Moving to higher tiers for soil carbon

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Moving to higher tiers for soil carbon

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Abstract

The 2023 revised LULUCF regulation will require Tier 2 methods for monitoring all land and carbon pools by the reporting of the 2026 emission year, and then later Tier 3 methods for a subset of land including, among others, forests and peatlands that undergo restoration or protection for nature directives. This requirement is particularly challenging for soil carbon for which Tier 1 is still used by many Member States for several land categories. This document offers answers to frequently arising questions in the topic of higher methodological tiers for soil carbon pool monitoring, as well as practical advice on how to implement them. Regarding Tier 2, we suggest a step by step method to estimate reference carbon stock (SOC_{ref}) and carbon stock modifying factors (eg. F_{LU}) using national datasets on soil carbon or international databases such as the LUCAS soil survey. We also propose a list of FMG emission factors for agricultural practices based on a literature review for the temperate zone. Regarding Tier 3, we distinguish between measurement-based methods (repeated soil inventories) and model-based methods. Measurement-based methods tend to be costly, but they are necessary as no model can guarantee an accurate national total in a context of environmental and management changes. Model-based methods allow to disentangle the different drivers of soil carbon changes and reduce the number of repeated measurements needed. Their evaluation, in line with the IPCC guidelines, is also discussed.

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1 Introduction

This document is part of a collaboration between the Joint Research Centre (JRC) and DG Climate Action (DG CLIMA) in supporting the EU Member States with greenhouse gas (GHG) inventory development and in preparing to meet the requirements in the LULUCF Regulations 2018/841 and 2023/839. The work was coordinated by the JRC and conducted by external experts who worked in their individual capacity. The document was prepared between December 2022 and June 2023, and is based on extensive literature review and dedicated workshops with countries (two online workshops organized by the JRC in March 2023, and the 2023 JRC LULUCF workshop[1], organized in a hybrid format. in physical attendance in Ispra and online, on 11-12 May 2023).

This document intends to provide scientific advice and reflections on frequently arising questions in the topic of higher tiers for soil carbon monitoring, in the context of the EU LULUCF legislation. A draft version of this document was shared with the JRC LULUCF workshop participants ahead of the meeting, and the comments received during the workshop and afterwards have been considered when revising the document. The editors and authors thank warmly the LULUCF experts from EU MS, Switzerland, Norway and the United Kingdom, as well as colleagues from the JRC, European Environmental Agency, and DG CLIMA for all the active discussions, sharing of experiences and views, and for the constructive comments received during the work.

Section 1 provides an overview of the 2023 revised LULUCF regulation. Section 2 aims at offering concrete advice on how to move to higher tiers on soil carbon monitoring, using the format of "Frequently asked questions".

We note that GHG reporting and accounting are subject to a continuously evolving process, following better understanding of soil behaviour as sink or source as a response to anthropogenic and natural events, and improved measuring methods and modelling tools. Consequently, scientific advice should be continuously observed by the GHG reporting experts and agencies, thus considering this document as one of the steps to be done for fully consistent reporting.

[1] https://forest.jrc.ec.europa.eu/en/activities/lulucf/workshops/workshop-2023

2 Overview of the LULUCF regulation – accounting and enhanced monitoring

The 2018 LULUCF (Land Use, Land-Use Change and Forestry) regulation (EU 2018/841) set out the commitments of Member States for the LULUCF sector that would contribute to achieving the objectives of the Paris Agreement and meeting the former greenhouse gas emission reduction target of the Union for the period from 2021 to 2030. This regulation also specified the rules for the accounting of emissions and removals from LULUCF and for checking the compliance of Member States with the earlier commitments. However, due to emerging scientific evidence since 2018 (including the recent IPCC AR reports), the relatively neutral policy approach of this regulatory framework had to be revised to include a contribution to the overall objectives of the Green Deal climate policy framework.

To support the climate neutrality goal of the EU, adopted by the Union law in 2021 (Regulation EU 2021/1119) with a commitment to deliver by 2030 at least 55 % net greenhouse gas emissions reduction compared to 1990, the Council and EU Parliament recently adopted a revised LULUCF regulation text, published as Regulation EU 2023/839[2] (19 April 2023, in force on 11 May). It details the process of meeting the increased net emission reduction targets of EU associated with its LULUCF sector. These targets specifically include the Union commitment to generate carbon removals of at least -310 Mt CO_2 eq. by 2030, as well as individual Member States targets, which make up therefore a significant part of the climate neutrality equation.

As a result, the importance of the LULUCF sector has substantially increased: the EU climate neutrality in 2050 cannot be reached without the enhanced contribution of LULUCF. It also means that transparent emission accounting, as well as monitoring and reporting of emissions and removals under the current commitments need to rely on adequately robust, timely (annually updated), trackable, and verifiable GHG inventories. Therefore, the LULUCF regulation revision includes both an upgraded system for the monitoring of emissions and removals and several requirements for methodological improvements relevant to LULUCF GHG inventories. It also includes a revised (more transparent and simplified) emission accounting system for the post-2025 period, which becomes fully compatible with the structure of LULUCF reporting under UNFCCC.

The following text gives a brief overview of the relevant content of the revised LULUCF regulation (EU 2023/839[2]). This revised regulation:

- amends the Regulation EU 2018/841 (LULUCF regulation) concerning the scope, simplifying accounting and compliance rules, and setting out the targets of EU Member States until 2030
    - Representing higher Union ambitions by setting the targets for Member States
    - Including entire managed land into accounting
    - Introducing targets assessed against reported GHG inventories by Member States, replacing for the post-2025 period the earlier arguable target setting
    - Improving governance by implementing a corrective action process led by the Commission
- amends the Regulation EU 2018/1999 ("Governance" regulation) concerning requirements in monitoring, reporting, tracking of progress and review
    - Improving estimation of emissions and removals through a specific requirement to use Tier 2 and Tier 3 methodologies, and adopting geographically explicit monitoring also beyond land-use changes (which was already required under Regulation EU 2018/841).

The amendments concern both the individual text articles and annexes. In the text below, we first summarize the key Articles of the LULUCF regulation that have been amended regarding the subject matter (Art. 1), scope and accounting principles (Art. 2 to 10), flexibility (11 to 13), corrective action (13d), governance and others (Art. 14 to 19). For these parts, the Commission has prepared an unofficial consolidated[3] version of the amendments that is available online.

2 https://eur-lex.europa.eu/TodayOJ/fallbackOJ/l_10720230421en.pdf
3 https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:02018R0841-20230511

Next, we mention the relevant amendments to Governance regulation in terms of methodological requirements for improved LULUCF inventories.

2.1 Targets, accounting and other topics

2.1.1 Subject matter (Art. 1)

The LULUCF regulation in its newly adopted wording (EU 2023/839[2]) addresses:

(a) Member state commitments for LULUCF sector and the period from 2021 to 2025;

(b) Accounting of GHG emissions and removals from the LULUCF sector and compliance check for the period from 2021 to 2025;

(c) A 2030 Union target for net greenhouse gas removals in the LULUCF sector;

(d) EU Member States' targets for net greenhouse gas removals in the LULUCF sector for the period 2026-2029 and 2030.

2.1.2 Reporting/accounting scope (Art. 2)

2.1.2.1 Period 2021-2025

Land accounting mandatorily includes all categories of managed land except Wetlands remaining Wetlands and Settlements remaining Settlements. All managed land remains reported. HWP (4G) is included as part of accounting for managed forest land.

2.1.2.2 Period from 2026 to 2030

All managed land reported by Member States in the UNFCCC Common Reporting Format (CRF) Table 4 is accounted. Additionally, HWP (4G), atmospheric deposition, nitrogen leaching, and run off are also included.

2.1.3 Definitions (Art. 3)

This article contains definitions of the key terms linked to emission inventories, such as sink, source, carbon pool, carbon stock, HWP, forest (Forest land), half-life value and instantaneous oxidation. The revised definitions include natural disturbance that (in effect from 2026) newly applies to all land categories, and a term of climate change that links to the standard UNFCCC definition.

2.1.4 Commitment and targets (Art. 4)

This article includes the current wording of the commitments and targets. In essence, the earlier adopted accounting framework remains unchanged for the first five years of this decade, whereas the target setting and compliance against the targets changed for the period 2026 to 2030. In short:

2.1.4.1 Period 2021-2025

A commitment to ensure that the accounted emissions do not exceed accounted removals (so called 'no debit' accounting including Forest reference level)

2.1.4.2 Year 2030 for EU as a whole

A Union net removal target of -310 Mt CO_2 eq. is set as a sum of emissions and removals reported by the MS for 2030 (i.e., report submitted in 2032).

2.1.4.3 Year 2030 for individual EU Member States

The net removal targets are set for individual EU Member States for 2030 as the difference between the reported net emissions for 2030 (in NIR 2032 submission) and the average reported net emissions for years 2016, 2017 and 2018. The targets for each Member State are specified in Annex III, column C. They are based on the total area of managed land in each EU Member State.

In other words, each Member State is committed to achieve net emissions corresponding to average net emissions 2016-2018 plus the target. In Regulation EU 2023/839, Annex III, column D gives an indicative total net emission value for each Member State that is based on average net emissions reported in NIR 2020 for years 2016-2018 (column B). The final compliance check will be made using NIR 2032 submission values.

2.1.4.4 Period 2026-2029

Member State targets expressed as a "budget" of the values set out on a linear trajectory from 2022 (average of 2021, 2022, 2023 as reported in NIR 2025 submission) to 2030 target value. It means that the linear trajectory will be set in 2025, while the overall compliance will be assessed in 2032, (checked against 2032 NIR submission). The compliance check includes both the deviation from the allocated budget for 2026-2029 and the target value in 2030.

2.1.5 General rules for accounting (Art. 5)

This article contains mandatory accounting rules such as the obligations to prepare and maintain emission accounts and other requested data ensuring that these follow the UNFCCC emission reporting principles of being accurate, complete, consistent, comparable and transparent, prevent double counting and other related technical requirements. The marginally revised text in this paragraph ensures the consistency with the implemented changes of accounting rules that became specific for the period 2021-2025 and for the period 2026-2030.

2.1.6 Specific accounting rules (Art. 6, 7, 8)

Similarly, the specific accounting rules differentiate handling of individual land use categories. The newly revised text concerning these paragraphs ensures the consistency with the implemented changes of accounting rules that became specific for the period 2021-2025 and for the period 2026-2030.

2.1.7 Harvested wood products (Art. 9)

This article specifies that the accounting of emission contribution from HWP that is estimated in line with the adopted and/or recommended IPCC methodologies as applicable for UNFCCC GHG emission reporting (IPCC, 2019, 2006).

2.1.8 Accounting for Natural disturbances (Art. 10)

For the period of 2021-2025, it is possible to exclude emissions resulting from natural disturbances on afforested land and managed forest land, which exceed the average emissions caused by natural disturbances between 2001-2020 (excluding statistical outliers), from accounting.

2.1.9 Flexibility (Art. 11 to 13a, b, c)

Art. 11 to 12 specify general and specific managed land accounting flexibilities, the text of which was also revised and enhanced. Art 13, relating to managed forest land accounting, was restricted to 2021 to 2025 and thus the forest reference level required under Art 8 is no longer needed.

For post 2025, a new system based upon the managed forest land flexibility of Art 13 was created under Art. 13b that also includes other land besides forest land. Moreover, the article extended the specific compensation mechanism to disturbance-related emissions.

2.1.10 Corrective action (Art 13d)

This article specifies a procedure to act when a Member State is not on track to meet its 2030 target if this is evident from reporting and annual reviews. The Commission will initiate a corrective action requesting and evaluating a "Corrective Action Plan" from the MS concerned (with the mandatory content detailed in Art. 13d) submitted to the Commission. The plan will become publicly available.

2.1.11 Governance and Other (Art. 14 to 19)

These articles include governance and administrative topics, including compliance reporting, registry and review process that has been revised to be coherent with the new accounting rules. The links to other policy areas - biodiversity in particular - have been considerably enhanced.

2.1.12 Comprehensive reviews

This amendment concerns Art. 38 of Regulation 2018/1999 and spells out that in 2025 a comprehensive review of the national inventory submissions will be carried out by the Commission. This review is needed to determine the trajectory used to build the 2026-2029 budget for EU Member States reflecting the adopted rules for the period 2026-2030 (chapter 1.1.4 above). This review is additional to the comprehensive reviews to be carried out in 2027 and 2032, which will check the compliance for the periods 2021-2025 and 2026-2030, respectively (Art. 38 of Regulation 2018/1999).

2.2 Enhanced LULUCF monitoring

An important amendment supporting development of adequately robust LULUCF inventories is the new text in Annex V Part 3 to Regulation 2018/1999 on Methodologies for monitoring and reporting in the LULUCF sector (included as Annex V to EU 2023/839[2]). In outline, this provides for the following principles for monitoring systems as a basis for GHG inventory reporting:

- As already present in the 2018 version of the legislation, use of **geographically explicit land-use conversion data** for monitoring
- **Encouragement to consolidate reporting with monitoring systems for other relevant policies regarding**
    - Land use with high carbon stock land (linked to Renewable Energy Directive II)
    - Protection sites
        - Land with high biodiversity values (linked to Renewable Energy Directive II)
        - Sites under Habitats Directive
        - Sites under Birds Directive
        - Sites under Water Framework Directive
    - Restoration sites
        - All sites under point b. above
        - Sites regarding environmental liability, prevention and remedying
        - Sites under Natural restoration in Member States
    - High climate risk zones
        - Natural disturbances under LULUCF regulation (Art. 13b)
        - Sites under Flood Directive
        - Endangered areas under national adaptation strategy in Member States
    - Soil carbon stocks (national statistical inventories, LUCAS dataset mentioned)
- Requirements on **methodological tiers**
    - For 2021-2025, at least Tier 1 except key emission categories by magnitude (with at least 25% share within a source or sink category) or trend, that require at least Tier 2 methodologies
    - From the 2028 National Inventory Submission (i.e. for emissions and removal year 2026) onwards, at least Tier 2 methodologies for all carbon pools
    - From the 2030 National Inventory Submission onwards, Tier 3 methodologies for all carbon pools in areas specified under points a, b, c, d above, except areas smaller than 1% of the managed land reported by the Member State, where Tier 2 methodology is also adequate.

Where areas for which the Regulation requires a Tier 3 method by 2030 (forests, peatlands, protected areas, etc.) are included in a land category that is, as a whole, reported using a Tier 3 method, our interpretation is that the requirement is met ipso facto.

Correspondingly, consolidating GHG reporting system with other monitoring systems does not imply redesigning the existing sampling strategy applied for monitoring land use categories in accordance with the IPCC Guidelines and reporting under UNFCCC. It implies that the specific areas (often spatially minor) included under the revised LULUCF regulation may be monitored with less statistical accuracy, but still provide useful quantitative and qualitative information relevant to both mitigation and other land use policies, in this way increasing their mutual coherency.

3 Moving to higher tiers for soil carbon

3.1 What does higher Tier mean for soil carbon?

3.1.1 How are higher Tiers defined in the IPCC Guidelines?

The definition of Tiers is provided for each land category and/or pool in the IPCC guidelines[4]. Regarding soil carbon, the definitions can be found in the 2019 Refinements ch4, p. 2.38. They follow the common pattern: Tier 1 consists in using the default equations and emission factors, Tier 2 consists in using the default equations with some country-specific emission factors (see 3.1.2 for details), and Tier 3 consists in using either models or direct measurements (see 3.3.2 for details).

3.1.2 Does Tier 2 require all used parameters to be derived from national measurements?

No, on two aspects.

First, a mix of IPCC default parameters and country-specific ones qualifies as Tier 2, as implied by the following quote from the IPCC guidelines:

"A Tier 2 method is an extension of the Tier 1 method that allows an inventory to incorporate country-specific data. **It is good practice for countries to use a Tier 2 method, if possible, even if they are only able to better specify certain components of the Tier 1 method**. For example, a compiler may only have data to derive country-specific reference C stocks, which would then be used with default stock change factors to estimate changes in soil organic C stocks for mineral soils." (2019 Refinements ch4, p. 2.38)

Second, the "country-specific" emission factors required to replace IPCC default emission factors need not be derived from national measurements as long as it can be argued that they are more accurate in the specific context of the country. Therefore, country-specific emission factors can be derived from a subsample of European or international databases such as SoilGrids or the LUCAS soil survey (see section 3.2.8 of this document for a detailed list of possible sources). Note that instead of simply using the average of the pixels or plots from the international database which fall into the country, more refined analysis can be relevant such as averaging all plots with similar climate and soil conditions, even if they are located in a neighbouring country, or using statistical analysis to identify the plots which are most comparable with the targeted conditions (eg. Schneider et al., 2021).

Note that for cropland, the 2019 Refinements offers a different kind of Tier 2 method, consisting in a simplified process-based model (2019 Refinements vol4, p. 2.15-2.26).

3.1.3 How to ensure time-series consistency when moving to higher Tiers?

A common worry when moving to higher tiers is to ensure time-series consistency. Time-series consistency indeed requires attention, but it should not prevent a methodological improvement or the use of a more reliable data source. As the IPCC Guidelines put it (2019 Refinements vol1, p5.5), "Both methodological changes and refinements over time are an essential part of improving inventory quality.". Otherwise, one would remain stuck with the generally poor data available in for the 1990s. Chapter 5 of the volume 1 of the IPCC Guidelines provide a list of pragmatic techniques and concrete examples on how to ensure time-series consistency: overlap, surrogate data, interpolation, trend extrapolation, and non-linear trend analysis. It also leaves room for "other techniques" when none of the above techniques can be satisfactorily implemented. This is the case for total standing volume in forests in the Polish NIR: because the old and new data sources do not overlap, a mix of surrogate data and trend extrapolation is used, whereby the pre-2009 data is "recalibrated" upwards to meet the extrapolated trend of the post-2008 data over a few years prior to the change in monitoring technique.

[4] 2019 Refinements to the IPCC guidelines are generally quoted in this document, but similar text/guidance exists in the 2006 guidelines.

3.2 Tracking key practices

3.2.1 Why tracking key land management practices?

Spending time and resources to think about which practices are worth tracking is almost necessary, no matter the other reporting choices (e.g. Tier 2 vs Tier 3, model vs measurements). Activity data on key practices for carbon storage are necessary inputs to both Tier 2 methods and Tier 3 process-based models. A measurement-based Tier 3 approach (repeated soil inventory) is the only method which allows to meet reporting requirements without tracking key land management practices. And even when opting for a measurement-based Tier 3 approach (repeated soil inventory), one can barely imagine the absence of monitoring of key practices, which are the levers that the government can pull and track to improve soil carbon storage. In addition, tracking key land management practices allows for a better stratification, and thereby improves the precision of the measurement-based estimates.

Note that strictly speaking, changes in practices rather than practices *per se* trigger SOC changes. This is why assumptions on practices will be needed for the time periods preceding the first data acquisition on key land management practices. These assumptions are similar to those needed for land-use changes for the 1970-1990 period, a period for which land-use data is lacking in most member states and which is nevertheless necessary to estimate carbon stock changes in 1990. Because these assumptions are necessarily coarse, and because the set of practices actually tracked will always be incomplete, a measurement-based (repeated soil inventory) Tier 3 approach (repeated soil inventory) may ultimately be the best way to secure an accurate estimate of SOC change at national scale, if only every 10-15 years.

Note that in the specific case of forest land, most management practices impacting SOC are expected to be mediated by biomass stocks and litterfall, which can be used as inputs to state of art soil models. In that sense, the necessity of a measurement-based estimate for the national total is less acute for forest land. Also note that with Tier 3 modelling approaches, it is beneficial to have data on management practices before actual reporting periods in order to ensure that legacy effects of soils are taken into account when models are applied for GHG inventory.

3.2.2 Which practices should generally be monitored?

Most of the European soil carbon storage potential lies in five major practices on agricultural lands which should therefore be generally followed: land-use changes (e.g. afforestation, cropland conversions to and from grassland), agroforestry – that is a field mixing crops and tree lines – and hedges, cover crops, substitution of maize with grass and peatland restoration (Table 1). With the addition of forest management retained for its biomass storage potential, the same practices are considered as "most effective" by the European Commission (European Commission, 2021).

Table 1. Estimates of soil sequestration potentials at EU level

	Current area (Mha)	Carbon sequestration potential in the soil ($MtCO_2\,yr^{-1}$)					
Management practices		Ref. [3] upscaled		Ref. [5]	Ref. [7]	Minimum	Maximum
		Min (€25 tCO_2^{-1})	Max (€250 tCO_2^{-1})				
Arable agroforestry	0.4	0.1	60			0	60
Cover crops	7.5	68	94	46		46	94
Grass/maize substitution	Not applicable	5	25	46		5	46
Peatland restoration	Negligible				109	109	109
All residuals left on field	Negligible			26		26	26
Total						186	334
Land-use changes		Ref. [34]		Ref. [5]	Ref. [33]	Minimum	Maximum
		Min (€25 tCO_2^{-1})	Max (€250 tCO_2^{-1})				
Afforestation		0	29		111	0	111
Conversion to grassland			266			266	266
Total						266	377

In the case of ref. [3], which assessed potentials at the national level in France, the original figures have been increased proportionally to the area of arable land for agroforestry and cover crops and to the number of cattle heads for grass/maize substitution. The resulting figures are relevant to the EU 27, whereas refs. [5,7] still cover the United Kingdom. For afforestation[33,34], original figures do not separate soil from biomass: the soil potential is obtained on the basis of the 11% share of soil in total storage for land converted to forest land in the European inventory.

Source: Bellassen et al. (2022)

In practice, this means that all countries should aim to monitor at least these practices, unless they have a strong rationale to neglect them. The rationale can be that they are not currently occurring in the country.

One example can be the documented negligibility of the area of drained organic soils. In the Global Peatland database for example, drained peatlands are estimated to occupy less than 0.1% of the area of Cyprus, Greece, Spain and Croatia (Tanneberger et al., 2017)[5]. One could argue that in these cases, monitoring peatland restoration is not a priority.

Other practices may of course be worth tracking if their impact or their potential is important, if only in a specific member state.

3.2.3 Which emission factors for these key practices?

The IPCC guidelines do not provide emission factors for soil carbon storage as a result of these practices. The list below is a suggestion, largely based on a recent literature review focused on the temperate zone (Bamière et al., 2023). As for forest lands there are limited and partly controversial results on the emissions factors due to different management operations (see section 3.2.7).

[5] In Slovakia, Luxembourg, the Czech Republic and Bulgaria, the figure is between 0.1% and 0.2%.

Table 2. Emission factors for soil carbon storage by key management practices

Management practice	**Annual storage (kgC ha^{-1} yr^{-1})**	**Period for which the factor is valid (first XX years)**	**Source**
Expansion of cover crops in croplands	313 ± 313	30	Bamière et al. (2023)
New organic C inputs in croplands	100 (sewage sludge), 100 (liquid manure), 300 (manure), 500 (compost)	30	Bamière et al. (2023)
Expansion of temporary grasslands in croplands (grass/maize substitution)	~130 to 500 kg C $ha^{-1}yr^{-1}$	10	Bamière et al. (2023)
Agroforestry	250 kg C ha^{-1} of UAA.yr^{-1} (-230; +730) in the soil (cropland only) 900 kg C ha^{-1} yr^{-1} (-430; +1350) in the woody biomass	30	Bamière et al. (2023)
Hedges	750 kg C ha^{-1} of hedges yr^{-1} (range of 490; 1020) in the soil (cropland only) 240 kg C ha^{-1} of UAA.yr^{-1} (-120; +370) in the woody biomass (authors' calculations)	30	Bamière et al. (2023)
Moderate intensification of extensive grasslands	0-210 ±70	30	Bamière et al. (2023)
Grazing instead of mowing in permanent grasslands	From 111 ± 11 to 380 ± 20 depending on biomass removal	30	Bamière et al. (2023)
Grass cover of vineyards (winter or permanent cover)	From 160 (winter) to 490 (permanent)	30	Bamière et al. (2023)
Peatland restoration	3,000 ± 2,000	Not applicable: avoided emissions	(Barthelmes et al., 2015; IPCC, 2014)
Residue management (leaving 100% straw on site instead of 50%)	100 (first 10 years) / 40 (first 40 years)	10 / 40	(Lugato et al., 2014)

3.2.4 Should we monitor grassland management practices?

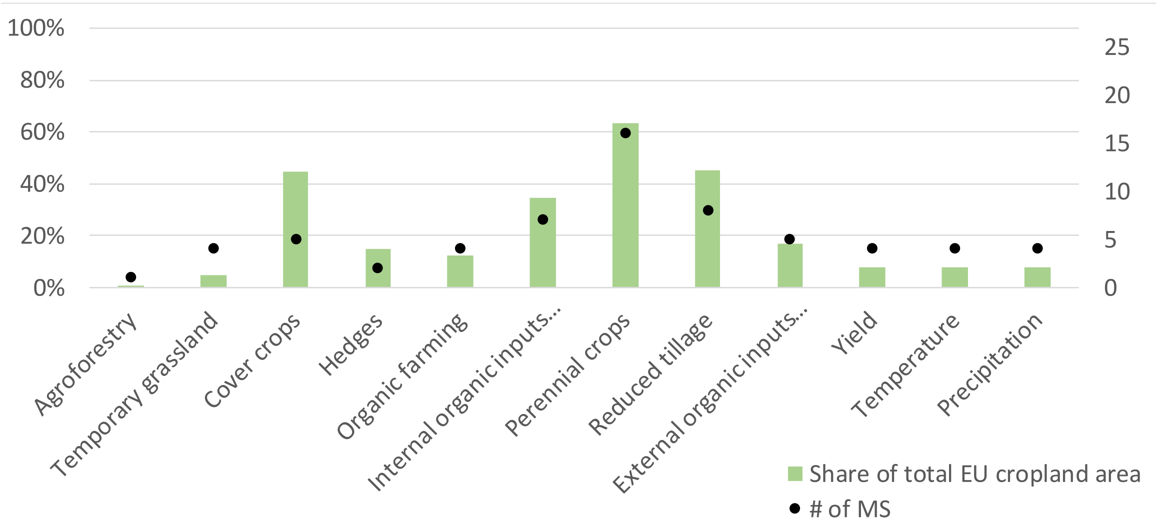
Apart from preserving grassland conversion to feed crops, few management practices are documented to increase soil carbon stocks and their large scale potential is limited (Bamière et al., 2023; Lugato et al., 2014).

Accordingly, we think that tracking grassland management practices should not be a priority as far as soil carbon is concerned. Note however that water table management with grasslands on peat soils may provide substantial climate benefits, in terms of several GHGs.

3.2.5 Which agricultural practices are commonly monitored?

Nine agricultural practices are currently being monitored by some member states (Figure 1). Three of them are being monitored for more than 40% of the EU cropland area: cover crops, perennial crops and reduced tillage. For all countries willing to follow some of the practices, a look at the NIRs of the member states already following them can be a source of inspiration on the method and data sources. The detailed list is downloadable here[6] (sheet "Practices captured_details" of file "21-06-30 - Soil_carbon_in_inventories.xlsx"). Note that no countries are currently monitoring practices related to water management in cropland and grassland (e.g., whose depth drives CH4 emissions or removals, or balance between CH4 and CH4 emissions), except for drainage and rewetting. Because it is explicitly listed in the IPCC Guidelines and in the CRF tables, biomass burning is generally monitored.

Figure 1. Practices and effects captured by the 2020 GHG inventories for cropland.



Source: Bellassen et al. (2022)[7]

3.2.6 Which agricultural practices are commonly monitored, but could be ignored?

Out of the nine practices listed in section 3.2.5, two of them – reduced tillage and organic farming – could arguably be ignored as far as soil carbon storage is concerned.

No/low-tillage practices could be ignored because the most recent meta-analyses conclude that, in the temperate zone context, they mostly redistribute soil organic carbon over the soil profile, with little to no increase in total soil organic carbon over the entire soil profile (Bamière et al., 2023; Haddaway et al., 2017; Ogle et al., 2019). The effect of conservation agriculture on SOC stocks is considered to arise essentially from the associated cover crops in temperate regions (Autret et al., 2016).

Organic farming could be ignored because it is more likely displacing storage through manure than actually triggering additional soil carbon storage when land-use changes (e.g. conversions from cropland to grassland required by the technical specifications) and the tendency to contain more hedges (observed tendency not required by the technical specifications) have already been accounted for (Gattinger et al., 2012; Ghabbour et al., 2017; Leifeld et al., 2013).

6 https://hal.inrae.fr/hal-03631358v2

7 An inventory is considered to be capturing the practice (agroforestry, ...) or effect (yield, ...) if a change in activity data for the practice or in the value of the effect is expected to result in a change of reported emissions. The share of total EU cropland area corresponds to the summed cropland area of countries whose inventory captures the practice over the total EU cropland area.

3.2.7 Which forestry practices could be monitored with a Tier 2 method?

Forest management practices are not explicitly monitored in GHG inventories when using Tier 2 estimates for soil carbon, with the exception of changes in forest species or "habitats" in Poland and Portugal. Two recent literature reviews have synthetized current knowledge on the impact of forest management practices on soil carbon (Mäkipää et al., 2023; Mayer et al., 2020). Based on these, we think that only one practice could be worth monitoring for the purpose of providing better Tier 2 estimates for soil carbon changes in the *Forest land remaining forest land* category:

— **Forest fertilization**: nitrogen fertilization increases soil carbon stocks by an average 23.5% in the mineral soil (Nave et al., 2009). Note that this climate benefit could be offset by increased N_2O emissions, so the overall GHG budget of forest fertilization remains unclear, and likely dependent on-site conditions (Mäkipää et al., 2023; Mayer et al., 2020). For GHG inventory purposes however, accounting for the soil carbon storage effect would make sense, because the other effects of fertilization (N_2O emissions and biomass growth) are usually already captured by the inventory.

Although whole tree harvesting - which consists in removing all aboveground wood, including harvest residues (small branches or stumps), from the harvesting site - has also been pointed out in some meta-analysis to result in a long-term decrease in soil organic carbon or litter, other meta-analysis find no effect on one or both carbon pools (Mayer et al., 2020). Accordingly, the IPCC Refinement (vol4, ch4, p. 4.8) do not recommend to track whole tree harvesting as a basis for Tier 2 estimates.

These literature reviews also conclude that clearcutting temporarily decreases total soil carbon (litter and soil carbon) by around 10%. However, because the recovery time is very heterogeneous, they do not venture to propose long-term average differences in soil carbon depending on rotation length. For this reason, using clearcut frequency as a driver of soil carbon changes in a Tier 2 method seems premature. The same rationale applies to stand thinning which is identified to result in a slight and temporary soil carbon loss.

Other forest management practices such as site preparation or species management are currently reported to have only minor, temporary or variable impacts on soil carbon stocks (Mäkipää et al., 2023; Mayer et al., 2020). In all cases, basing Tier 2 estimates on these practices currently seems premature and a repeated soil inventory or a reliable, litter-driven process-based model seem to be the only ways to properly account for management impacts on forest soils. In all cases, the revised LULUCF regulation requires a Tier 3 method for forest land by 2030 (see section 2.2).

3.2.8 Which are the possible data sources to monitor activity data for key practices or derive country-specific emission factors?

This section lists a series of data sources which can be used in most member states to derive country-specific emission factors or activity data. For each database, the emission factors and/or activity data which can – in our opinion – be derived from the database are explicitly listed. On this topic, readers may also usefully consult section 4 in Arets et al. (2021).

3.2.8.1 Emission factors

— LUCAS soil survey, other soil measurements, soil maps

The LUCAS soil survey, national soil measurements or inventories, and downloadable soil maps can be used to derive country-specific values for at least SOC_{REF} and F_{LU} (see section 3.5).

Existing analysis of the LUCAS soil survey already provide Tier 3 measurement-based estimates of soil carbon changes in cropland and grassland for the 2009-2018 period for all Member states (De Rosa et al., under submission).

3.2.8.2 Activity data

— Geographically explicit data

Three data sources are briefly presented below: LPIS, IACS and Copernicus. This list is not exhaustive. Other geographically explicit data exist at national (eg. OSO in France) or international (eg. Global Forest Database) levels.

— Integrated administration and control systems (IACS) and Land parcel identification systems (LPIS)

An LPIS is an information system recording the land-use of all parcels for which a subsidy from the Common Agricultural Policy is requested. There is not a unique European portal to access these systems, but some Member states allow access to their LPIS through the internet, and the reporting agency should have internal access to them, at least for non-confidential attributes. LPISs will typically provide activity data on:

- Land-use and management changes (at least between annual crops, perennial crops and grassland). This information is geographically explicit and exhaustive, and therefore good material for an Approach 3 to land representation, at least for these land-uses.
- Permanent versus temporary grassland (different impact on soil carbon).

Note that the agricultural fields that do not receive CAP subsidies are not always included into LPIS systems, and their quantity can vary between member states.

IACS is another tool related to the Common Agricultural Policy, to process its subsidies. There again, the type of activity data which can be retrieved from IACS varies between countries. In Denmark for example, afforestation subsidies recorded in IACS are used as activity data for Afforestation. Agro-Environmental and Climatic Measures (AECMs) recorded in IACS, as well as future Eco-Schemes, could provide activity data for some management practices, provided that these practices do not take place without CAP support.

For both LPIS and IACS, a first assessment of data availability in a given member state can be found on the INSPIRE website: https://inspire-geoportal.ec.europa.eu/index.html. It is however likely that much more data is available from country-specific websites or agencies.

— Copernicus

The Copernicus Land Monitoring Service (CLMS) https://land.copernicus.eu/, is one of the 6 operational Copernicus services, providing operational EO based products on various elements of Land Cover and Land Use (among others), free and open for all users. Although the main focus of the available data is on biophysical parameters and land cover products, there are also elements of land use. Among others, the following Copernicus products can contribute to improved geospatially explicit mapping and monitoring of activity data (or proxies to activity data):

- Land-use changes:
  - Long time series of land use and land cover change: Corine Land Cover (CLC): https://land.copernicus.eu/pan-european/corine-land-cover
  - Note that several informal feedbacks are consistent in judging that the accuracy of CLC maps not high enough to derive reliable land transition matrices.
  - A highly accurate pan-European land cover map (CLC+ Backbone), available for 2018, with an update for 2021 available end of 2023, and then updates every 2 years https://land.copernicus.eu/pan-european/clc-plus/clc-backbone
  - Maps of vegetation and vegetation change (tree cover and forest, grassland) https://land.copernicus.eu/pan-european/high-resolution-layers
- Hedges, agroforestry, trees outside forests: small woody features maps https://land.copernicus.eu/pan-european/high-resolution-layers
- On burnt area: the global component of the CLMS has burnt areas in their portfolio https://land.copernicus.eu/global/products/ba and there is also a global fire monitoring element of the Copernicus Atmosphere Monitoring Service https://atmosphere.copernicus.eu/global-fire-monitoring

As a part of the new CLC (named "CLC+"), the CLMS is **currently developing tailor made 100m grid products that try to approximate LULUCF activity data categories**, the so called "LULUCF instances". These combine existing land cover and land use data in a web-application/database (CLC+ Core). CLC+ Core is also available for countries to use, and additional training can be offered in the second half of 2023. First prototypes will be available from Q2/2023.

— Farm Accountancy Data Network (FADN)

FADN is a European database originally focused on farm accounts (products, costs, profits, …) in euros, although it is evolving towards data on physical amounts in tons or number of animals, with the objective of performing environmental assessments. It is updated annually and covers only a representative sample of farms.

The European FADN can already provide activity data on the extent of organic farming in hectares, although the relevance of this practice for soil carbon monitoring is debatable (see 3.2.6).

More interestingly, the national FADNs usually contain more data than what is sent to DG Agri for the European compilation. This data can sometimes be the activity data for a relevant practice regarding soil carbon. The Italian FADN for example contains data on the amounts of organic inputs to soils. Whether your national FADN contains useful activity data for soil carbon monitoring is to be assessed on a country-by-country basis.

— Agricultural census

There is no aggregated agricultural census at the European level. However, most Member states conduct an exhaustive agricultural census or similar non-exhaustive surveys at variable frequencies (3-15 years). Similarly, to national FADNs, whether your agricultural census contains useful activity data is to be assessed on a country-by-country basis. One may hope to find activity data on food standards (eg. organic, geographical indications), the number of hedges or agroforestry plots, etc.

— Farm practices surveys

There is no aggregated farm practices survey at the European level. However, most Member states conduct such surveys on a small sample of farms or fields at variable frequencies (5-15 years). Similarly, to national FADNs, whether your farm practices survey contains useful activity data is to be assessed on a country-by-country basis. One may hope to find activity data on the amounts of organic inputs to soils, the number of hedges or agroforestry plots, the extent of cover crops, etc.

3.3 Deriving country-specific emission factors (Tier 2)

3.3.1 What are the obvious candidates for country-specific emission factors?

According to the IPCC Guidelines, there are four candidate parameter sets which can be customized based on national measurements (2019 Refinements ch4, p. 2.38-2.39):

- Defining management systems
- Climate regions and soil types
- Reference C stocks (SOC_{REF})
- Stock change factors (F_{LU}, F_{MG} and F_I)

We think that SOC_{REF} and F_{LU} are the easiest to start with. In many countries, there is data to derive country-specific values for at least SOC_{REF} and F_{LU}. Section 3.5.1 explains where to find soil carbon measurements and how to derive SOC_{REF} and F_{LU} based on these data sources.

Note that you will need to define what you consider to be the “reference condition”, where SOC = SOC_{REF}. In principle, the reference condition is the native vegetation for a given climate region and soil type, but under Tier 2, you can define your own “non native” reference condition for SOC_{REF}, as long as it can be assumed to be at a steady-state regarding soil carbon. To increase comparability with other inventories, it is preferable to select the land use and management with the highest carbon stock in most climate regions and soil types as the reference condition, typically conventionally managed forest or extensive grassland.

Once you have country-specific SOC_{REF} and F_{LU} values for each stratum (see section 3.5.1 on the necessity of stratification), you may want to customize the other stock change factors, which will require the acquisition of data on management practices (cover crops, amount of inputs, …) together with the soil measurements. To lower costs, an option can be to relocalize management-related surveys (e.g. farm practice surveys, FADN, …) on the soil inventory plots (e.g. LUCAS soil survey, national soil inventory plots, …). Alternatively, you may want to use the simple steady-state approach proposed in the 2019 IPCC refinements (see section 5.2.3.1 and Box 5.1 in the 2019 IPCC refinements).

3.3.2 Is Tier 2 enough? Relevant questions to be asked before moving to Tier 3

For wetland, forest land, protection sites, restoration sites and areas, and areas under climate risk, the revised LULUCF regulation requires a Tier 3 monitoring method from the 2030 inventory submission onwards (see section 2). For other areas, Member States can choose between Tier 2 and Tier 3.

In order to make the best choice between Tier 2, model-based Tier 3 and measurement-based Tier 3, this section offers two considerations – a typology of Tier 3 methods and the IPCC Guidelines requirement on model evaluation – and then a series of three questions which we think should be positively answered to prefer model-based Tier 3 over Tier 2 or measurement-based Tier 3. To put it simply, a good Tier 2 can be more accurate and more informative for policy makers than a bad Tier 3.

3.3.2.1 Typology of Tier 3 methods

Tier 3 methods cover two different approaches: measurement-based methods and model-based methods (see 2019 Refinements ch2, p. 2.42-2.48 and 2.57-2.66 for details). Measurement-based methods mobilize repeated soil inventories for which soil samples are being collected over hundreds of sites. In the 2020 submissions, this strategy was implemented by Sweden for forests and grassland, by Germany for forests and by Belgium for grassland (Bellassen et al., 2022). In model-based methods, a process-based model (mostly involving half-life based decay factors and carbon transfers between different organic matter pools such as Yasso07, C-Tool, Roth-C, CBM-CFS3 and others) simulates soil carbon changes based on inputs such as weather data, soil type, litter input (which is derived e.g. from forest inventory and harvest statistics data). In the 2020 submissions, this strategy was implemented by Finland, Austria and Ireland for forests, and by Finland, Sweden and Denmark for cropland. And in the later UNFCCC submission more countries have opted for models into their inventories, like Czechia for Forest land.

3.3.2.2 Evaluating a process-based model for soil carbon at national scale, a challenging requirement

Where a Tier 3 model is used, the IPCC Guidelines require that it be evaluated in the national context and at national scale. More specifically, the Guidelines require that:

« For Tier 3 approaches, **a set of benchmark sites will be needed to evaluate model results**. Ideally, a series of permanent, benchmark monitoring sites would be established with statistically replicated design, **capturing the major climatic regions, soil types, and management systems** as well as system changes, and would allow for **repeated measurements** of soil organic C stocks over time (Smith, 2004a). Monitoring is based on re-sampling plots every 3 to 5 years or each decade;" 2019 Refinements ch2, p. 2.43

Note that while this requirement still leaves room for interpretation, it makes clear that the evaluation is needed not for the model alone, but rather for the entire modelling setup as applied for the inventory, including the country-specific input data and all explicit and implicit assumptions needed. In other words, referring to the evaluation of the same model with a couple of long-term experimental sites in another country is not sufficient. Furthermore, evaluating the model should consider how both the level and the trend of emissions are captured.

However, evaluation of models may prove challenging in practice for soil carbon models. The findings in scientific literature show both more and less successful results for model evaluation with measured data. In particular, while reproducing a single number – e.g., the national average soil carbon change over a single time period – may be relatively straightforward, reproducing several numbers such as a trend between different regions or different time periods is much more challenging (Bellassen et al., 2022).

Countries have tested soil models against measurements and results of these tests have been variable, some of them more successful, such as Ortiz et al. (2013) for regional level for forest land, and for agriculture with organic amendments Karhu et al. (2012), for land-use change Karhu et al. (2011) and for Japanese agricultural lands (Shirato et al., 2004). However, it has been also found that in some cases models were not able to predict carbon stock changes, e.g. for broadleaved species in France (Mao et al. 2019). Also, according to NFAP of Sweden and Austria (Federal Ministry for Sustainability and Tourism, 2019; Ministry for the Environment, 2019) model-based estimates for soil C stocks differed from those of measured showing that models were not able to reproduce measurements for specific regions in Austria and for Sweden. While, Ortiz et al. (2013) found for Sweden that the uncertainties of the soil models Yasso and Q and repeated soil C measurements are of the same magnitude for the estimated soil C stocks and stock changes among the different methods. For examples of Tier 3 model applications for mineral soil c stock change and testing against data, see Box 2.2d in IPCC (2019) refinement.

Beyond the lack of specific recommendations on statistical tests, the evaluation requirement can be based e.g. on testing if the historical repeated soil C measurements and model-based estimates for soil C change differ statistically. According to Rantakari et al. (2012) it was found that soil C change based Biosoil soil inventory and Yasso07 soil model did not differ statistically, when uncertainties measurements and modelling were accounted for. Process-based models contain many parameters which can be adapted, arguably to better represent national circumstances or default parameter setting can be used. It is also important to note, that when testing models against measurements, input data (e.g. time series of litter inputs and weather) for models should be unbiased. Also, prerequisite for the fair model and data testing is that measurement and sampling errors for data reasonable low and quantified.

Considering the likely challenges in evaluating the models for Tier 3 estimations of soil carbon changes, it is not straightforward to say that it would result in more reliable estimates than Tier 2 or measurement-based Tier 3. Therefore, the choice of the most meaningful Tier method for the national circumstances should be carefully considered. In particular, the following questions should be positively answered before deciding for Tier 3 model application for GHG inventory.

3.3.2.3 Do I have the necessary input data?

When applying soil models, monitoring key practices is as necessary for Tier 3 as it is for Tier 2. Where key practices are not satisfactorily monitored, inventory estimates will remain inaccurate, not matter whether they are based on Tier 2 or model-based Tier 3. Input data on weather, yield and soil characteristics is also necessary. Note that in the specific case of forest land, the impact of many management practices on soil carbon is – in theory – mediated by the amount of litterfall and harvest residues. Data on these two elements may be available from repeated national forest inventories and harvesting statistics. Accordingly, management-induced changes in the biomass and litter fall and thereafter in the soil C change can be likely be captured by models using this data, lessening the importance of tracking practices and narrowing it to practices whose impact are not mediated by litter (eg. site preparation).

3.3.2.4 Do I have enough soil measurements to evaluate the model?

Model-based Tier 3 approaches can reduce the number of measurements needed compared with measurement-based Tier 3 (see section 3.5.3), but they do not remove the necessity of actual measurements, representative of the national diversity and regularly updated, for model evaluation (see evaluation requirement above). Where measurements representative of national circumstances cannot be identified, a model-based Tier 3 cannot meet the evaluation requirement of the IPCC Guidelines. Note, however, that measurements from neighbouring countries or international data sources can, where demonstrated, be representative of the national circumstances. Logically testing the soil C model against measurements should be preferably done with spatial scale that equals with that of the GHG inventory reporting. Also, measurements about soil heterotrophic respiration and measurements of soil C stocks can be used for model testing (see e.g Tupek et al. (2019, 2016)).

3.3.2.5 Do I have enough expertise to implement a Tier 3 model and interpret its results?

In principle, one of the advantages of a model over a measurement-based estimate is that it allows to disentangle the effects of climate, **practices** and differences between different models in the estimated national or regional totals. However, in-depth knowledge of the model and the implementation of several counter-factual simulations are necessary to exploit this advantage. Where the necessary time and expertise cannot be sustained in the inventory team, model will remain as a “black box” which do not inform either inventory compilers or policy makers on the drivers of observed carbon stock changes. Therefore, it is recommended that reasonable resources will be allocated for model application and for the model testing.

3.4 Using process-based models (model-based Tier 3)

3.4.1 Why not to measure soils for soil C stock change?

Repeated soil inventories are valuable data sources for monitoring changes in soil health, soil function and other soil properties, like soil carbon stock. Countries that have existing soil monitoring programs are fortunate, as soil inventories are expensive, and establishment of new soil inventory schemes is unlikely if national budgets for environmental monitoring are limited. According to Mäkipää et al. (2008) one round of forest inventory would have cost of a 4 mill. € for Finland in 2008. And current estimates for annual costs for soil inventory would be ca. 1 mill € based on the experience from Norway and Sweden.

The EU commission and the EEA are jointly collecting soil data from member states, namely LUCAS inventory is used for mapping soil properties (see section 3.2.8). LUCAS inventory collects soil samples from the top 30 cm soil layer and since 2022 a special focus has been given to differentiate soil organic and mineral layers, which facilitates the use of this data in future for detection of soil property changes also in forest lands. In the current form LUCAS data can facilitate soil model testing, e.g., testing measured C:N ratios against C:N ratios derived from soil model.

Establishment of a soil inventory requests a long-term commitment from the country or from the regions. The field campaign can take several years depending on the extent of the land area, and thereafter laboratory work takes time before producing data to be analysed. In order to monitor changes in the soil properties, one needs to redo field monitoring e.g. after 10 years (Schrumpf et al., 2011) and the results on the soil property changes are only ready for analysis around 15 years after the initialization of the first inventory round.

When establishing soil inventories, one should pay extra attention to procedures minimizing potential bias that may originate if there are changes in the field- or lab procedures during the consecutive soil inventories. To minimize these error sources extra attention should be given for training field and lab personnel. Also, an appropriate number of samples should be taken from a single field plot in order to minimize the impact of high spatial variability, especially with forest soils (Häkkinen et al., 2011).

Drained peatland soils are emissions hot-spots, and climate change mitigation by reducing emissions from those lands is of high priority (Griscom et al., 2017). Measurement of the soil C stock change of peatlands is challenging, as vertical peat profile position varies due to moisture and peat layers may have a depth of tens of meters. This implies that for that carbon stock change in peat soils, other approaches, like empirical modelling are needed (Alm et al., 2022).

3.4.2 What resources do I need to secure before considering Tier 3?

To move to Tier 3 level of emission estimation methods, an entity running GHG inventory needs to have relevant expertise with personnel having permanent contracts, long term institutional commitment for this statutory task. Moreover, in optimal case this task should be conducted by a research institute which has research on this field, and which develops GHG estimation methods.

3.4.3 Which input data is required to run a model?

The minimum input data for running simple soil models for forest land includes time series of annual litter production that can be derived from the consecutive forest inventories. To estimate biomass and litterfall from forest inventory data one needs to have biomass equations or biomass expansion factors (BEF) and turnover rates for litterfall by components (e.g. foliage, branches bark, woody roots and fine roots). In addition to litter from living biomass, time series of inputs to soils from natural mortality, understory vegetation and harvest residues should also be accounted for to close total carbon budget of forest ecosystem.

Soil models also need weather data for simulating soil C stock change. Typically, models require air temperature and precipitation data. The time resolution of weather data depends on the soil model, varying typically between one day and one year.

It is known that soil texture affects soil carbon stabilization by mechanism where clay soils have higher potential for locking soil organic matters to soil aggregates. Some models (e.g. CENTURY) do account variability in the soil texture and that texture information for model input can be based on the soil inventories (e.g. LUCAS) or on the databases, like SoilGrids.

3.4.4 Initial soil carbon: spin-up or soil carbon map?

According to (Peltoniemi et al., 2006), it took less than 15 years to eliminate the impact of spin-up run to actual soil C change estimates for Yasso model. Therefore, it is recommended that model initialization starts well before the time series that is to be reported. For example, if reporting starts from 1990, then it would be important to initialize soil C model during the 1970s to minimize effect of the spin-up assumption to reported soil C change estimates.

Another alternative for this is to use soil C measurements, but this approach is challenged by the fact that measured soil C stock may not be in-line with estimated litter fall (quantity and quality) e.g. due to land use history and therefore one needs evaluate model derived soil C change estimates carefully after initialization with measurements as there might be a “transient” period where model is approaching the state where litter fall and decay are in-line according to the model decay rates.

For these reasons, we recommend that a 15 to 20 years spin-up initialized with times series of litter fall and using either mean measured soil C stocks or a soil carbon map as the starting point of simulations. Moreover, a carbon map based on interpolated soil measurements can be used as one of the elements to evaluate the model, by comparing it to spin-up values. It is important to quantify the impact of model initialization on the soil carbon change estimates and to assess the necessary period for the initialization of the model.

3.4.5 Which soil data is required to evaluate a model?

Model evaluation, that is demonstrating its ability to reproduce historical data, is a key IPCC requirement (see section 3.3.2 of this document). One can evaluate soil carbon models against soil carbon stock, soil carbon stock change and soil respiration measurements. For using soil carbon models in the case of land-use change, validating the predicted carbon stocks for each land-use in the reporting classes (e.g. regions, soil types, etc.) type conditions can be considered sufficient. However, when for estimating soil carbon changes in "land remaining land" categories, soil carbon stock change data are recommended for model validation.

In order to test and improve detailed functionality of a process-based soil model, one can also use soil heterotrophic respiration data that has been acquired e.g. using trenching approach (Schindlbacher et al., 2012).

3.4.6 What are the relevant temporal and spatial scales to validate a model?

Optimal model validation scales are those that agree with scales that model has been applied in the GHG inventory. For example, if modelling results are provided at regional level, e.g., due to fact that data on harvesting residues and natural mortality are available on that scale, then it would be natural to test the model at the same scale.

If testing has been done against soil carbon change measurement, those are available with a temporal resolution, which varies typically between 5 and 20 years. The temporal scale of validation is often defined by the data availability.

3.4.7 What are the relevant temporal and spatial scales to report the simulated values?

Countries must decide what is the relevant temporal and spatial resolution for their reporting categories. For example, Finland reports soil carbon stock changes separately for Southern- and Northern Finland. Countries may opt for finer spatial resolution if they see it appropriate. Note, that the uncertainty of sample-based data increases when moving for finer break-down of subcategories (e.g. the uncertainty of the input from NFI or repeated soil inventory).

Temporal scales for model results varies between member states. In particular, some MS opt for smoothing the annual variability of the climatic forcing by using long-term moving average climate as an input for the model, and some opt for averaging the outputs by reporting multi-year averages.

Finally, let us note that to ensure timely reporting, that is the reporting of estimates for year y-2 in the NIR of year y, measurement-based methods are necessarily complemented by models. These can be extrapolations, as proposed in Chapter 5 of the volume 1 of the IPCC Guidelines, or more complex models such as those mentioned above.

3.5 Using soil carbon measurements and soil carbon maps

3.5.1 How to derive the reference carbon stock and carbon stock modifying factors based on soil measurements?

3.5.1.1 Step 1: identify data sources

The most obvious data source to derive country-specific SOC_{REF} and F_{LU} values is the LUCAS soil survey (2009-present) which is freely downloadable and whose sample density is comparable to national soil inventories (see 3.5.3). Bulk density is only measured since 2018 and only for a limited number of sites so a pedotransfer function is needed to estimate it where it has not been measured (see for example Schneider et al. (2021) on how to choose and implement a pedotransfer function) and thereby obtain carbon content estimates (instead of carbon concentration) for all LUCAS points. Note, that on forest land sampling with LUCAS, miscommunication with field crews resulted in partial mixing organic and mineral soil layers in forests of several member states before 2022 (at least Finland and Germany). This problem is therefore worth checking in other member states who would be willing to used pre-2022 LUCAS data for forests.

The LUCAS soil survey can be completed or replaced with national measurements of soil carbon content where they exist.

Another alternative is the LUCAS-ML high resolution map of soil carbon stocks (to be published on the ESDAC website), or similar maps at national or international level (e.g., FAO soil maps or SoilGrids). The advantage of these maps is that they already provide an estimate of soil carbon stocks per pixel, without the need to manipulate data on soil carbon concentration, bulk density and pedotransfer functions. The inconvenient is that they are not direct measurements and therefore, they already come with some modelling uncertainty. They will also need to be overlaid with a land use map to be obtained separately, which will add its own modelling uncertainty, whereas direct measurement usually come with the associated land-use, with no further effort and modelling error.

3.5.1.2 Step 2: the "similarity guidance", a call for stratification

The crucial « similarity » guidance of the IPCC guidelines is regularly overlooked in GHG inventories: « it is *good practice* that the **plots being compared have similar histories and management as well as similar topographic position, soil physical properties** and be located in close proximity." (2019 Refinements ch4, p. 2.39). There is a sound rationale behind this guidance: historically, the most fertile soils, which tend to have higher carbon stocks, were preferentially chosen for cropping. Similarly, the less fertile soils were left forested or where naturally reforested first in cases of agricultural decline. Therefore, if topographic position, soil physical properties etc. are not controlled for, F_{LU} values will be biased, generally in favour of cropland (and to a lesser extent grassland).

In practice, we propose to interpret this requirement as « plots being at least in the same climate region and soil type ». In all cases by consequence, a simple difference of average soil carbon stock per land use at the national level is not accurate, unless it can be argued that the entire country falls within a single climate region and soil type. Therefore, a stratification of the country should be undertaken with the aim of grouping soil measurements into consistent climate regions and soil types, while ensuring that each strata retains enough measurements to average out the sampling error. At the very least, fewer than five sites per major combination of climate x soil x management system, with three measurements per site (Poeplau et al., 2022), would not seem reasonable. Note that, where relevant, soil measurements from a neighbouring country with similar conditions to one of your strata can be added to it in order to increase sample size.

3.5.1.3 Step 3: compute the average per land use for each stratum

For each stratum, you can then compute the average soil carbon stock for each land use (and possibly subdivided into different management types). The average soil carbon stock of the "reference condition" (usually forest or extensive grassland, see section 3.3.1) will be your SOC_{REF} for this stratum.

F_{LU_i} for each land-use (or land-use and management combination) i present in this stratum can then be computed as $F_{LU\_i} = \frac{SOC_i}{SOC_{REF}}$ where SOC_i is the average soil carbon stock for land-use (or land-use and management combination) i in this stratum.

Note that there are more satisfactory ways to fulfill the "similarity" requirement than these averages per stratum, such as the use statistical models controlling for topography, climate, soil type, etc. Schneider et al. (2021) provides an interesting example of statistical model applied on the LUCAS soil survey to derive F_{LU} values.

Also note that this method implicitly relies on the assumption that the measured sites have reached a steady-state equilibrium. Generally, the fraction of the sample likely affected by land-use change over the recent past is sufficiently small to broadly justify the steady-state assumption, but this can be refined where more data is available, for example by excluding sites which have recently undergone land-use changes.

3.5.1.4 Step 4: quality assurance

Once you have obtained your country-specific estimates for SOC_{REF} and F_{LU}, it makes sense to verify them against default values (for SOC_{REF}: 2019 Refinements ch4, p. 2.35 for SOC_{REF}; for F_{LU}: 2019 Refinements ch4, p. 5.27 and p. 6.6; see also Poeplau et Don (2011) and Schneider et al. (2021)).

If there are substantial/counter-intuitive differences between your country-specific values and the default ones regarding SOC changes as the result of land-use changes (eg. opposite sign such as an F_{LU} for cropland equal or higher than forest and grassland), we advise that you provide an interpretation, preferably backed by peer-reviewed papers, in your NIR. If you cannot find any rationale to justify large discrepancies, and in particular opposite signs, between your estimates and default values, it may be preferable to revert to default values.

3.5.1.5 Step 5: “Planned improvements”

Finally, here are two ideas of “planned improvements” once you have country-specific estimates for SOC_{REF} and F_{LU}.

First, you can try to obtain country-specific estimates for the other stock change factors (F_{MG} and F_I). To do so, you will need to collect data on management practices at the measurement points, for example by including management practices to future data collection campaigns on soil or by coordinating soil inventories with other surveys, or even by explore existing data from various research.

Second, you can look for or fund measurement or modelling studies relevant to your national circumstances. These studies can either aim to estimate new country-specific stock change factors (see paragraph above) or to move to Tier 3 for some land categories.

3.5.2 Why are regular soil measurements necessary for Tier 3, even under a modelling approach?

Soil measurements are necessary for Tier 3, even if a modelling approach is chosen, in order to meet the evaluation requirement of the IPCC Guidelines (see section 3.3.1), noting that the number of measurements is reduced if their purpose is only to evaluate a model (see section 3.4.1).

3.5.3 How many soil measurements is enough? What is the typical uncertainty of soil inventories?

There is no easy answer to this question. One can however document the number of soil measurements in countries which are using or are planning to use a measurement-based Tier 3 approach (Table 3). This list also shows that the density of the LUCAS soil survey is not substantially different than existing national soil inventories. Also note that the indicative sample size per 1,000 km^2 should be considered with care: heterogeneity, not size, drives the necessity for a larger sample. Because heterogeneity and size are correlated, the indication is useful, but because they are not proportional, one can expect that larger countries require fewer samples per 1,000 km^2. Finally, Member states can consider the possibility to use points from neighbouring countries or regions with similar characteristics to their own.

Table 3. Sample size (number of sites, with often 4-5 measurements per site[8]) of a few existing soil inventories

Member State	LUCAS soil sample size in 2015	Sample size of the National soil inventory[9]	
		Total	Per 1,000 km²
France	3050	2158	4
Belgium	146	629	20
Denmark	222	336-590	11
UK	744	256-591	3
Sweden	1903	6500[10]	16

Source: Bellassen et al. (2022), updated

Countries which are planning to use a model-based Tier 3 approach also need a minimum number of repeated soil measurements for validation purposes (see section 3.3.1). There again, there is no objective way to tell how many are enough. The more the better, as it allows to reduce the substantial sampling error: for example, the 95 % confidence interval of the national for forests was estimated at 0.25[11] tC ha^{-1} yr^{-1} (106 % of the estimated change over the 1994-2000 period considered) in Sweden (Ortiz et al., 2013) and 0.22[12] tC ha^{-1} yr^{-1} (54 % of the estimated change over the 1990-2007 period considered) in Germany (Grüneberg et al., 2014). At the very least, fewer than five sites per major combination of climate x soil x management system, with three measurements per site (Poeplau et al., 2022), would not seem reasonable. In Finland, Heikkinen et al. (2021) finds that several hundred measurements would be needed to detect a SOC change of 1 tC ha^{-1} at a field level, which indicates that monitoring should be done at the regional level.

3.6 Organic soils

Because drained organic soils typically emit around 10 tCO_2e ha^{-1} yr^{-1} with a large variability (Barthelmes et al., 2015; IPCC, 2014), improving the monitoring of organic soils should arguably be a top priority of countries with a large area of drained organic soils. At EU level, emissions from organic soils are comparable to the carbon stock changes probably occurring in mineral soils, but they are concentrated on 5% of the land (Bellassen et al., 2022). A first critical step is to secure reliable and up-to-date activity data on the extent of organic soils and their drainage or rewetting.

Because large areas of organic soils fall into the forest land or wetland categories, a second step will be required by 2030, namely moving to a Tier 3 approach for soil carbon stock changes in these soils. There again, a choice has to be made between measurement-based and model-based methods, but both require specific considerations when it comes to organic soils.

3.6.1 Which soil measurements for organic soils?

Because the organic layer may exceed sampling depth, soil carbon measurements are generally not reliable for organic soils. Alternatively, the IPCC 2013 wetland supplement recommends the use of flux methods or subsidence methods (p. 2.49-2.51).

3.6.2 Does it make sense to use a model for organic soils?

Monitoring peat soils with repeated inventories, is challenging due to high spatial variation, peat depth and due to vertical movement of peat layers due to soil moisture. Therefore, the basis of monitoring of these lands has been the use of emission factors and/or modelling on agricultural and forest lands.

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8 Poeplau et al. (2022) shows that 3 measurements per site is enough to substantially reduce variability at plot level.

9 When the sample size varies between measurement campaigns, a range is provided. In that case, the middle of the range is used for the size per 1,000 km².

10 4500 from the NFI on mineral soils (https://doi.org/10.1038/s41598-017-15801-y) and 2000 for cropland (: https://www.slu.se/en/departments/soil-environment/environment/akermarksinventeringen/undersokningar/soil-and-crop-inventory/).

11 Original figure of 7 TC yr^{-1} divided by the 28,084 kha of forests reported for the year 2000 in the Swedish inventory.

12 Standard error multiplied by 1.96, including measurement errors. The sampling error was estimated at 0.06 tC ha^{-1} yr^{-1}.

For example, Finland used to estimate emissions from drained forested peat soils with a Tier 2 method: the estimate of the emissions was based on the difference between heterotrophic respiration and belowground litter input (more input, less emissions and vice versa). It was found that this method produced estimates that were not logical in the long term as mean tree biomass increased and the litter input was also increasing while the soil heterotrophic estimates remained the same. Therefore, Finland moved from a Tier 2 method to a Tier 3 method. The new method (Alm et al., 2022) is using also heterotrophic respiration data and forest inventory, but in the new modelling method, other predictors such as summer temperature, aboveground biomass (basal area) and amount of harvesting residues are also considered. In principle, this Tier 3 approach could be applied to drained forested peat soils in other countries as well, provided that the input data is available. In practice, it would require validation and potentially calibration on sites representative of national conditions, as all Tier 3 models (see section 3.3.2).

The next development tasks with Finnish GHG-inventory and with drained peatlands forests relate to new findings on the CH_4 emissions and sinks from ditches on drained peatland forests (Rissanen et al., 2023). Also, more research is needed urgently on the GHG emissions from soils of clear-cut drained peatland, see e.g. Korkiakoski et al. (2023) for results from Lettosuo site.

4 Conclusions

The 2023 revised LULUCF regulation will require Tier 2 methods for monitoring all land and carbon pools by the reporting of the 2026 emission year, and then later Tier 3 methods for a subset of land including, among others, forests and peatlands that undergo restoration or protection for nature directives. This requirement is particularly challenging for soil carbon for which Tier 1 is still used by many Member States for several land categories. This document offers answers to frequently arising questions in the topic of higher methodological tiers for soil carbon pool monitoring, as well as practical advice on how to implement them. Regarding Tier 2, we suggest a step by step method to estimate reference carbon stock (SOC_{ref}) and carbon stock modifying factors (eg. F_{LU}) using national datasets on soil carbon or international databases such as the LUCAS soil survey. We also propose a list of FMG emission factors for agricultural practices based on a literature review for the temperate zone. Regarding Tier 3, we distinguish between measurement-based methods (repeated soil inventories) and model-based methods. Measurement-based methods tend to be costly, but they are necessary as no model can guarantee an accurate national total in a context of environmental and management changes. Model-based methods allow to disentangle the different drivers of soil carbon changes and reduce the number of repeated measurements needed.

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List of abbreviations and definitions

AECM	Agro-Environmental and Climatic Measure
C	Carbon
CAP	Common agricultural policy
CLC	Corine Land Cover
CLMS	Copernicus Land Monitoring Service
CRF	Common Reporting Format
DG CLIMA	Directorate-General for Climate Action – European Commission
EU MS	Member State(s) of the European Union
FADN	Farm Accountancy Data Network
GHG	Greenhouse gas
HWP	Harvested Wood Products
IACS	Integrated administration and control systems
IPCC	Intergovernmental Panel on Climate Change
IPCC AR	IPCC Assessment Report
JRC	Joint Research Centre – European Commission
LPIS	Land parcel identification systems
LUCAS	Land Use and Coverage Area frame Survey
LULUCF	Land Use, Land-Use Change and Forestry
NIR	National Inventory Report
SOC	Soil organic carbon
SOC_{ref}	Reference carbon stock
UAA	Utilised agricultural area
UNFCCC	United Nations Framework Convention on Climate Change

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