}$ 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.

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

6.2.3.5 UNCERTAINTY ASSESSMENT

No refinement.

6.2.4 Non-CO_2 greenhouse gas emissions from biomass burning

No refinement.

6.3 LAND CONVERTED TO GRASSLAND

No refinement.

6.3.1 Biomass

No refinement.

6.3.2 Dead organic matter

No refinement.

6.3.3 Soil carbon

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

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

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

6.3.3.1 CHOICE OF METHOD

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

Mineral soils

Tier 1

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

Tier 2

The Tier 2 method for mineral soils also uses Equation 2.25, but involves country-specific or region-specific reference C stocks and/or stock change factors and more disaggregated land-use activity and environmental data. For biochar C amendments, Tier 2 methods utilize a top-down approach in which the total amount of biochar generated and added to mineral soil is used to estimate the change in soil organic C stocks with country-specific factors. See Section 2.3.3.1, Chapter 2, Volume IV for more information.

Tier 3

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

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

Organic soils

No refinement.

The *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* provides additional guidance that updates the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. See Section 2.3 of the *2013 Wetlands Supplement* for guidance on Tier 1, 2, and 3 approaches for land use conversions associated with drained organic soil.

6.3.3.2 CHOICE OF STOCK CHANGE AND EMISSION FACTORS

Mineral soils

Tier 1

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

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

Tier 2

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

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

The Tier 1 method may over- or under-estimate soil C stock changes on an annual basis, particularly with land use change (e.g., Villarino et al., 2014). Therefore, land use change, such as Croplands converted to Grasslands, may include development of factors that estimate changes over longer periods of time than the default of 20 years, and may better match the period of time over which carbon accumulates or is lost from soils due to land use change. When C stock changes extend over periods of many decades, activity data for historical land-use change are needed to estimate the soil C stock changes that are still occurring in the current inventory year.

The carbon stock estimates may be improved when deriving country-specific factors for F_{LU} and F_{MG}, by expressing carbon stocks on a soil-mass equivalent basis rather than a soil-volume equivalent (i.e. fixed depth) basis. This is because the soil mass in a certain soil depth changes with the various operations associated with land use that affect the density of the soil, such as uprooting, land levelling, tillage, and rain compaction due to the disappearance of the cover of tree canopy. However, it is important to realize that all data used to derive stock change factors across all land uses must be on an equivalent mass basis if this method is applied. This will be challenging to do comprehensively for all land uses. See Box 2.2C in Chapter2, Section 2.3.3.1 for more information.

For biochar C amendments, the parameter F_{perm_p} can be based on H/Corg or O/Corg measured directly from representative samples of biochar, or from published data for biochar produced using similar process conditions as the biochar that is applied to soils in the country. Tier 2 emission factors may be disaggregated based on variation in environmental conditions, such as the climate and soil types, in addition to variation associated with the biochar production methods that generates production types defined by the specific feedstock type and conversion process, where production type is defined as a process utilizing a specific feedstock type, and a specific conversion process. See Section 2.3.3.1, Chapter 2, Volume IV for more information.

Country-specific emission factors (i.e., permanence factors) for biochar C for grassland may be different from the past land use for *Land Converted to Grassland,* and these differences need to be addressed in the calculations. This requires estimating the biochar carbon stocks from past biochar carbon additions that remain in *Land Converted to Grassland* after conversion. The biochar C stocks are then subject to the conditions for grassland, which may lead some additional loss of biochar C.

Tier 3

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

Tier 3 methods for biochar C amendments are country-specific and may involve empirical or process-based models to account for a broader set of impacts of biochar amendments. These methods will likely estimate biochar C stocks and associated changes over time so the biochar C stocks in Land Converted to Grassland will need to be tracked through the land use change process.

Organic soils

No refinement.

The *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* provides additional guidance that updates the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. See Section 2.3 of the *2013 Wetlands Supplement* for guidance on Tier 1, 2, and 3 approaches for land use conversions associated with drained organic soil.

6.3.3.3 CHOICE OF ACTIVITY DATA

Mineral soils

Tier 1 and Tier 2 –Default Equations

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

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

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

For biochar C amendments, the activity data for the Tier 2 method includes the total quantities of biochar distributed for amendment to mineral soils. These data must be disaggregated by production type, where production type is defined as a process utilizing a specific feedstock type, and a specific conversion process. Changes in soil C associated with biochar amendments is considered to occur where it is incorporated into soil. However, due to the distributed nature of the land sector in which this can take place, inventory compilers may not have access to data on when or where biochar C amendments occur. Inventory compilers may be able to compile data on the total amount of biochar applied to grassland mineral soils from biochar producers, importers, exporters, distributors, and/or from those applying biochar to grassland in the country. Note that exported biochar is not included in the total amount of biochar amended to soils in the country. Additionally, activity data on the amount of biochar amendments may be disaggregated by climate zones and/or soil types if country-specific factors are disaggregated by these environmental variables. The additional climate and soil activity data may be obtained with a survey of biochar distributors and land managers.

Tier 3

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

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

Organic soils

No refinement.

The *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* provides additional guidance that updates the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. See Section 2.3 of the *2013 Wetlands Supplement* for guidance on Tier 1, 2, and 3 approaches for land use conversions associated with drained organic soil.

6.3.3.4 CALCULATION STEPS FOR TIER 1

Mineral soils

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

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

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

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

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

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

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

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

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

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

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

Example: For tropical moist, volcanic soil that has been under long-term annual Cropland, with intensive tillage and where crop residues are removed from the field, carbon stocks at the beginning of the inventory time period (1990 in this example), $SOC_{(0-T)}$ are:

70 tonnes C ha^{-1} ● 0.90 ● 1 ● 0.92 = 58.0 tonnes C ha^{-1}.

Following conversion to improved (e.g., fertilised) pasture, carbon stocks in the last year of inventory (2010 in this example) (SOC_0) are:

70 tonnes C ha^{-1} ● 1 ● 1.17 ● 1 = 81.9 tonnes C ha^{-1}.

Thus the average annual change in soil C stock for the area over the inventory time period is calculated as:

(81.9 tonnes C ha^{-1} – 58.0tonnes C ha^{-1}) / 20 yrs =1.2 tonnes C ha^{-1} yr^{-1}.

Organic soils

No refinement.

The 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands provides additional guidance that updates the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. See Section 2.3 of the 2013 Wetlands Supplement for guidance on Tier 1, 2, and 3 approaches for land use conversions associated with drained organic soil.

6.3.3.5 UNCERTAINTY ASSESSMENT

No refinement.

6.3.4 Non-CO_2 greenhouse gas emissions from biomass burning

No refinement.

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

No refinement.

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

Default stock change factors have been updated in Table 6.2 based on an analysis of a global dataset of experimental results for grazing intensity to a 30cm depth. Management change was defined as high-intensity grazing from low to moderate grazing intensity. The grazing intensity categories were those used by the authors of the published studies and so are their interpretation of the relative livestock grazing stocking density in relation to the grassland productivity and resilience. Management factors represent the effect on C stocks after 20 years following the management change. Data were compiled from published literature based on the following criteria: a) must be an experiment with a control and treatment; b) provide soil organic C stocks or the data needed to compute soil organic C stocks (bulk density, OC content, gravel content); c) provide depth of measurements; d) provide the number of years from the beginning of the experiment to C stock sample collection; and c) provide location information. There were 31 published studies with 176 observations of grassland management (i.e., high intensity grazing versus low to moderate intensity grazing). There was insufficient data to develop reliable factors by climate or soil.

Semi-parametric mixed effect models were developed to estimate the new factors (Breidt et al., 2007). Several variables were tested including depth, number of years since the management change, climate, and the first-order interactions among the variables. Variables and interactions terms were retained in the model if they met an alpha level of 0.05 and decreased the Akiake Information Criterion by two. For depth, data were not aggregated to a standardized set of depths but rather each of the original depth increments were used in the analysis (e.g., 0-5 cm, 5-10 cm, and 10-30 cm) as separate observations of stock changes. Similarly, time series data were not aggregated, even though those measurements are taken from the same plots. Consequently, random effects were included to account for the dependencies in times series data and among data points representing different depths from the same study.

Special consideration was given to representing depth increments in order to avoid aggregating data across increments from the original experiments. Data are collected by researchers at various depths that do not match among studies. We created a custom set of covariates, which are functions of the increment endpoints. These functions come from integrating the underlying quadratic function over the increments. This approach was needed in order to make statistically valid inferences with the semi-parametric mixed effect model techniques, and to avoid errors associated with aggregating data into a uniform set of depth increments.

Using this customized approach, we estimated grassland management factors to a 30 cm depth. Uncertainty is quantified based on the prediction error for the model, and represents a 95 percent confidence interval for each of the factor values. The resulting confidence intervals can be used to construct probability distribution functions with a normal density for propagating error through the inventory calculations.

References

REFERENCES NEWLY CITED IN THE *2019 REFINEMENT*

Breidt, F. J., Hsu, N.-J. & Ogle, S. (2007) Semiparametric mixed models for increment-averaged data with application to carbon sequestration in agricultural soils. *Journal of the American Statistical Association* **102**(479): 803-812.

Cao, J., Wang, X., Sun, X., Zhang, L. & Tian, Y. (2013) Effects of grazing intensity on soil labile organic carbon fractions in a desert steppe area in Inner Mongolia. *SpringerPlus* **2**(1): S1.

Ding, W., Sun, X., Jia, H., Qin, P., Jia, Y. & Jin, J. (2014) Effect of grazing intensity on soil organic carbon in north slope of Tianshan mountain meadow grassland. *Southwest China Journal of Agricultural Sciences* **27**(4): 1596-1600.

Du, Y., Guo, X., Zhou, G., Cao, G. & Li, Y. (2017) Effect of Grazing Intensity on Soil and Plant δ15N of an Alpine Meadow. *Polish Journal of Environmental Studies* **26**(3): 1071-1075.

Frank, A., Tanaka, D., Hofmann, L. & Follett, R. (1995) Soil carbon and nitrogen of Northern Great Plains grasslands as influenced by long-term grazing. *Journal of Range Management*: 470-474.

Franzluebbers, A. & Stuedemann, J. (2009) Soil-profile organic carbon and total nitrogen during 12 years of pasture management in the Southern Piedmont USA. *Agriculture, Ecosystems & Environment* **129**(1-3): 28-36.

Gao, X., Thomas, B. W., Beck, R., Thompson, D. J., Zhao, M., Willms, W. D. & Hao, X. (2018) Long-Term Grazing Alters Soil Trace Gas Fluxes from Grasslands in the Foothills of the Rocky Mountains, Canada. *Land Degradation and Development* **29**(2): 292-302.

Gao, Y. H., Luo, P., Wu, N., Chen, H. & Wang, G. X. (2007) Grazing intensity impacts on carbon sequestration in an alpine meadow on the eastern Tibetan Plateau. *Research Journal of Agriculture and Biological Sciences* **3**(6): 642-647.

Gillard, P. (1969) The effect of stocking rate on botanical composition and soils in natural grassland in South Africa. *Journal of applied ecology*: 489-497.

Han, G., Hao, X., Zhao, M., Wang, M., Ellert, B. H., Willms, W. & Wang, M. (2008) Effect of grazing intensity on carbon and nitrogen in soil and vegetation in a meadow steppe in Inner Mongolia. *Agriculture, Ecosystems and Environment* **125**(1-4): 21-32.

He, N., Yu, Q., Wu, L., Wang, Y. & Han, X. (2008) Carbon and nitrogen store and storage potential as affected by land-use in a Leymus chinensis grassland of northern China. *Soil Biology and Biochemistry* **40**(12): 2952-2959.

Ingram, L. J., Stahl, P. D., Schuman, G. E., Buyer, J. S., Vance, G. F., Ganjegunte, G. K., Welker, J. M. & Derner, J. D. (2008) Grazing impacts on soil carbon and microbial communities in a mixed-grass ecosystem. *Soil Science Society of America Journal* **72**(4): 939-948.

Kioko, J., Kiringe, J. W. & Seno, S. O. (2012) Impacts of livestock grazing on a savanna grassland in Kenya. *Journal of Arid Land* **4**(1): 29-35.

Kölbl, A., Steffens, M., Wiesmeier, M., Hoffmann, C., Funk, R., Krümmelbein, J., Reszkowska, A., Zhao, Y., Peth, S. & Horn, R. (2011) Grazing changes topography-controlled topsoil properties and their interaction on different spatial scales in a semi-arid grassland of Inner Mongolia, PR China. *Plant and Soil* **340**(1-2): 35-58.

Li, C., Hao, X., Zhao, M., Han, G. & Willms, W. D. (2008) Influence of historic sheep grazing on vegetation and soil properties of a Desert Steppe in Inner Mongolia. *Agriculture, Ecosystems & Environment* **128**(1-2): 109-116.

Liu, N., Zhang, Y., Chang, S., Kan, H. & Lin, L. (2012) Impact of grazing on soil carbon and microbial biomass in typical steppe and desert steppe of Inner Mongolia. *PLoS One* **7**(5): e36434.

Manley, J. T., Schuman, G. E., Reeder, J. D. & Hart, R. H. (1995) Rangeland soil carbon and nitrogen responses to grazing. *Journal of Soil and Water Conservation* **50**(3): 294-298.

Martinsen, V., Mulder, J., Austrheim, G. & Mysterud, A. (2011) Carbon storage in low-alpine grassland soils: effects of different grazing intensities of sheep. *European Journal of Soil Science* **62**(6): 822-833.

Potter, K. N., Daniel, J. A., Altom, W. & Torbert, H. A. (2001) Stocking rate effect on soil carbon and nitrogen in degraded soils. *Journal of Soil and Water Conservation* **56**(3): 233-236.

Qi, S., Zheng, H., Lin, Q., Li, G., Xi, Z. & Zhao, X. (2010) Effects of livestock grazing intensity on soil biota in a semiarid steppe of Inner Mongolia. *Plant and Soil* **340**(1-2): 117-126.

Rutherford, M. C. & Powrie, L. W. (2011) Can heavy grazing on communal land elevate plant species richness levels in the Grassland Biome of South Africa? *Plant Ecology* **212**(9): 1407-1418.

Schulz, K., Voigt, K., Beusch, C., Almeida-Cortez, J. S., Kowarik, I., Walz, A. & Cierjacks, A. (2016) Grazing deteriorates the soil carbon stocks of Caatinga forest ecosystems in Brazil. *Forest Ecology and Management* **367**: 62-70.

Schuman, G. E., Reeder, J. D., Manley, J. T., Hart, R. H. & Manley, W. A. (1999) Impact of grazing management on the carbon and nitrogen balance of a mixed-grass rangeland. *Ecological Applications* **9**(1): 65-71.

Segoli, M., Bray, S., Allen, D., Dalal, R., Watson, I., Ash, A. & O'Reagain, P. (2015) Managing cattle grazing intensity: Effects on soil organic matter and soil nitrogen. *Soil Research* **53**(6): 677-682.

Smoliak, S., Dormaar, J. & Johnston, A. (1972) Long-term grazing effects on Stipa-Bouteloua prairie soils. *Journal of Range Management*: 246-250.

Sun, D. S., Wesche, K., Chen, D. D., Zhang, S. H., Wu, G. L., Du, G. Z. & Comerford, N. B. (2011) Grazing depresses soil carbon storage through changing plant biomass and composition in a Tibetan alpine meadow. *Plant Soil Environ.*

Talore, D. G., Tesfamariam, E. H., Hassen, A., Du Toit, J., Klampp, K. & Jean-Francois, S. (2016) Long-term impacts of grazing intensity on soil carbon sequestration and selected soil properties in the arid Eastern Cape, South Africa. *Journal of the Science of Food and Agriculture* **96**(6): 1945-1952.

Teague, W. R., Dowhower, S. L., Baker, S. A., Haile, N., DeLaune, P. B. & Conover, D. M. (2011) Grazing management impacts on vegetation, soil biota and soil chemical, physical and hydrological properties in tall grass prairie. *Agriculture, Ecosystems and Environment* **141**(3-4): 310-322.

Villarino, S. H., Studdert, G. A., Laterra, P. & Cendoya, M. G. (2014) Agricultural impact on soil organic carbon content: Testing the IPCC carbon accounting method for evaluations at county scale. *Agriculture, Ecosystems & Environment* **185**: 118-132.

Wang, H., Dong, Z., Guo, J., Li, H., Li, J., Han, G. & Chen, X. (2017) Effects of grazing intensity on organic carbon stock characteristics in Stipa breviflora desert steppe vegetation soil systems. *Rangeland Journal* **39**(2): 169-177.

Wei, L., Hai-Zhou, H., Zhi-Nan, Z. & Gao-Lin, W. (2011) Effects of grazing on the soil properties and C and N storage in relation to biomass allocation in an alpine meadow. *Journal of soil science and plant nutrition* **11**(4): 27-39.

Xu, M. Y., Xie, F. & Wang, K. (2014) Response of vegetation and soil carbon and nitrogen storage to grazing intensity in semi-arid grasslands in the agro-pastoral zone of northern china. *PLoS One* **9**(5): e96604.

Yanfen, W., Zuozhong, C. & Tieszen, L. T. (1998) Distribution of soil organic carbon in the major grasslands of Xilinguole, Inner Mongolia, China. *Acta Phytoecologica Sinica* **22**(6): 545-551.

Zhang, B., Thomas, B. W., Beck, R., Willms, W. D., Zhao, M. & Hao, X. (2018) Slope position regulates response of carbon and nitrogen stocks to cattle grazing on rough fescue grassland. *Journal of Soils and Sediments*: 1-7.

Zhou, X., Wang, J., Hao, Y. & Wang, Y. (2010) Intermediate grazing intensities by sheep increase soil bacterial diversities in an Inner Mongolian steppe. *Biology and Fertility of Soils* **46**(8): 817-824.

Zou, Y. L., Niu, D. C., Fu, H., Zhang, Y. C. & Wan, C. G. (2015) Moderate grazing promotes ecosystem carbon sequestration in an alpine meadow on the Qinghai-Tibetan plateau. *Journal of Animal and Plant Sciences* **1**(25(Suppll 1)): 165-171.

REFERENCES COPIED FROM THE 2006 IPCC GUIDELINES

Anderson, D.J., Perry, R.A. and Leigh, J.H. (1972). Some perspectives on shrub/environment interactions. In: McKell C.M., Blaisdell J.P., Goodon J.R. (eds), Wildland Shrubs – Their Biology and Utilization. USDA Forest Service, General Tech. Report INT-1.

Armentano, T.V. and Menges, E.S. (1986). Patterns of change in the carbon balance of organic soil-wetlands of the temperate zone. *Journal of Ecology* **74**: 755-774.

Conant, R.T. and Paustian, K. (2002). Potential soil carbon sequestration in overgrazed grassland ecosystems. *Global Biogeochemical Cycles* **16**: pp. 90_1-90_9.

Conant, R.T., Paustian, K., and Elliott, E.T. (2001). Grassland management and conversion into grassland: Effects on soil carbon. *Ecological Application* **11**: 343-355.

Falloon, P. and Smith, P. (2003). Accounting for changes in soil carbon under the Kyoto Protocol: need for improved long-term data sets to reduce uncertainty in model projections. *Soil Use and Management* **19**:265-269.

Follett, R. F., Kimble, J.M. and Lal, R. (2001). The potential of U.S. grazing lands to sequester soil carbon. Pages 401-430 *in* R. F. Follett, J.M. Kimble, and R. Lal, editor. The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect. Lewis Publishers, Boca Raton, FL.

IPCC (1997). *Revised 1996 IPCC Guidelines for National Greenhouse Inventories*. Houghton J.T., Meira Filho L.G., Lim B., Tréanton K., Mamaty I., Bonduki Y., Griggs D.J. Callander B.A. (Eds). Intergovernmental Panel on Climate Change (IPCC), IPCC/OECD/IEA, Paris, France.

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

Kauffman, B., Cummings, D.L. and Ward, D.E. (1998). Fire in the Brazilian Amazon. 2. Biomass, nutrient pools and losses in cattle pastures. *Oecologia*, **113** pp 415-427.

McGill, W. B. (1996). Review and classification of ten soil organic matter models. In: Powlson D.S., Smith P., and Smith J.U. (eds.). Evaluation of Soil Organic Matter Models Using Existing Long-Term Datasets. Springer-Verlag, Heidelberg: pp. 111-132.

McKeon, G.M., Hall, W.B., Henry, B.K., Stone, G.S. and Watson, I.W. (2004). Pasture Degradation and Recovery in Australia's Rangelands: Learning from History. Queensland Department of Natural Resources, Mines and Energy. pp. 256.

Monte, L, Hakanson, L., Bergstrom, U., Brittain, J., and Heling, R. (1996). Uncertainty analysis and validation of environmental models: the empirically based uncertainty analysis. *Ecological Modelling* **91**:139-152.

Naeth, M.A., Bailey, A.W., Pluth, D.J., Chanasyk, D.S., and Hardin, R.T. (1991). Grazing impacts on litter and soil organic matter in mixed prairie and fescue grassland ecosystems of Alberta. *Journal or Range Management* **44** pp 7-12.

Nusser, S.M. and Goebel, J.J. (1997). The National Resources Inventory: a long-term multi-resource monitoring programme. *Environmental and Ecological Statistics* **4**:181-204.

Ogle, S.M., Breidt, F.J., Eve, M.D. and Paustian, K. (2003). Uncertainty in estimating land-use and management impacts on soil organic carbon storage for U.S. agricultural lands between 1982 and 1997. *Global Change Biology* **9**:1521-1542.

Ogle, S.M., Breidt, F.J. and Paustian, K. (2006). Bias and variance in model results associated with spatial scaling of measurements for parameterization in regional assessments. *Global Change Biology* **12**:516-523.

Ogle, S.M., Conant, R.T. and Paustian, K. (2004). Deriving grassland management factors for a carbon accounting approach developed by the Intergovernmental Panel on Climate Change. *Environmental Management*. **33**:474-484.

Ojima, D.S., Parton, W.J., Schimel, D.S., Scurlock, J.M.O. and Kittel, T.G.F. (1993). Modeling the effects of climatic and CO_2 changes on grassland storage of soil C. *Water, Air, and Soil Pollution* **70**: pp. 643-657.

Powers, J. S., Read, J. M., Denslow, J. S. and Guzman, S. M. (2004). Estimating soil carbon fluxes following land-cover change: a test of some critical assumptions for a region in Costa Rica. *Global Change Biology* **10**:170-181.

Smith, J.E. and Heath, L.S. (2001). Identifying influences on model uncertainty: an application using a forest carbon budget model. *Environmental Management* **27**:253-267.

Smith, P., Powlson, D.S., Smith, J.U. and Elliott, E.T. (eds) (1997). Evaluation and comparison of soil organic matter models. Special Issue, *Geoderma* **81**:1-225.

Vanden Bygaart, A.J., Gregorich, E.G., Angers, D.A., *et al.* (2004). Uncertainty analysis of soil organic carbon stock change in Canadian cropland from 1991 to 2001. *Global Change Biology* **10**:983-994.

Veldkamp, E. (2001). Changes in soil carbon stocks following conversion of forest to pasture in the tropics. In: Holland E.A. (ed.): Notes from Underground: Soil Processes and Global Change. NATO ASI Series Berlin: Springer.