Received: 30 October 2023 | Revised: 7 February 2024 | Accepted: 8 March 2024

DOI: 10.1111/ejss.13477

SURVEY ARTICLE

European Journal of Soil Science WILEY

How does national SOC monitoring on agricultural soils align with the EU strategies? An example using five case studies

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Funding information

European Joint Programme Soil; Horizon 2020 Framework

Abstract

Soil functioning contributes to the delivery of a vast range of ecosystem goods and services, and ecosystem health is therefore reflected by the capacity of the soil to perform underlying functions. Soil organic carbon (SOC) is a key indicator for soil quality as it is an integral driver of many soil functions and associated ecosystem services. Across the globe, SOC stocks are declining due to expanding agriculture and unsustainable practices. Awareness of the fact that soil is a non-renewable resource and its functioning important for all life on Earth is increasing, especially among policymakers. As such, goals for the preservation and restoration of SOC are formulated in policies under the European Green Deal. However, the evaluation of these goals at the European level is hampered by a non-harmonized diversity in national SOC monitoring strategies. While some SOC indicators can be useful for the evaluation of most policy goals (i.e., baseline and potential SOC stocks), additional and contrasting SOC data are often required for the evaluation of the goals formulated by the different EU directives. This study provides an overview of five ongoing SOC monitoring programmes across Europe and discusses how national programmes may be aligned to evaluate goals at the EU level. Five countries with very different soil monitoring programmes were included in a case study to illustrate the potential for harmonization and standardization of SOC assessment. Based on this study, we conclude that SOC monitoring strategies can be harmonized, but not standardized. We further suggest five sampling strategies that have potential for harmonization under the proposed Directive on Soil Monitoring and Resilience.

KEYWORDS

agricultural soil, harmonisation, SOC, soil health indicators, soil monitoring, standardisation

1 | INTRODUCTION

1.1 | Importance of soil organic carbon for soil health and ecosystem functioning

If soil biodiversity is the engine, soil organic carbon (SOC) is the fuel.

Soil science is at the crossroads of many scientific disciplines that aim to address urgent environmental challenges related to climate change, biodiversity preservation, water and food safety and security. This is because soil is the largest carbon (C) sink on Earth and can contribute to a range of ecosystem services that in turn help to address needs, such as the provision of food, nutrient cycling, climate regulation, sequestration of atmospheric carbon dioxide (CO_2), flood regulation, habitat for organisms, water purification and soil contaminant reduction (FAO, 2015; IPCC, 2022). Following the renewed EU Soil Strategy (COM (2021) 699), the protection of soil functions has garnered much attention from the European Union. Common principles for protecting soil functions against a range of threats were manifested there in with the objective to protect the soil while using it sustainably, through the prevention of further degradation, the preservation of soil functions and the restoration of degraded soils.

Soil organic matter (SOM) supports the development of soil structure and the formation of stable aggregates (Beare et al., 1994; Waters & Oades, 1991) and improves the infiltration and the storage of water and nutrients (Jones et al., 2005). These characteristics render the monitoring of SOM highly meaningful to evaluate soils regarding their potential capability (*soil quality*) and actual capacity (*soil health*) to deliver ecosystem services (Faber et al., 2022; Martínez et al., 2008). It has been long recognized that soil organic carbon (SOC), a major component of SOM, is the most often assessed soil quality indicator and a key component of any terrestrial ecosystem (Batjes, 1996) and that storing more C improves soil health and ecosystem functioning. Moreover, SOC provides energy for all soil processes and thus is a fundamental entity. The World Soil Charter (FAO, 2015) highlights the importance of soil as 'a key enabling resource, central to the creation of a host of goods and services integral to ecosystems and human well-being'. However, in major parts of the world, SOC stock is declining due to expanding and unsustainable agricultural practices (e.g., Sleutel et al., 2003), resulting in, among others, decreasing crop yields and soil health and increasing atmospheric CO_2 emissions. Soil health can be improved by, for example, implementing management options that foster an increase in SOC content, or preserve an existing stock, in particular soils of already high SOC content. A potential increase in SOC stock is, however, 'not a matter of climate change mitigation at first' (Deluz et al., 2020), but it is essential for the functioning of a soil as 'cornerstones of ecosystem services' (Deluz et al., 2020; Hooper et al., 2005). Eventually, soil functioning and soil health largely depend on SOC content (Bunemann et al., 2018; Lal, 2006).

Highlights

- Soil organic carbon (SOC) is the most often assessed soil quality indicator.
- Five monitoring programs across Europe are compared with regard to soil sampling and SOC analysis.
- SOC monitoring strategies can be harmonized, but not standardized.
- We suggest sampling strategies with the potential for harmonization under the Soil Monitoring Law.

Soil is a non-renewable resource. Therefore, changes in soil health indicators should carefully be monitored to avoid further degradation due to human activities (McBratney & Field, 2015). In addition, increases in SOC stocks are slow and relatively small compared to the total stock and are therefore hard to establish. Consequently, long-term SOC monitoring in combination with modelling potential evolution of SOC stocks is essential to inform policy and decision-makers on the soil's status and its capacity to help solve urgent environmental challenges.

To this end, this study presents an overview of selected SOC monitoring programmes across Europe that include SOC measurements and discusses how to align national programmes for pan-European assessments of soil health in view of the objective of the European Soil Strategy that all European soil ecosystems shall be in healthy condition by 2050.

1.2 | Soil organic carbon in European policy

The Common Agricultural Policy (CAP) has a major influence on the soil management activities of Member States as they subsidize sustainable agricultural practices (CAP, 2022). Each Member State implements the CAP with a strategic plan at the national level (see CAP, 2023). This national plan targets the specific needs of individual countries and is expected to simultaneously contribute to the ambitions of the European Green Deal. The preservation and restoration of SOC has also been formulated in

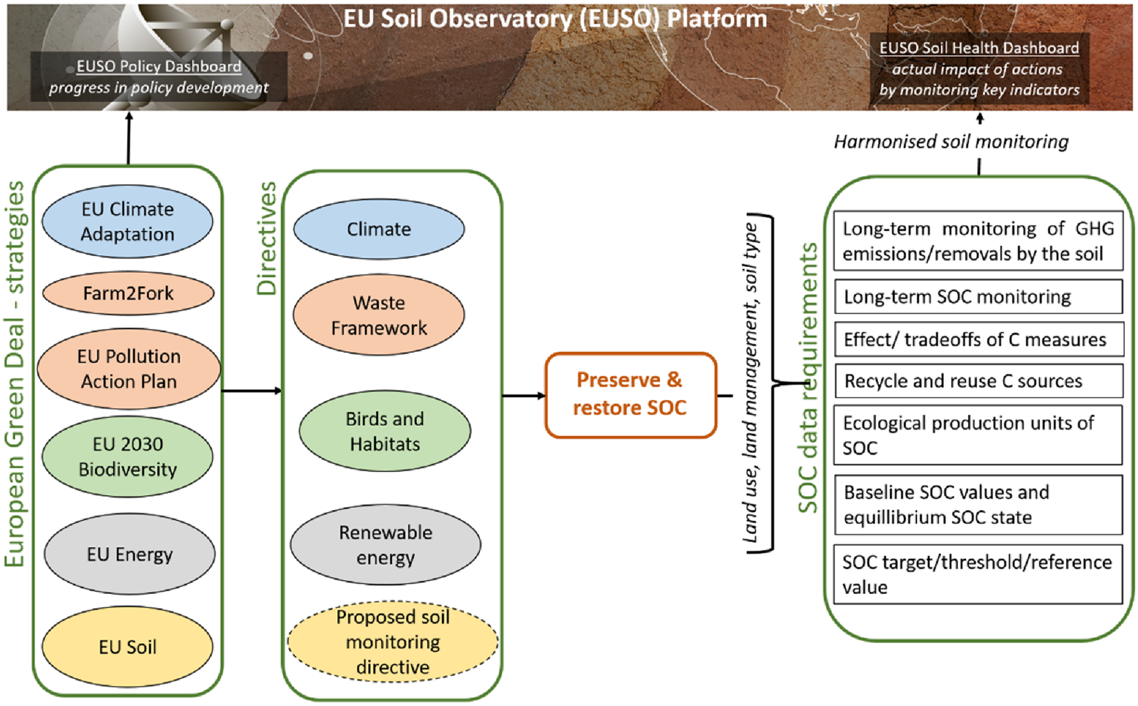

FIGURE 1 Structure of the EU Strategies and Directives that have formulated a goal for the preservation and restoration of soil organic carbon (SOC) and the SOC data required for a quantitative evaluation of the actual impact of actions. Arrows to the EUSO Platform indicate how information will flow back to the EUSO Policy Dashboard and how data will feed into the EUSO Soil Health Dashboard. Data need to be placed in the context of land use, land management and soil type. The colours indicate the link between a strategy and associated directive.

different EU Strategies, for example, Farm2Fork Strategy, EU Climate Adaptation Strategy, EU Pollution Action Plan, EU Biodiversity Strategy, EU Energy Strategy and the new EU Soil Strategy, all with specific objectives stated for the year 2030 (Figure 1). These strategies formulate pathways on how to reach the goals set by the EU Green Deal. For example, the EU Climate Adaptation Strategy has formulated a plan for '*how the EU can adapt to the unavoidable impacts of climate change and become climate resilient by 2050*'. Strategies formulate descriptive principal objectives and goals are formulated according to the SMART-principle in the EU Directives (see https://www.oecd.org/regreform/policyconference/46528683.pdf for a description of the SMART-principle). The European Commission formulated the European Climate Law that aims to cut greenhouse gas emissions by at least 55% by 2030 compared to 1990, and the goal is to reach climate neutrality in the EU by 2050. Additionally, the Agriculture, Forestry and Other Land Use (AFOLU) sector should be climate-neutral by 2035 and moreover sequester CO_2 after 2035. EU Member States committed themselves to these goals in a declaration of the United Nations Framework Convention on Climate Change (UNFCCC). Key soil quality indicators, such as SOC, will be monitored by Member States and by the EU for evaluation of the actual impact of the aforementioned strategies and measures. The results of the EU monitoring by the LUCAS programme (Orgiazzi et al., 2018) are displayed on the EU Soil Observatory (EUSO) Soil Health Dashboard (https://esdac.jrc.ec.europa.eu/esdacviewer/euso-dashboard/). Harmonization of monitoring programmes, that is, an agreement between EU Member States on monitoring the same indicators in comparable ways, is essential for a quantitative evaluation of SOC stocks and soil health at the European level. In doing so, it is crucial to differentiate between harmonization and standardization: in this paper, we refer to *harmonization* as the EU-wide unified use of indicators on the basis of legally binding policy, while methods of sampling and analysis may still differ, and *standardization* as the unified use of protocols for sampling and analysis methods, for example, as described in the ISO (International Organization for Standardization) guidelines. *Harmonization* between countries facilitates comparison and integration to a continental scale, particularly if methods are standardized as well. *Standardization*, however, is not required to this extent, if translation of data can be facilitated by the use of 'transfer functions'. These should preferably be made transparent by peer-reviewed publication. Despite various initiatives striving for harmonization of SOC monitoring (IPCC, 2019; Maréchal et al., 2023; Montanarella & Panagos, 2021; Smith et al., 2019), EU Member States tend to stick to their particular methods for reasons of continuity in data sequences (Bispo et al., 2021).

The European Commission's proposal for a renewed EU Soil Strategy is anchored in the EU's 2030 Biodiversity Strategy, the Climate Adaptation Strategy and the EU Action Plan. It rests on three pillars of the Green Deal: climate, biodiversity and circular economy. Recently, the European Commission launched soil as the fourth pillar. Each pillar has formulated specific goals and actions. Actions related to the preservation or restoration of SOC and the data that need to be collected include the following (Figure 1):

- EU Climate Action Plan: 55% reduction in greenhouse gas emissions by 2030 compared to 1990 levels and climate neutrality by 2050. A monitoring strategy for assessing long-term CO_2 emissions and removals by the soil is required together with data on the effect and trade-offs of carbon measures.
- Farm2Fork: have a neutral or positive environmental impact while ensuring food security. The effect and trade-offs of measures (e.g., diets) together with data on the reuse and recycling of waste products in the food system are required.
- EU Pollution Action Plan: improving soil health by reducing nutrient losses and chemical pesticide use by 50%. Data on the reuse and recycling of waste products (e.g., manure) into valuable products that can return to the system are required.
- EU 2030 Biodiversity Strategy: put Europe's biodiversity on a path to recovery by 2030. Data on the ecological production units of SOC are required.
- EU Energy Strategy: renewable energy needs to increase to 40%–45% by 2030. Harvesting of agricultural waste and residues should hereby not lead to a negative impact on the soil health and the SOC stock. Therefore, consistent sampling of SOM is proposed and a set of essential soil management or monitoring practices should be applied to promote carbon sequestration in soils and soil health.
- EU Soil Strategy: 70% sustainably managed agricultural soils by 2030 and 100% by 2050. The proposal for a Directive on Soil Monitoring and Resilience (published on 5th July 2023 (COM (2023) 416) and currently in negotiation by the European Parliament and Council) includes the monitoring of SOC concentration. This stresses the need for long-term monitoring. Evaluation of results by thresholds may be dependent on the context of soil texture, land use and climate zone.

The evaluation of formulated goals will be enhanced when a potential SOC stock (i.e., desired state) can be evaluated against a baseline (i.e., starting point). Therefore, it is important to set threshold, target and reference values for SOC indicators (e.g., C concentration, C stock (topsoil and subsoil), organic matter quality and SOC evolution) at national and European levels. These values should be assessed in context of land use, land management and soil type (EEA, 2023; Faber et al., 2022).

1.3 | Soil organic carbon monitoring strategies

Soil monitoring has the general goal to assess soil properties in a systematic way in order to detect spatial and temporal changes (FAO/ECE, 1994). In contrast to long-term field experiments, which are controlled systems that allow testing of hypotheses, for example, related to management practices and crop rotations, monitoring programmes are usually established in order to evaluate the status of natural or managed soils at the local or national level. These programmes exist across Europe and overviews are provided by Jandl et al. (2014), Morvan et al. (2008), and van Leeuwen et al. (2017). All three studies highlight the need for better harmonization and standardization of sampling and analysis between countries. van Leeuwen et al. (2017) further highlighted that the soil properties currently collected by individual countries are insufficient as indicators of specific soil functions. In particular, the authors found that monitoring strategies mostly involve measuring chemical parameters and that biological and physical parameters are underrepresented. At the European level, there are different initiatives aiming to better align the European strategy for SOC monitoring with current national monitoring. For example, the European Commission has encouraged Member States to develop a soil monitoring strategy and the Intergovernmental Panel on Climate Change (IPCC) came up with a systematic approach for estimating SOC stock changes using alternate Tier 1, 2, or 3 approaches (IPCC, 2019). Currently, the usage of these approaches is rather heterogeneous across Europe (Smith et al., 2019). While the Tier 1 approach to calculate SOC stocks is used by France, Spain and the United Kingdom (Moxley et al., 2014), Lithuania and Norway use national statistics and the Introductory Carbon Balance Model (ICBM) model (Andrén & Kätterer, 1997) to monitor SOC stock changes (Tier 2). The Tier 3 approach is, for example, used in Denmark, where the C-TOOL model is run with data on temperature and estimated C inputs (crop residues and manure) from national databases (Smith et al., 2019).

Montanarella and Panagos (2021) suggested that an effective monitoring, reporting and verification (MRV) system is necessary for the accounting of SOC stocks for climate change mitigation purposes. A first step in that direction has already been made by the Land Use/Cover Area frame statistical Survey (LUCAS) soil monitoring system (Orgiazzi et al., 2018). However, besides the large number of sampling points and countries included, the programme falls short on some metadata (e.g., historic and current land management) and the list of parameters collected does not allow the quantification of soil functions (van Leeuwen et al., 2017). More engagement related to remote sensing tools, modelling and scenario analysis is needed (Montanarella & Panagos, 2021). Another ongoing initiative is to use spatial modelling to estimate the SOC stock (e.g., Jones et al., 2005; Lugato et al., 2015). However, such estimates require validation with actual (point) observations taken under different land uses, land managements and soil types. Since data are often not collected in that context, it is currently challenging to assess actual SOC stocks at larger scales and to implement adequate actions.

SOC measurements are often commissioned by local or regional governments as part of broad-purpose environmental monitoring strategies. However, for estimating SOC stocks and monitoring changes over time, fit-for-purpose sampling designs must be considered in space and time (Brus & de Gruijter, 2011). Even if several standards are available either for sampling and analysis of organic C, bulk density and coarse fragments (see FAO, 2020; ISO 23400, 2021), discrepancies exist between countries, as data collection and analysis are not fully harmonized at the European level. Because of this, in specific cases, data acceptance is also hampered due to the use of different sampling methods and laboratory protocols (e.g., Jankauskas et al., 2006). Although attempts have been made by suggesting correlation coefficients between methods to harmonize datasets (e.g., Jankauskas et al., 2006; Meersmans et al., 2009), the assessment of SOC storage trends at the European scale is still methodologically limited. It is therefore of high importance to overcome this obstacle by matching both sampling and analysis methods, in order to facilitate comparability between countries, assist international carbon sequestration assessments (Jankauskas et al., 2006), improve EU reporting to UNFCCC and evaluate the current situation with regard to targets set in different policy programmes for 2030 and beyond.

1.4 | Aim of this study

An inventory of SOC monitoring strategies among EU Member States was carried out as part of two consecutive tasks within the European Joint Program (EJP) SOIL (www.ejpsoil.eu). The first task was stocktaking different soil and soil management-related issues within the EU. Among others, the usage of indicators to quantify agricultural soil management practices affecting soil health was synthesized by Pavlů et al. (2021). The second task was within the project ‘SIREN’ (Stocktaking for Agricultural Soil Quality and Ecosystem Services Indicators and their Reference Values), which built upon the aforementioned stocktake aiming at establishing an inventory of European evaluation frameworks for ecosystem services and soil health in use. SIREN further took stock of target, that is, desirable values of soil quality indicators and identification of the knowledge needs for pedo-climatic and agricultural system contexts. Using questionnaires, the SIREN consortium collected information from associated EJP SOIL partners on the national use of soil data in the assessment of ecosystem services and the implementation of evaluation criteria for soil health indicator data in monitoring schemes. The full set of questionnaires can be found in the final report of the SIREN project (Faber et al., 2022). For the study presented here, we primarily take into account information gathered in *Section B—Ecosystem Services assessment based on Soil Quality Monitoring*. The starting point of this questionnaire was the above-mentioned stocktake presented by Pavlů et al. (2021) which, among others, provided an overview of indicators used in national monitoring strategies of Member States. The aim of the SIREN questionnaire was to evaluate the use of the collected data in the assessment of soil-related ecosystem services. The questionnaire (*Section B*) has been circulated among and sent back by the contact persons of 21 Member States involved in the SIREN project (see Faber et al. (2022) for more details).

In this study, the SOC monitoring strategies of five Member States were analysed to illustrate the possibilities and limitations for harmonization and standardization between very different existing SOC monitoring programmes. Please note that the choice of the countries was not related to their responses related to ecosystem services provided in the SIREN questionnaire, as this is not the focus of this study, but rather on the details provided on the respective monitoring strategies and the diversity among them. Another selection criterion was that at least two monitoring campaigns had to be completed. This should ensure that monitoring strategies are included that focus on SOC trends, enabling a better process understanding on how different variables influence SOC and, consequently, adding to the framework for appropriate MRV (Smith et al., 2019). Finally, the aim was to have a wide geographical spread across Europe, following the main European regions (Northern, Eastern, Southeastern, Southern, Western and Central Europe) used by Pavlů et al. (2021) and generally within the EJP SOIL programme. Given the criteria mentioned above, that is, the status of monitoring schemes across Europe, a full coverage of all regions was not possible. The shortlist of countries that finally were included in this study includes the Netherlands (Western), Sweden (Northern), Estonia (Northern), Slovakia (Central) and Switzerland (Central).

2 | RESULTS

2.1 | Evaluation of national soil monitoring programmes at European level

Many European countries have established soil monitoring programmes. According to the outcomes of a stocktake presented by Pavlů et al. (2021), 96% of the countries involved (24 European countries in total) monitor SOC concentrations on a frequent basis. Other parameters related to SOM, such as SOC stock, SOM quality and SOC concentration changes over time (SOC shift), are monitored by, respectively, 71%, 42%, and 79% of the countries. Besides SOC being a vital soil quality indicator, the usage of the observed values differs between countries and is certainly determined by the overall purpose of the monitoring programme itself (Faber et al., 2022). More specifically, the different approaches often include more or less complex (crop) models, in order to estimate water- and nutrient-related ecosystem services, or pedotransfer functions (PTFs) for the assessment of soil quality or natural hazards. In some cases, assessment factors are used for determination of national SOC stock changes and climate regulation following the IPCC guidelines. Consequently, some countries use the monitoring data in national reporting and decision-making, for example, related to fertilization limits and strategies (Faber et al., 2022).

SOC stocks and changes represented the largest commonality in soil quality and soil health indicators implemented in national soil monitoring programmes (Faber et al., 2022). However, established reference or target values for SOC could not be compared between countries because the values refer to different land uses, soil types, soil depths, farm types and even organic carbon types in the case of organic soil.

2.2 | In-depth analysis on national soil monitoring programmes: Five case studies

Following the criteria mentioned above (see Section 1.4), five countries were selected as case studies (Table 1). In this study, we only focus on SOC, but a list of parameters considered in the individual monitoring programmes can be found in Table S1.

Essential differences between countries occur already in the sampling protocols, with variances in the prescribed number of sites, area and sampling depth (Table 1). While the Netherlands, Slovakia, Sweden and Switzerland use coring (soil cores) for collecting soil samples, Estonia uses composite samples from soil pits (representing the A-horizon). In terms of sampling depth, only Sweden and Switzerland stick to a sampling depth of 0–0.20 m for the topsoil in their national monitoring programmes. In Switzerland, deeper depths may sometimes be sampled as well, depending on associated projects, adding to the data stored in the national monitoring database. In Slovakia, samples are taken in the top 0.10 m and then below the plough layer (0.35–0.45 m, depending on the layer thickness). In the Netherlands, a topsoil sample covers 0–0.30 m depth. In Estonia, a bulked sample covering the A-horizon is taken. The depth of sampling consequently follows the thickness of this horizon.

The Estonian monitoring programme was started in 1983 and has been running for 40 years (Table 1). It ran until 1992 and was revitalized in 2002. The monitoring schemes in Switzerland and Sweden started shortly after that in 1985 and 1988, respectively. Slovakia started its monitoring in 1993, and the Netherlands did the first sampling in 1998, that is, 25 years ago. As for the monitoring periodicity, Estonia, Slovakia and Switzerland are revisiting sampling sites every 5 years. Up to now, the Netherlands repeated sampling on a 20-year basis, but future re-sampling campaigns aim for a shorter time interval beginning with a re-sampling campaign scheduled for 2024. In Sweden, sites are re-sampled every 10 years. For determination of changes in SOC, a period of 10 years is usually recommended as changes may be below the detection limit when sampled in shorter time intervals (e.g., Saby et al., 2008; Schrumpf et al., 2011; Smith, 2004). Sampling frequency may be affected by the number of sites and sampling density, for example, because of the costs involved. The number of individual sites included in the monitoring schemes is different between the countries and varies between 30 (Estonia) and up to 2000 sites (Sweden). This is clearly related to the sizes of the respective countries and the area of agricultural land. In Sweden, during the first inventory, the sampling density was 1 sample per 900 ha agricultural land (Eriksson et al., 1997) and approximately 1 per 1300 ha during the second (Eriksson et al., 2010) and third sampling campaign. In contrast, the sampling density in the Netherlands was about 1 sample per 2500 ha in 2018 (Knotters et al., 2022). In Switzerland, where roughly 35 of the 114 sampling sites are on arable land, the sampling density is thus approximately 1 sample per 11,400 ha. Estonia has the lowest sampling density with 1 sample per 32,000 ha of active agricultural land. In

TABLE 1 Soil monitoring programmes included in this study, responsible institutions and monitoring set-up.

Country	Monitoring programme	Funding institution	Programme start	Sampling cycle [yrs]	Proceeded cycles	No. of sites	Sampling area per field	Sampling depth (s) [m]	Georeferenced
NL	Soil Sampling Program of the Netherlands	Ministry of Infrastructure and Environment	1998	Inconsistent	2[a]	~1100[b]	Five soil cores: one in the centre, four at distance of 2 m in the cardinal directions N, E, S, W[b] (12.6 m^2)[b]	1998: each soil horizon 2018: 0–0.30 and 0.30–1.00	Yes
SE	Swedish soil and crop monitoring programme	Swedish Environmental Protection Agency	1988[c]	10	3	~2000[d]	Circle with 3 m radius (28.3 m^2)	0–0.20 0.20–0.40[e]	Yes
EE	Agricultural soil monitoring	Estonian Environment Agency in collaboration with Centre of Estonian Rural Research and Knowledge	1983[f]	5	8	30	60 × 180 m (10 800 m^2)	A-horizon	Yes
SK	Soil Monitoring System of Slovakia	Ministry of Agriculture and Rural Development of the Slovak Republic	1993	5[g]	6	318 (incl. 21 key sites)	Circle with 10 m radius (314 m^2)	0–0.10[h] 0.35–0.45[h]	Yes
CH	Swiss Soil Monitoring Network (NABO)	Jointly operated by the Swiss Federal Office for Agriculture (FOAG) and the Swiss Federal Office for the Environment (FOEN)	1985	5	8	114[i]	10 × 10 m (100 m^2)	0–0.20	Yes

Abbreviations: CH, Switzerland; EE, Estonia; NL, the Netherlands; SE, Sweden; SK, Slovakia.

[a] In 1998, 2018 and scheduled for 2024 and around 2030.

[b] 1396 (inventory I) and 1152 (inventory II) (Knotters et al., 2022).

[c] Three inventories: 1988–1997 (inventory I), 2001–2007 (inventory II) and 2010–2017 (inventory III).

[d] 3108 (inventory I), 2034 (inventory II) and 2039 (inventory III).

[e] New sites only.

[f] 1983–1992, then revitalized in 2002.

[g] More dynamic soil properties (bulk density, porosity, pH, Al, P and K) are monitored annually at key monitoring sites (Bielek et al., 2005).

[h] Depth is adjusted to characterize the main soil horizons (Bielek et al., 2005).

[i] Total number of sites sampled with 35 sites from arable lands and 62 from arable land + grasslands.

Slovakia, sampling density is 1 site per 7500 ha in every sampling period.

The sampling area per site is smallest in the Netherlands (12.6 m^2) followed by Sweden (28.3 m^2), Switzerland (100 m^2) Slovakia (314 m^2) and is largest in Estonia (10,800 m^2). In addition, the sampling set-up differs between countries. While in the Netherlands, Sweden and Slovakia, samples are taken within a circle of 2, 3 and 10 m radius, respectively, Switzerland and Estonia chose a squared (10 × 10 m) and rectangular (60 × 180 m) area for sampling, respectively.

The protocol currently being followed in the LUCAS Soil sampling is based on the FAO 2006 Guideline for Soil Profile Description and the 2006 BIOSOIL sampling manual (accessible at https://www.icp-forests.org/pdf/manual/2000/Chapt_3a_2006(1).pdf). The approach followed in the LUCAS monitoring is very similar to the one used in the Netherlands, that is, samples are taken from a centre point and additional four samples at a distance of 2 m following the cardinal directions (North, East, South and West) (Fernández-Ugalde et al., 2017). By doing so, the sampling represents an area of ~12.6 m^2. The initial sampling depth of 20 cm (spade depth) was increased to 30 cm, in order to reflect IPCC requirements (Jones et al., 2021) related to reference soil C stocks and stock change factors (IPCC, 2019).

In contrast to the sampling methods, the current soil laboratory methods seemed to be comparable in these countries as they follow ISO or EN standards (Table 2). However, the analysed soil parameters differ between countries, and while the Netherlands determine both SOC and SOM, Estonia, Sweden, Slovakia and Switzerland analyse soil samples for SOC only. In Switzerland and Slovakia, the factor of 1.725 is used to convert observed SOC into SOM. Estonia analysed SOC and SOM up to 2018, but now only uses SOC as indicator. Analysis of SOM is performed using 'loss on ignition' and following EVS-EN 12879 in the Netherlands and Estonia used GOST 26123 (1992). For SOC, the two methods used are 'Walkley and Black chromic acid wet oxidation method' (Walkley & Black, 1934), which is used in Switzerland, and 'dry combustion' (ISO, 1995) used by all five countries. In comparison, at the European scale, soil samples collected within the LUCAS topsoil survey are analysed for SOC by dry combustion (Fernández-Ugalde et al., 2022; Tóth et al., 2013).

The main difference between wet and dry combustion is that for wet combustion, the sample is normally boiled in a closed CO_2-free system with a mixture of potassium dichromate ($K_2Cr_2O_7$), sulfuric acid (H_2SO_4) and phosphoric acid (H_3PO_4), while during dry combustion, the soil is heated (~1000°C) in an O_2 or CO_2-free furnace. In both methods, the evolving CO_2 is quantified by gravimetric, titrimetric, volumetric, spectrophotometric or gas chromatographic techniques (Nelson & Sommers, 1996). A brief description of the individual methods is presented in the Supplementary Material, as well as advantages and disadvantages (Table S2). The obtained SOC content differs depending on the analysis method used. This can be caused by the variation in the composition of SOM (Roper et al., 2019). As long as analysis methods are not aligned, national SOC concentrations will be difficult to compare without the development of harmonized indicators (e.g., based on PTFs, scoring methods or other conversion functions).

In Slovakia, the analysis method for SOC has changed over time (Table 2) from the Turin method (Kononova, 1963), which is very similar to the Walkley and Black method, to dry combustion (since 2008). The other countries have kept their initial method since the beginning of the monitoring. Still, adaptation and upgrades of the equipment have led to changes in the methods, such as the temperature and duration of the combustion (e.g., in Sweden; Table 2). This complicates the comparison of SOC stocks over time even within countries.

2.3 | Countries' usage of SOC data

The usage of SOC data is strongly dependent on the aim of the monitoring programme, but most often the data are used for both research and policy support and are made available to the wider public. In Switzerland, data collected by NABO are stored in an open access database (NABODAT; https://www.agroscope.admin.ch/agroscope/en/home/topics/environment-resources/soil-bodies-water-nutrients/nabo/nationale-bodeninformation/nabodat.html). The data are used for scientific analyses on the state and development of agricultural soils across the country (e.g., Gubler et al., 2019; Moll-Mielewczik et al., 2023), as well as policy recommendations and governmental reports. The database not only includes data from NABO but also includes information from different local-scale monitoring programmes (e.g., soil mapping and soil monitoring). Via a geographic information system (GIS) interface, the harmonized soil information can be placed in a spatial context and further processed locally (https://www.nabodat.ch/index.php/de/service/bodenkartierungskatalog/karte). However, the relatively newly developed national agency (Competence Center for Soils—KOBO) aims to further coordinate and standardize methods and instruments for the collection, evaluation and provision of soil information in Switzerland.

Similar to Switzerland, Estonia stores the soil monitoring data in a publicly accessible database and the sites

TABLE 2 Parameters related to soil organic carbon determined in the different monitoring programmes and analyses used.

Country	Monitoring programme	Parameter	Analyses	Carbonates	Calculation
NL	Soil Sampling Program of the Netherlands	SOM concentration [%] SOC concentration [%]	1998, 2018: loss on ignition 1998: not measured 2018: dry combustion	Dried (40°C), milled and sieved (2 mm) soil samples were stored in a glass jar. SOM was determined by loss on ignition (550°C). SOC as elemental C following dry combustion (550°C). Total carbon (TC)—which includes SOC and inorganic carbon (TIC)—by dry combustion at 1150°C. Total inorganic carbon (TIC) up to 1000°C (ISO, 1995).	TC = SOC + TIC
SE	Swedish soil and crop monitoring programme	SOC concentration [%]	Dry combustion (ISO 10694) Adaptation in equipment: 1988–1995: LECO CHN 700 2001, 2003: LECO CHN 600 at 950°C (5 minutes) 2005, 2007: LECO CN 2000 at 1250°C (5 minutes) 2010–2017: LECO Trumac CN at 1350°C (5 minutes)	1988–1995: pH >6.7: treatment with 2 M HCl prior to combustion 2001, 2003: pH >6.8: treatment with 2 M HCl prior to combustion 2005, 2007: pH >6.8: 550 C (5 hours) to remove organic carbon, then 1250°C and measurement of CO_2 2010–2017: pH >6.8: 550 C (5 hours) to remove organic carbon, then 1350°C and measurement of CO_2	Samples with $CaCO_3$: $C_{org} = C_{tot} - CaCO_3$ Samples without $CaCO_3$: $C_{org} = C_{tot}$
EE	Agricultural soil monitoring	SOC concentration [%] SOM concentration [%]	Since 2007: dry combustion elementary analysis (ISO 10694) 1983–1992, 2002–2018: GOST 26123 (1992)		
SK	Soil Monitoring System of Slovakia	SOC concentration [%] SOC stock [kg ha^{-1}] SOC quality ($C_{HA}/C_{FA}, Q_6^4$)	1993–2007: Walkley and Black Since 2008: dry combustion Calculated from SOC concentration Kononova-Belcikova method	1993–2007: Walkley and Black Since 2008: CN analyser (Euro EA 3000)	

(Continues)

TABLE 2 (Continued)

Country	Monitoring programme	Parameter	Analyses	Carbonates	Calculation
CH	Swiss soil monitoring network (NABO)	SOC concentration [%] Humus	Swiss Reference Method (FAL, 1996) or dry combustion SOC × 1.725	Walkley and Black CN analyser (LECO True Spec CN, 2010) to measure C_{tot} and subtracting the inorganic C where appropriate. The contents of inorganic C were determined by digestion with sulfuric acid and by the volumetric measurement of the produced CO_2 using a Scheibler apparatus	C_{org} measured directly or where inorganic C is subtracted from C tot (dry combustion). Conversion factors to recalculate wet oxidation results to the level of the dry combustion method as described by Gubler et al. (2019)

Abbreviations: CH, Switzerland; EE, Estonia; NL, the Netherlands; SE, Sweden; SK, Slovakia.

are visualized via a GIS interface. SOC data have been used in developing pedotransfer functions of SOC concentration in mineral soils (Ritz et al., 2015; Suuster et al., 2012). In addition, the data were used for characterizing the organic matter composition of soil samples using Fourier transform infrared (FTIR) spectroscopy (Pärnpuu et al., 2022). Additionally, Kmoch et al. (2021) used monitoring data to train a random forest model for predicting the distribution of SOC all over the country. Nevertheless, as the monitoring sites are very scarce, this SOC map showed a quite high uncertainty at the national level. Soil monitoring data are also used in policymaking and national reporting. More specifically, as soil bulk density is also measured in the soil monitoring, the exact estimates of SOC stocks can be calculated, as well as the changes over time. Therefore, soil monitoring provides the most accurate estimates of SOC stocks in mineral soil in Estonia.

In the Netherlands, the data of the Soil Sampling Program (SSP) of 1998 have long been used for official reporting and as independent validation dataset to other soil surveys and studies. This survey included 1396 locations that were selected following a stratified simple random sampling design (Visschers et al., 2007). In 2018 and 2019, 1152 of these sampling locations could be re-sampled; however, the results of the 1998 and 2018 monitoring campaigns are not openly available at present. It is work in progress to make the 1998 data available as an online dataset in the near future. Data of the 2018 campaign is available in aggregated form, which means that individual farms are not traceable. The campaign of 2018 had the aim to assess the change in SOC content between 1998 and 2018 (Knotters et al., 2022; van Tol-Leenders et al., 2019). Data on SOM and SOC content, texture and bulk density were obtained in contrast to the SSP of 1998 where SOC and bulk density were not obtained (Visschers et al., 2007). The 2018 survey resulted in an updated SOC stock map of the topsoil (0–0.30 m) and the subsoil (0.30–1.00 m) of mineral soil based on strata. These maps are publicly available and can be used for other monitoring or soil assessment projects and as a basis for national policymaking. The data can also be used for (i) further processing by a statistical model (according to the principles of Helfenstein et al., 2022) or (ii) the dynamic carbon turnover model RothC (Coleman & Jenkinson, 2014) for the assessment of the potential CO_2 sequestration in mineral agricultural soil (Lesschen et al., 2021) or (iii) for reporting CO_2 emissions and removals in mineral agricultural soils for the Land Use, Land Use Change, and Forestry (LULUCF) sector in the National Inventory Reports.

In Sweden, the data of the National Soil and Crop Monitoring are, among others, available for initializing the ICBM model (Andrén & Kätterer, 1997), which is further used in the Swedish Greenhouse Gas Reporting for estimating changes in SOC stocks in Swedish arable land for mineral soils (Bolinder et al., 2018). As the monitoring programme only provides SOC concentrations, pedotransfer functions are used to estimate the bulk density based on texture and SOC, in order to be able to provide the initial SOC stocks to ICBM. The crop and soil data are publicly available without spatial coordinates or on an aggregated level (down to municipality with a minimum of 10 sampling points) through a website (https://miljodata.slu.se/mvm/aker). The crop and soil data with coordinates both are made available for researchers upon request (see Henryson et al., 2022; Poeplau et al., 2015).

Similarly, in Slovakia, SOC concentration data of individual monitoring intervals are available for estimating nationwide SOC stocks on agricultural land. Related to that, SOC data from individual soil monitoring localities were used to test the RothC model in predicting SOC stocks on the national (Barančíková et al., 2010, 2012) and regional level (Skalský et al., 2020). More recently, regional estimates of topsoil SOC stocks using SOC data from the 2018 sampling together with stratified predictors (altitude, land cover, topsoil texture and soil type) was done for the 78 administrative regions, provided the most up-to-date regional figures on the state of topsoil SOC in agricultural soil of Slovakia (Skalský et al., 2024). SOC concentration data were further used to establish the bulk density PTF model (Makovníková & Širáň, 2011). The data are part of the Environmental Monitoring Database and are used together will additionally monitored indicators for evaluation of current state and development of agricultural soil health (Kobza et al., 2017). SOC data were used as the main indicator of the assessment of the regulatory ecosystem service—climate regulation, and as part of the assessment of the regulatory service—immobilization of pollutants in various climatic regions of Slovakia (Makovníková et al., 2019, 2020). Collected data are further reported to the Joint Research Centre (JRC) and the European Environmental Agency (EEA) (Kobza et al., 2017), adding to the evaluation of the actual state and the evolution of soils at the EU level.

3 | DISCUSSION

3.1 | Soil heterogeneity and uncertainty in SOC stock assessments

Soil heterogeneity is an obstacle to the precise determination of any soil parameter at larger scales. Regarding SOC, concentrations vary as a function of related parameters, such as soil texture, landscape, drainage, plant productivity and bulk density—parameters that themselves also vary non-uniformly across fields and landscapes (Conant et al., 2011) and may differ markedly between soil on different parent materials and (historic) land uses (Lark, 2012). Furthermore, soil-forming processes often include different spatial scales (Miller et al., 2016). This means that the spatial heterogeneity of SOC may occur at a finer spatial scale than what can be endorsed by sampling and subsequent laboratory analyses: 'Two samples taken from different areas in the same field are likely to have different SOC concentrations' (Conant et al., 2011), as even the sampling method has been shown to affect the results obtained for SOC (e.g., Francaviglia et al., 2017). Even though composite soil samples were taken to correct for small-scale variability, the sampling area within the field differed much among Member States. As shown by Poeplau et al. (2022), a higher number of soil profiles sampled also helps to account for small-scale variability and greatly decreases the random sampling error, but this requires additional resources. In general, errors arising from incorrect sampling methods are considered the largest single source of error in the monitoring (e.g., Motsara & Roy, 2008). The same applies to and is even more difficult for bulk density as it is variable in space and time and cannot be composited to smooth variability (Alletto & Coquet, 2009).

Sampling techniques have been developed to determine the within-field variation in SOC and other properties and are often based on a grid or zones (Ladoni et al., 2010). It has been suggested that the smallest number of samples required to provide a representative subset of samples, while at the same time holding the costs low, should be determined by remote sensing (e.g., Ladoni et al., 2010).

The time between sampling campaigns strongly differed between the countries included in this study. The soil variability is again an issue when re-sampling after some time in the same location. This has been greatly facilitated by use of GPS systems but it is crucial to pay particular attention to be sure to re-sample the same location (Jolivet et al., 2022).

In general, a period of 10 years is recommended for determination of SOC changes in soil, as changes may be below the detection limit when sampled in shorter time intervals (e.g., Saby et al., 2008; Schrumpf et al., 2011; Smith, 2004). The IPCC (2019) even suggested 20 years as the default time period for transition between equilibrium SOC values. Nevertheless, the sampling cycle is strongly dependent on the objective of the monitoring system. In Slovakia, for example, key monitoring sites are sampled every year, with focus only on highly dynamic variables (bulk density, porosity, pH, Al, P and K; see Table 1).

Moreover, the number of sampling sites, sampling density and the financial resources influence how often samples can be taken. In Sweden, ~2000 sites are sampled and the distribution of the sites along the country is related to the proportion of agricultural area in the respective counties. Therefore, most sampling sites are in the southern part of the country with extra high sampling density in the counties Skåne and Västra Götaland. In 2021, the two counties covered 39% of the agricultural area in Sweden (SCB, 2021).

3.2 | Possibilities and limitations for standardization of SOC indicators

With regard to the assessment of changes in SOC concentrations, all five countries included in this study (the Netherlands, Sweden, Estonia, Slovakia and Switzerland) use dry combustion as analysis method and one (Switzerland) additionally adopts the Walkley and Black method (Table 2). In general, the nature of the Walkley and Black method bears the risk to underestimate the content of SOC (e.g., Gubler et al., 2019; Sleutel et al., 2007). This is because, even though H_2SO_4 provides heating for the oxidation reaction with temperatures up to 100°C, only part of the OM in the soil reacts with the $K_2Cr_2O_7$. Sleutel et al. (2007) recommend therefore to assess the efficiency of this method, which is usually assumed to be 75% (De Leenheer & Van Hove, 1958), at the regional scale and across different pedo-climatic conditions. Nevertheless, Sleutel et al. (2007) found a good agreement between dry combustion methods and wet oxidation methods, such as Walkley and Black, for Belgian soils, enabling the comparison of old and new data. Similar to that, Barančíková and Makovníková (2015) compared dry combustion and the Walkley and Black method for Slovakian soils and found that they agreed well for SOC contents below 3%, but that they differed at higher SOC contents with the Walkley and Black method underestimating SOC contents for Slovakian soils. This fact has been confirmed by other studies, such as Meersmans et al. (2009) for Belgian soils. They further highlight the importance of pedo-climatic conditions and land use to correct the Walkley and Black method for incomplete oxidation. Nevertheless, correction factors have been proposed for the Walkley and Black method for different regions and land uses (e.g., Díaz-Zorita, 1999; Drover & Manner, 1975; Mikhailova et al., 2003; Santi et al., 2006; Sleutel et al., 2007).

3.3 | Possibilities and limitations for standardization of sampling protocols

For the prospect of harmonization, larger differences between investigated countries exist for the sampling method and protocol (Table 2). This lack of a common method for soil sampling can be a serious obstacle for reflecting European goals set by different directives (Francaviglia et al., 2017; Stolbovoy et al., 2007). As already highlighted by Stolbovoy et al. (2007), the slow change of soil properties makes it challenging to ascertain soil health changes over time, which in turn highlights the importance of harmonized sampling methodologies between participating countries and to visit the same georeferenced sampling points at each sampling campaign. Besides the ISO standards ISO 23400 (ISO, 2021), ISO 10381-1 (ISO, 2002a), and 10381-4 (ISO, 2002b) describing the principles for designing soil sampling strategies and techniques, the 'Area-Frame Randomized Soil Sampling' (AFRSS) has been developed by the European Commission's Directorate General Joint Research Centre (JCR) (Stolbovoy et al., 2005; Stolbovoy et al., 2007), with a specific focus on common, simple, transparent and cost-effective methods to identify changes of SOC in mineral soil of the EU. In addition to that, the FAO tried to design a scheme that strongly focusses on SOC prediction, including sampling intensity and interval, soil layers and the position and total number of sample points (FAO, 2012).

The choice of sampling methods when assessing the evolution of SOC stocks and the potential for C sequestration is important to provide results that are reliable and comparable and can be extrapolated to larger scales (Lal, 2005). For example, the method of how to collect the soil (soil cores vs. soil pits) is crucial to consider. From a time perspective, collecting soil cores is typically less time-intensive, therefore enabling a higher number of samples to be collected at a greater precision in a given time period. This is especially important in spatially heterogeneous sites (Davis et al., 2018). Soil pits can, in comparison to soil cores, easily reveal soil structure and horizon development (Perkins et al., 2013) and can make it easier to adjust sampling depths according to the soil profile. However, digging soil pits produces large soil disturbances and thus diminishes possibility for re-sampling at the same location at a later time (Davis et al., 2018). This can affect the precision of SOC estimates and, consequently, SOC stocks (Perkins et al., 2013). A recommendation could be to dig pits at the implementation of the soil monitoring or when adding a new field site and sample soil cores in the following campaigns. The description of the soil horizon is important to correctly classify the soil, characterize the horizons and derive meaningful sampling depths.

When sampling a large number of sites, shallower depths make fieldwork less time-consuming and more efficient as, especially in managed agricultural soils, SOC predominantly accumulates in the topsoil and the main rooting zone (Jandl et al., 2014). In general, many studies report data up to 0.30 m soil depth, which is the standard IPCC depth (IPCC, 2003). Consequently, information on subsoil and down to 1 m depth is seldom available (e.g., Meurer et al., 2018). However, SOC pools in the subsoil may contribute to the total soil C pool despite their less dynamic behaviour (Lorenz et al., 2011) as SOC can be transported to deeper soil horizons and thus contribute to subsoil C storage (Lorenz & Lal, 2005; Parras-Alcántara & Lozano-García, 2014). In order to avoid over- or underestimation of temporal SOC changes, many researchers now advise a sampling depth of at least 1 m (e.g., Resende et al., 2006) and even down to 2 m (Olson & Al-Kaisi, 2015). However, the Kyoto Protocol specifies that samples should be taken in the mineral topsoil (Stolbovoy et al., 2007), which is what the inventories included in this study focus on. However, the sampling depths in the topsoil range from 0.10 m (Slovakia) to 0.30 m (the Netherlands). Sampling the A-horizon (Estonia) is advantageous in terms of the sound description of the monitoring site, for example, soil type, structure and mineralogy, which are needed as metadata and in addition to the frequently monitored data (Kibblewhite et al., 2008). However, the exact determination of the pedogenic horizon can be subjective. Moreover, this approach impedes the comparison of observations between sites and inventories. According to Kibblewhite et al. (2008), fixed-depth sampling ensures standardization between sites and campaigns and allows assessment of anthropogenic contaminants (heavy metals, pesticides, etc.) that show a strong gradient near the surface. In practice, the sampling depth is mainly dependent on the purpose of the monitoring programme. Differences in sampling depths among European sampling strategies have also been found in a study presented by Theocharopoulos et al. (2001) in which 15 European soil sampling guidelines were compared. The authors outlined the differences in soil sampling guidelines among European countries and further highlighted the need for harmonization. However, even though only Switzerland is included in both studies, namely, Theocharopoulos et al. (2001) and the one presented here, the fact that we come to the same conclusion shows that European soil monitoring systems have not yet succeeded to adjust sampling depths and follow a collaborative approach. This step, however, may not be necessary, let alone possible, according to Kibblewhite et al. (2008). Enforcing a European-wide sampling depth would imply changes in already established sampling routines of individual existing inventories, which in turn would cause differences in comparing the future data to the data from previous samplings. One step towards a more harmonized approach could, however, be the reporting of SOC data based on the same soil mineral mass (Ellert & Bettany, 1995), rather than based on a fixed depth (Morvan et al., 2008; Kibblewhite et al., 2008). This approach is already highly recommended when it comes to soil management comparisons, for example, tillage versus non-tillage (e.g., Meurer et al., 2018). This approach implies that soil bulk density is measured in addition to SOC, in order to determine changes in soil mineral mass as a result of management or land use change. Not all inventories included in this study currently determine the soil bulk density as a standard measure and including undisturbed samples in the routine will certainly increase costs, labour and time. However, given the high value of the additional data with regard to a more accurate determination of SOC stocks and the harmonization prospects, this should be considered worth the effort at the European scale.

Apart from direct measurements of SOC or SOM, Schulp et al. (2013) recommended to include the current and historic land use in monitoring programmes. In their analysis, they found that the error of the SOC stock estimate decreased in 60% of the studied area when land use history was used to explain the SOC variability. Regarding the inventories included in this study, all countries but the Netherlands record the current and/or historic land use on the sites sampled, but this information is available through annually updated land use maps. In the Swedish and Estonian monitoring, which focus on agricultural soils only, the current crop is recorded (winter wheat, barley or oats) and samples are taken for analysis of micro- and macronutrients. In Sweden, general information on farm type (animals, production and organic certificate), crop rotation (dominated by cereals, ley or mix) and type of manure (if regular use of farmyard manure) are followed up through short interviews with the farmers in connection with the sampling. Estonia also collects management data for the monitoring sites, including for the years in between monitoring campaigns.

At present, the LUCAS monitoring is considered a standard for monitoring at the European scale, given its consistency in measurement and analysis techniques across countries. A comparison over time between the SOC data for arable land available from the three LUCAS inventories (available upon request at https://esdac.jrc.ec.europa.eu/resource-type/datasets) in four out of five countries included in this study (Switzerland was only monitored in 2015) reveals no clear trend over time for any of the countries when considering mineral (OC <7%; Poeplau et al., 2015; Henryson et al., 2022) arable soils (Figure 2). A list of the land use types included in this analysis is provided in Table S3. Besides slight differences in the median SOC concentration between the countries, the time between the inventories seems to be too short to determine differences over time.

3.4 | Systematic monitoring versus long-term field experiments

Soil monitoring is the systematic recording of soil variables with respect to their temporal and spatial changes

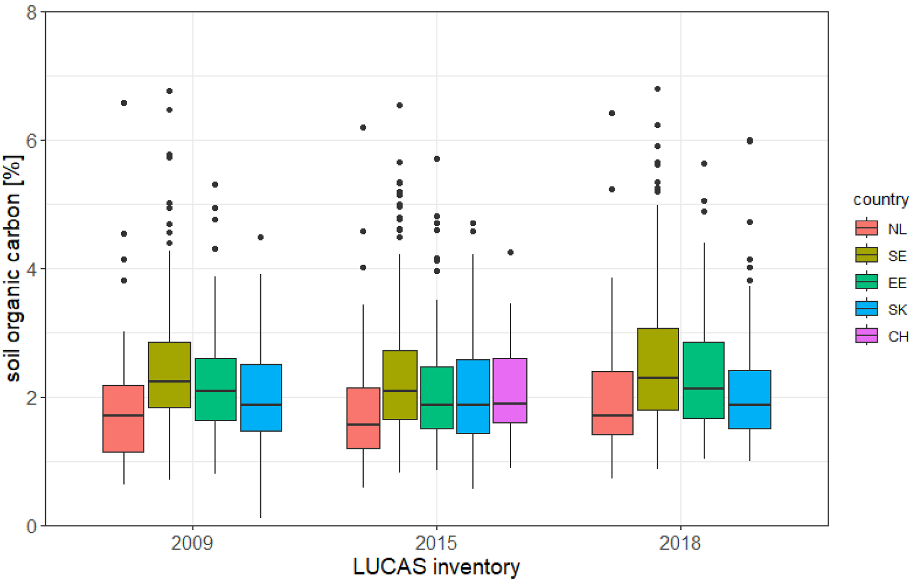

FIGURE 2 Soil organic carbon in mineral arable soils in the Netherlands (NL), Sweden (SE), Estonia (EE), Slovakia (SK) and Switzerland (CH) as reported during the three LUCAS inventories. Note that in CH, sampling has been carried out in 2015 only, while the other countries were sampled in 2009, 2015 and 2018. For those countries, the figure includes re-sampled sites only. Number of samples taken: 43 in the Netherlands, 158 in Sweden, 63 in Estonia, 99 in Slovakia and 28 in Switzerland.

(FAO/ECE, 1994). Those systems are integral for determining trends in SOC, which in turn is an indicator of soil conditions and soil functions and plays an important role in climate regulation. Soil monitoring systems focussed on changes in SOC are, however, not intended to detect or evaluate short-term changes related to spontaneous changes in land management or individual years of drought. They are rather designed to observe and monitor the impact of continuous management, as well as (permanent) land use changes. This makes them especially important for longer-term assessments (Saby et al., 2008).

Long-term field experiments (LTEs) do not usually represent the average situation on actual farms (Henryson et al., 2022) but are idealized and controlled systems that allow testing of hypotheses related to management practices and crop rotations. They are designed for knowledge improvement, process understanding and scenario building, for example, in relation to changing weather conditions, and are essential for designing sustainable production systems (e.g., Grahmann et al., 2022). In that respect, applied management is very often relatively constant, in order to determine long-term effects of a specific treatment. Spontaneous choices and adaptations that are naturally made by the farmer, for example, in response to weather or price changes for seeds and fertilizer, do not necessarily apply to LTEs, which have a smaller area and where the final crop yield is not always the main target variable. Years of low or exceptionally high precipitation or temperature further our understanding and improvement of management options, providing the freedom of almost extensive testing without dependence on high yields as income security. The periodic sampling provides priceless information regarding soil change and functioning, past and present dynamics and can therefore be key to better predict future conditions and serve as sources of process knowledge and model testing (Smith et al., 2019). As suggested by Jandl et al. (2014), LTEs 'can serve as a backbone for SOC monitoring', because these experiments help us to understand and explain soil processes, which may help with interpreting and explaining changes in SOC observed during the monitoring. Moreover, the results from LTEs could be used to correct the results from soil monitoring to an average year, that is, to better understand the effect of variations in SOC stocks. Therefore, there is a strong need for collaboration between the monitoring programmes and LTEs, such as the Long-Term Field Experiments in EUROPE (https://www.bonares.de). For example, some monitoring systems, such as the Swedish Soil and Crop Inventory (https://www.slu.se/en/research/research-excellence/research-infrastructure/databaser-och-biobanker/soil-and-crop-inventory/), do not allow the estimation of SOC stocks and SOC stock changes, as information on the soil bulk density is not readily available and not included in the monitoring. For assessments on SOC stocks and stock changes, pedotransfer functions are being used (e.g., Henryson et al., 2022). Moreover, if information on (changes of the) soil management is not included in national or European soil monitoring, a better understanding of the processes driving the SOC changes observed is hampered. An exemplary monitoring scheme in that respect is the French monitoring network, which includes questionnaires to record management practices (Jolivet et al., 2022). The five national monitoring systems included in this study further showed that soil monitoring programmes are modified over time and that not all sampling locations can be revisited due to changes in land use. This is why some studies rely on data from both LTEs and monitoring programmes either in a completive or comparative manner (e.g., Kirchmann et al., 2009).

4 | CONCLUSION AND RECOMMENDATIONS

In the EU, an increase in SOC stocks by 2050 is urged and aimed for. As SOC is a well-acknowledged soil quality and soil health indicator, most soil monitoring systems measure SOC concentrations at different temporal and spatial intervals. Currently, LUCAS provides a de facto standard method for soil monitoring at the European scale, repeated at regular intervals. This can be valuable in countries where national monitoring strategies are uncertain (e.g., due to uncertain funding) or not present at all. However, the sampling protocol has changed since the start of the programme (e.g., sampling depths changed from 0–20 cm to 0–30 cm) and the sampling sites are not all revisited (De Rosa et al., 2024), making the detection of carbon stock changes over time difficult. Furthermore, certain information, such as soil management or land use history, are not monitored in enough detail in LUCAS even though it is of high importance for understanding and interpreting observed trends in SOC concentrations. Thus, it is essential to have more accurate data at the national level. We therefore suggest that data collected at the national level should be used to complement and correct the data provided by LUCAS.

In order to answer the question of whether national SOC monitoring strategies align with EU strategies, we conducted a case study of five countries, namely, the Netherlands, Sweden, Estonia, Slovakia and Switzerland. What we found was that national monitoring strategies strongly diverge in soil sampling methods, while there is more agreement in the analytical methods. In order to enable the usage and comparison of the national SOC data at the EU level, we recommend that countries should preferably follow standardized analysis methods and sampling protocols as much as possible. However, we are aware that standardization across countries is rather difficult and that harmonizing data, that is, allowing comparison of data that have been sampled in different ways, would be a first but highly crucial step towards accurate MRV as imposed in the proposed Soil Monitoring and Resilience Directive and by the Soil Mission. A harmonized exercise is currently running within EJP SOIL taking profit of the LUCAS 2022 sampling campaign.

With this in mind, we propose a set of aspects of sampling strategies that require harmonization across Europe: First, we consider *soil depth* the most important factor in terms of a first step towards a more harmonized monitoring at the European scale. Whether to sample fixed soil depths or soil horizons can be argued as both have their advantages and disadvantages (Hendriks et al., 2016). Currently, SOC data are mainly collected for monitoring spatial and temporal differences. From that perspective, we recommend fixed sampling depths as it eases continuous spatial and temporal modelling. Moreover, we strongly recommend including both top- and subsoil in sampling schemes. Being a key parameter for calculating C stocks, bulk density should also be included as it will also provide additional information on soil health (e.g., soil compaction). Moreover, the (historic) land use and land cover, as well as management practices, must be recorded by each country and with a common vocabulary (Fujisaki et al., 2023) in order to interpret the effect of land use and management changes under different pedo-climatic conditions. Also, the time between sampling events should be aligned. A time span of 10 years has become a rule of thumb in order to be able to detect measurable changes in SOC. The LUCAS monitoring has had three inventories over a period of 9 years, which has shown no significant trends in SOC concentrations on mineral agricultural soils in our case study. This means that for the medium-term evaluation in 2023, a SOC stock increase (associated with the policy objective of ‘no net loss’) might be difficult to detect. Nevertheless, rather than evaluating national average SOC stocks and stock changes, site-to-site comparisons should be considered. Finally, a minimum sampling density should be aligned between countries for a representative coverage of the proportion of agricultural land. This will, however, slightly change per sampling campaign due to changes in land use and land cover. Another source of uncertainty is the analytical methods used in the different laboratories across Europe. Although we see that analytical methods for SOC concentrations are rather similar between countries and that transfer functions are available, we evaluate that standardized analytical methods would be nice to have but are of minor importance, given the strong differences in the sampling protocols between countries. In addition, we are aware that national monitoring systems are not limited to SOC and requesting countries to change their established methods for sampling and/or analysis must in no circumstances interrupt long-term targeted investment in soil monitoring.

AUTHOR CONTRIBUTIONS

Katharina H. E. Meurer: Conceptualization; investigation; writing – original draft; formal analysis; data curation; methodology. **Chantal M. J. Hendriks:** Conceptualization; investigation; writing – original draft; formal analysis; data curation; methodology. **Jack H. Faber:** Conceptualization; writing – review and editing; funding acquisition; project administration; methodology. **Peter J. Kuikman:** Writing – review and editing. **Fenny van Egmond:** Data

curation; writing – review and editing. **Gina Garland:** Data curation; writing – review and editing. **Elsa Putku:** Data curation; writing – review and editing. **Gabriela Barancikova:** Data curation; writing – review and editing. **Jarmila Makovníková:** Data curation; writing – review and editing. **Claire Chenu:** Writing – review and editing. **Anke M. Herrmann:** Writing – review and editing. **Antonio Bispo:** Writing – review and editing.

ACKNOWLEDGEMENTS

This study was part of the SIREN project ('Stocktaking for Agricultural Soil Quality and Ecosystem Services Indicators and their Reference Values'), part of the EU European Joint Program on Soil (EJP SOIL), co-funded under H2020 Grant Agreement No. 862695. During the manuscript preparation, C.H. received funding as 'Visiting Scientist' under the EJP SOIL programme. The authors further thank Johanna Wetterlind for discussion and her feedback on an earlier version of the manuscript.

DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Meurer, K. H. E., Hendriks, C. M. J., Faber, J. H., Kuikman, P. J., van Egmond, F., Garland, G., Putku, E., Barancikova, G., Makovníková, J., Chenu, C., Herrmann, A. M., & Bispo, A. (2024). How does national SOC monitoring on agricultural soils align with the EU strategies? An example using five case studies. *European Journal of Soil Science*, *75*(2), e13477. https://doi.org/10.1111/ejss.13477