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Soil Organic Carbon Changes in Agricultural Areas of Europe—Synthesis of Repeated Regional Soil Surveys

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ABSTRACT

Across Europe, increasingly more soil-related data is being collected. Soil organic carbon (SOC) is one of the most frequently collected parameters from soil monitoring networks due to the connections between SOC and many soil health indicators and ecosystem functions. Furthermore, SOC changes are also related to CO_2 emissions and sinks, thus influencing climate change. SOC-related data is therefore also fundamental for greenhouse gas emission reporting in the sector land use, land use change and forestry. Much of the SOC data at continent-, country-, and regional-level scale in Europe come from soil monitoring networks (SMNs) that are highly diverse and scattered. In this review, we gather results from European SMNs covering agricultural land with more than one completed sampling campaign in order to compare changes in SOC content and stock from SMNs across Europe. Sixteen countries and regions are represented in the review, representing 24% of the agricultural land (cropland and grassland) of the European Union, United Kingdom and Switzerland. The results and data included in this review were collected between 1955 and 2024. While both gains and losses in SOC are found from European croplands and grasslands, a loss of SOC was found for 56% of the agricultural area covered by the included studies. In cropland areas and general agricultural land, SOC loss and gain were found equally frequently, while SOC loss was found for the majority of the grassland areas surveyed. Given the prevalence of SOC loss, soil health appears under pressure, and improved and harmonized soil monitoring data are needed to quantify SOC changes and their consequences for soil health at the continental scale.

1 | Introduction

Soil organic carbon (SOC) facilitates important ecosystem functions, for example, water storage capacity, nutrient availability, and erosion control (Chaney and Swift 1984; Hudson 1994; Smith et al. 2015; Adhikari and Hartemink 2016; Kopittke et al. 2022; Prăvălie et al. 2024). Changes in SOC are also affecting the atmospheric CO_2 concentration and can thereby mitigate or accelerate climate change. Land use, management, and climate change itself can strongly influence SOC dynamics (Freibauer et al. 2004; Powlson et al. 2011; Berthelin et al. 2022; Padarian et al. 2022; Poeplau and Dechow 2023). Globally, soils have been a source of CO_2 since the onset of land use, and land-use change continues to be an important driver of carbon loss, mainly due to tropical deforestation (Ward et al. 2014; Sanderman et al. 2017). However, for agricultural soils of the European continent, which have been under intensive use for centuries, the current direction of change is certainly less clear and potentially highly specific to certain regions or time periods (Bellassen et al. 2022; de Rosa et al. 2024).

Highlights

- SOC change (content and stock) from soil monitoring networks with repeated sampling campaigns
- Results from 21 studies covering 16 European countries and regions sampled between 1955 and 2024.
- SOC loss found for 56% of the agricultural area covered by the included studies.
- 76% of agricultural area in Europe is not covered by repeated national soil monitoring networks.

As soils can be both a source and a sink for greenhouse gases (Kopittke et al. 2024), reporting of national greenhouse gas emissions must contain emission estimates from soils, including changes in the SOC pool (Kyoto protocol, UN 1997). In order to obtain nationally-representative data, many countries and regions have established soil monitoring networks (SMNs) (Froger et al. 2024). Saby, Arrouays, et al. (2008) and Saby, Bellamy, et al. (2008) define soil monitoring networks as "a spatial arrangement for soil-monitoring sites, designed to be representative of soil type, land use and climatic zones", and SMNs can thus include both officially designated SMNS as well as other datasets containing repeated samplings from the same locations over time, where the original intention was not soil monitoring but nonetheless are functionally similar to SMNs; in this study, all datasets that contain information about SOC from sites that are revisited and that cover a European region or country are considered to be SMNs. In addition to national and regional SMNs in Europe, the LUCAS (Land Use/Cover Area frame statistical Survey) dataset, established and managed by the Joint Research Center of the European Union (EU) since 2009, also provides valuable information and context to soil and SOC dynamics at the continental scale (de Rosa et al. 2024).

SOC is frequently assessed both in terms of SOC content (i.e., the relative amount of SOC in a given soil mass or sampling depth) or in terms of SOC stocks (i.e., the total amount of SOC in a given soil volume depth). While both SOC content and stock are reported frequently at both regional and national scale across Europe, changes in SOC content or stocks are much less reported, as this requires at least two sampling campaigns. Assessing the historical changes in SOC in Europe is important to provide a baseline for the changes SOC has undergone in recent history. Furthermore, historical spatio-temporal changes in SOC can provide context to the magnitude, spatial distribution and direction of future SOC change. Based on known spatial and temporal SOC evolution, well-informed policy decisions can be made, and the data can contribute to a plethora of scientific purposes outside the immediate scope of soil monitoring and emissions reporting. At the European scale, the regional and national SMNs provide essential data regarding SOC dynamics and distribution, which has previously been briefly summarized (Goidts and van Wesemael 2007; van Wesemael et al. 2011; Gubler et al. 2019). However, a systematic comparison of SOC trends available from the European SMNs does not exist yet. Comparison of SOC changes in time and space may elucidate trends and patterns beyond the scale of the SMN and can thus be used to complement assessments of SOC dynamics at the continental scale (de Rosa et al. 2024). While the LUCAS Soil dataset covers Europe at large, national and regional SMNs have often existed for a longer period and often have more samples per km^2 than LUCAS Soil, particularly for smaller countries (Froger et al. 2024), and can thus often provide insight into SOC changes over a longer time period and in greater spatial detail.

In this synthesis, we collect the reported changes in SOC in European soils under agricultural use (i.e., annual croplands and permanent grasslands) from SMNs with repeated sampling campaigns. The aim of this review is to (i) determine the current knowledge base of any national or regional SOC change datasets being produced, and (ii) compare the reported SOC changes in time and space across Europe.

2 | Methodology and Materials

2.1 | Literature Search and Review

The studies, reports and datasets that form the basis of this review were aggregated on the basis of multiple available sources of information. First, the report by Armolaitis et al. (2021) gives an overview of current soil monitoring networks in the EU; on the basis of the information in the report, published reports and peer-reviewed studies were found in the reference list, allowing for the identification of records of SMNs published in local languages. Secondly, an additional thorough search on Google Scholar was undertaken using the keywords "SOC," "Soil organic carbon," and "COUNTRY NAME" for each country in the European Union as well as Norway, Switzerland and the United Kingdom (UK). Additionally, relevant studies previously reported in aggregations of SOC change (Goidts and van Wesemael 2007; Gubler et al. 2019) were included, if they had not yet been found by the literature searches. Lastly, we reached out to researchers and data managers to share information or national reports if we did not find any published information regarding results from SMNs while knowing soil monitoring is ongoing in the region or country [e.g., from the report by Armolaitis et al. (2021)].

As this review focuses on observed changes in SOC for agricultural soils, reports, articles, and datasets were included if they fulfilled all of the following criteria: (i) data must have been collected on at least two separate occasions (multiple sampling campaigns) in order to report on changes in SOC, (ii) the same sites must have been revisited (as opposed to sampling a new set of representative sites), (iii) data must be reported for agricultural land uses (cropland, grassland, agriculture) separately from other land uses (e.g., forest) and land covers (e.g., built up areas), and (iv) the stated changes in SOC must be from observational data (as opposed to a modelled result). The included studies are assumed to be representative for the area under the specified land use of the country or region from which they originate.

In total we included 21 studies and datasets covering 16 countries and regions, and spanning the years 1955–2024. The complete list of included studies, reports and datasets is found in Table S1. An additional list with identified studies that report regional or national SOC changes but do not satisfy all requirements above is included in Table S2.

2.1.1 | Sampling Depth

As the sample collection methodology differs between SMNs, results from various sampling depths across SMNs were grouped into three conceptual depths (topsoil, subsoil, and full profile) based on local definitions in order to allow for a generalized comparison of results between regions and countries. The data was not harmonized to standard depths to avoid assumptions regarding SOC distribution in depth necessary for extrapolation or reduction in depth.

2.1.2 | Mineral and Organic Soils

Across the literature and data included in this review, soil is frequently classified as mineral or organic, however the definition of mineral and organic soil varies between studies; in this review, the study-, report-, or SMN-specific definition was used to filter the data and studies. To maximize comparability of the presented data, results from mineral-only soil were prioritized over organic-only and all-soil results when available. Data from organic soils were excluded from this review.

2.1.3 | Land Use

Data included in this review was divided into three land use classes: cropland, grassland, and agricultural land. These categories are based on the most frequently used categories in the literature, and the classification in this review is based on the stated land use in the literature.

Cropland typically covers soil under crop production and allows for short-term periods of ley in the crop rotation. Grassland typically comprises long-term grass cover of the soil, consisting of meadows and pastures. Agricultural land covers sites where the land use was either reported as “agricultural”, where the specific subtype of agricultural use (i.e., cropland or grassland) was not stated, or where the two previous categories were reported together. Some studies report SOC changes for both cropland and grassland, while others report for only one land use class; Slovakia reported change in SOC for agricultural land in addition to both cropland and grassland. As the definition of land use is typically not given in the literature reporting on SOC dynamics, it is not possible to confirm whether the land use categories are directly comparable between the studies from different countries and regions.

2.2 | Reporting Units

SOC can be quantified in multiple ways, which broadly can be classified either as SOC stock or SOC content; change in SOC can furthermore be quantified in terms of a relative change or conceptualized as a generalized tendency (i.e., direction of change; gain or loss of SOC).

SOC content is the most common reporting form of the studies and datasets included in this review, accounting for 58% of the studies and datasets. 38% of the studies and datasets reported SOC change in terms of SOC stock, while 21% of studies and datasets reported changes in relative terms. Furthermore, 25% of the studies and datasets reported qualitative SOC change tendencies only (see Section 2.2.4). As studies and datasets can report SOC change using multiple forms, for example, both SOC content and a relative change, the sum of the percentages does not add up to 100%.

The time between sampling campaigns varies widely between studies, ranging from 4 to 50 years (Figure 1). Thus, the change in SOC must be corrected relative to the sampling interval; some studies included the rate of change in SOC per year in the results section. For the remaining studies, the rate of change in SOC was calculated using Equation (1):

$$\Delta SOC_{rate} = \frac{SOC_j - SOC_i}{Y_j - Y_i} \tag{1}$$

where SOC_i and SOC_j are the initial and subsequent SOC values (content or stock), respectively, from sampling campaigns undertaken in year Y_i and Y_j. In cases where the sampling campaign took more than 1 year, the middle year of the sampling campaign range was used.

2.2.1 | SOC Stock Changes

Nine studies report the SOC change in terms of SOC stock. SOC stock quantifies the total amount of SOC in a given soil depth and is typically calculated using the SOC content and additional soil information such as bulk density, soil layer depth, and coarse fragment content (Poeplau et al. 2017; Harbo et al. 2022). Thus, changes in SOC stock may also reflect changes in these parameters in addition to changes in SOC content, for example, soil compaction or soil loosening.

Two different units were used in the included studies and reports to quantify SOC stock: Mg C ha^{-1} (and variations hereof, e.g., tons ha^{-1}) and kg C m^{-2}. To be able to compare the values to each other, kg C m^{-2} was converted to Mg C ha^{-1} using Equation (2):

$$Mg\ C\ ha^{-1} = 10 \times kg\ C\ m^{-2} \tag{2}$$

2.2.2 | SOC Content Changes

Fourteen studies report the SOC change in terms of SOC content. SOC content cannot accurately be converted into SOC stock without site-specific information regarding bulk density, coarse fragment content, and sampling depth, which were not available for any of these studies.

Several different units were used to quantify SOC content change in the included studies: g C kg^{-1}, % SOC (and variations of SOC, e.g., C and OC), mg C g^{-1}, % SOM, and g SOM kg^{-1}. All values were converted to g C kg^{-1} to allow for direct comparison using Equations (3–6).

$$g\ C\ kg^{-1} = 10 \times \%SOC \tag{3}$$

$$g\ C\ kg^{-1} = mg\ C\ g^{-1} \tag{4}$$

$$g\ C\ kg^{-1} = \frac{10 \times \%SOM}{1.9} \tag{5}$$

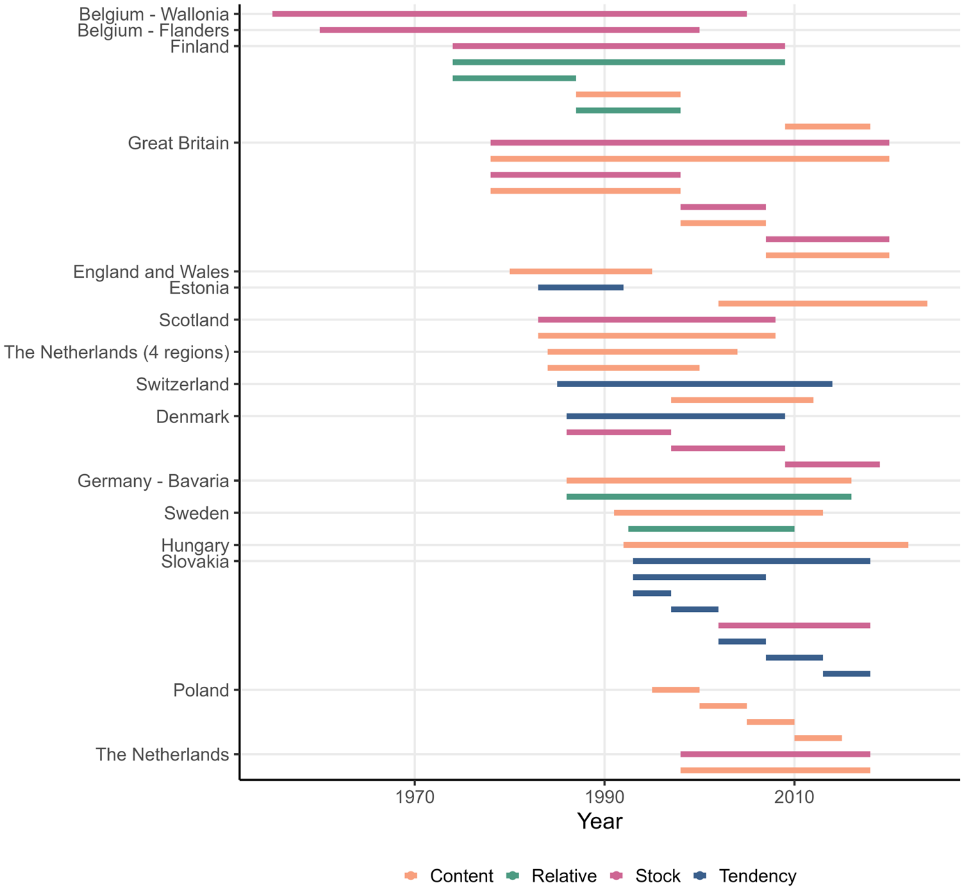

FIGURE 1 | Schematic of the time periods where SOC data is available from the regions and countries included in the review, arranged by earliest sampling time. Each line indicates a reported time period of SOC change, and the color indicates how the change was reported (i.e., SOC content (orange), SOC stock (pink), a relative change in SOC (green) or a tendency in SOC change (blue)). Note: In Estonia, each site has its own 5-year sampling rotation, however the exact sampling years differ between sites and general national sampling rotations can thus not be defined.

$$g\ C\ kg^{-1} = \frac{g\ SOM\ kg^{-1}}{1.9} \qquad (6)$$

where SOC quantified in percentage is converted using a factor of 10, while SOM is first converted to SOC using a factor of 1.9 (Pribyl 2010; Minasny et al. 2020) and then converted from percentage to g kg^{-1} if necessary.

2.2.3 | Relative Changes

Changes in SOC were also reported relative to the initial SOC value in five studies. Additionally, the relative change was calculated if either the initial or final SOC value is reported alongside a change in SOC. Converting the SOC change from an absolute value to a relative value allows for comparison across reporting units.

One pitfall regarding correcting a relative change with regards to the time between sampling campaigns is that the unit inevitably becomes "percentage points per year" which may be falsely interpreted as percent per year. While "percentage points per year" suggests a linear change, corresponding to the assumptions of the yearly rates calculated for SOC stock and SOC content, a percentage change per year would result in a non-linear change, which cannot be assessed using a few time points typically available from the SMNs.

2.2.4 | Tendency

In six studies and reports, the change in SOC is reported as a tendency (or qualitative change) rather than a quantitative assessment of the change. In this review, a tendency may also be based on studies or reports that do not quantify SOC change for the entire region or country but rather report for individual or selected soil types. Scaling SOC values reported for soil types requires data regarding the total area of each soil type for reported land use(s) as well as assumptions regarding representativity of the soil types, which is too speculative for this study. Thus, a general trend was reported if the direction of change for the reported soil types was consistent. All reported numerical SOC changes were also converted into a SOC tendency based on the direction of SOC change reported. When a change in SOC was reported to be not statistically significant, the trend is determined to be "stable", that is, there has been no change in SOC.

2.3 | Area-Weighted Scaling

In order to determine the proportion of agricultural land in Europe undergoing SOC loss and SOC increase, the number of studies reporting either SOC increase, SOC loss, or stable SOC values was multiplied by the land use-relevant area of the region or country the study or report covers.

TABLE 1 | Lower boundary (cm) for the reporting layers in the included literature for topsoil, subsoil, and full profile across all reporting "units." For the topsoil and full profile, the upper boundary is 0 cm; for the subsoil, the upper boundary is the lower boundary of the corresponding topsoil layer. The number of studies and reports from the cropland and agricultural land use is reported in the table, with the number of studies and reports covering grassland land use separately given in brackets. Estonia is not included due to variable sampling depth between sites.

Lower boundary (cm)	5	10	15	20	25	30	50	100
Topsoil	(1)	(1)	8 (3)	7 (1)	5	3 (3)		
Subsoil							3	1 (1)
Full profile							2	2 (2)

The area under agricultural land uses was gathered from EUROSTAT (Eurostat 2025) and is based on the LUCAS Survey from 2018. The area of arable land (B00) and grassland (E00) was included for each relevant NUTS1 region in the EU; area data for Switzerland originates from the Bundesamt für Statistik and covers the period 2013–2018 (Bundesamt für Statistik 2024). While the agricultural area in Europe likely has changed during the time period covered by this review, direct comparison of the agricultural area across regions and countries was prioritized over representation of the agricultural area of the sampling period of the regions and countries, as this may have changed within the time period between sampling campaigns, further complicating assessment of spatial coverage of the SMNs.

Due to differences in sampling periods and reporting units for the included studies and reports, the calculation of a generalized, area-weighted SOC change rate for the included countries and regions is not undertaken.

3 | Results

3.1 | Spatial, Temporal and Depth-Wise Data Distribution

The data included in this study originates from 21 studies and 2 datasets and covers 16 regions and countries in Europe. They cover 29% of cropland area and 18% of grassland area in the EU (Table 2). In this study, the earliest reported SOC inventory is found in Belgium (Wallonia) from 1955, and the longest covered time period is also in Belgium (Wallonia; 1955–2005) (Figure 1). Most of the available data have been collected in the 1980s and 1990s. Data from SMNs established from the 2010s and onwards may be unavailable through literature reviews as the sampling frequency in the SMNs is often 5–10 years, and a second sampling campaign may thus not be publicly available yet.

Most regions and countries have had only two sampling campaigns (56%). Great Britain and the Netherlands have data reported from three sampling campaigns; Denmark and Finland have data from four sampling campaigns; Poland has data reported for five sampling campaigns; and Slovakia has undertaken six sampling campaigns. Sampling in Estonia is not conducted in individual campaigns, as sites are sampled in rotations starting at various time points. Most sites have been sampled six or seven times, while few have been sampled up to eight and nine times.

Across the soil monitoring networks, sampling depths vary. While all included studies report SOC changes in the upper-most soil layer, few studies include a deeper soil layer (Table 1).

The definition of "topsoil" ranges from 0–5 cm to 0–30 cm; the most common reporting depths for topsoil were 0–20 cm and 0–15 cm (Table 1). Estonia samples the A-horizon ranging from 23.9 cm to 61.5 cm (mean 31.8 cm), and the data from the A-horizon are assigned to the topsoil in this review.

3.2 | Relative Changes in SOC

The relative change in topsoil SOC across the countries and regions included in the study spans a range of both increase and decrease of ±1% point per year for all land use classes (Figure 2); slightly more and slightly larger losses are generally reported for cropland as compared to gains in SOC (up to −1.75% point per year); however, the largest SOC change is found in croplands in Estonia, with an increase of nearly 2% points per year. It is important to note that in 2007, the analysis method in Estonian SMN was changed from the Tyurin method to the dry combustion method, which may have an effect on such increase in SOC. Furthermore, fewer studies report changes in SOC for grasslands as compared to croplands; however, the general range of SOC change is comparable between the land use classes.

Overall, there appears to be no explicit spatial patterns in the distribution of relative rates of SOC change (Figure 3). More changes, both positive and negative, are found in the agricultural and cropland land uses as compared to the permanent grasslands, where SOC losses or stable SOC levels were found more frequently. The largest SOC gains were found in the croplands in Estonia and the greatest SOC losses were found in the croplands of The Netherlands, closely followed by agricultural land in Poland and Finland (Figure 3).

When accounting for the area represented by each of the SMNs included in this review, the vast majority of the arable land in the EU + United Kingdom + Switzerland (76%) was not covered by a national or regional SMN with more than one sampling campaign (Table 2). For the areas covered by the SMNs, decreases in SOC are found more frequently for all three land use types than increases in SOC (Table 2). For croplands and broadly agricultural land, 15% of the area of the EU + Switzerland experienced SOC loss, while 12% of the area underwent SOC increase; 2% of the land did not change, while the remaining 71% of the cropland area was not covered by an SMN with a repeated sampling campaign. For the grassland area of the EU + UK + Switzerland, 12% underwent

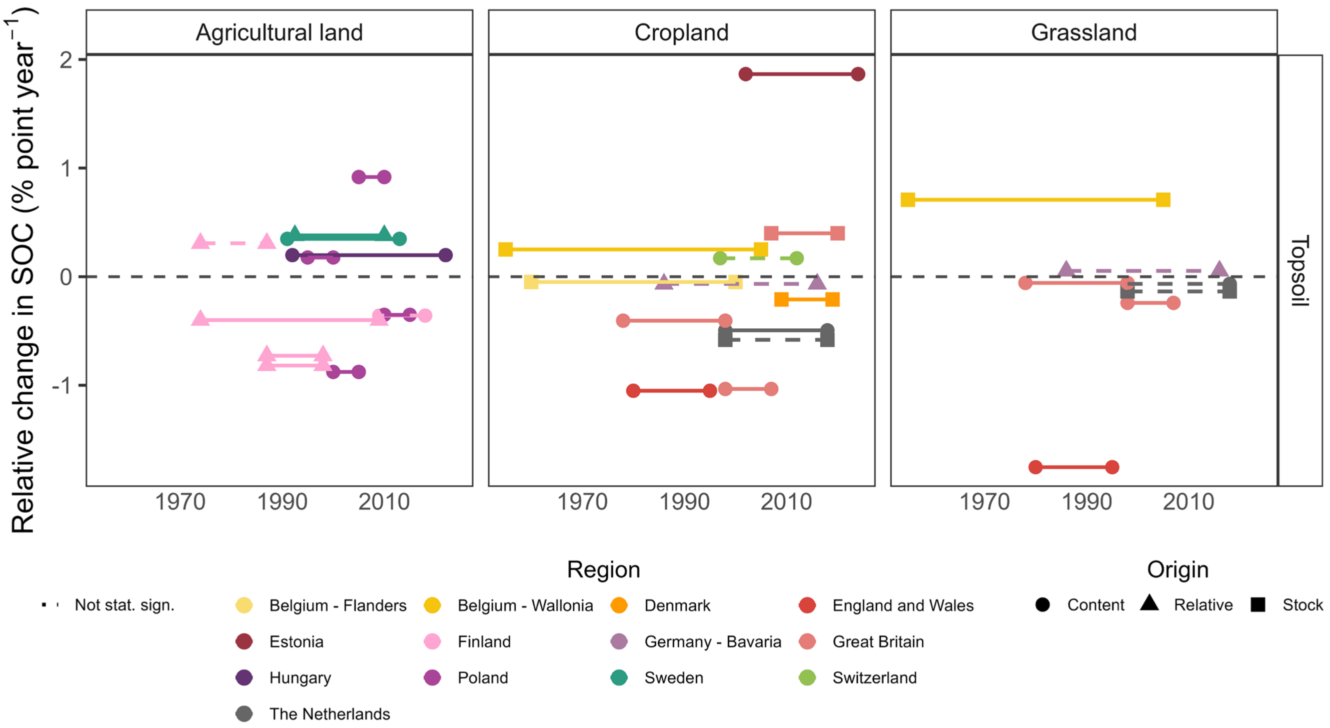

FIGURE 2 | Reported relative change in SOC in the topsoil (converted to percentage points per year), by sampling years, land use category, and regions (colors). Shapes denote original reporting unit (circles for SOC content, triangles for relative change and squares for SOC stock). Dashed lines represent reported non-significant changes in SOC.

SOC loss, while only 3% experienced SOC increase, and 3% of the grassland area was stable; 82% of the total grassland of the EU + UK + Switzerland was not included in this review due to lack of studies and data. In total, 8% of the agricultural land area (cropland + grassland + unspecified agricultural areas) in the EU underwent SOC increase, while 14% of the agricultural area underwent SOC loss. Grassland areas of the EU + Switzerland are studied less frequently (18% of EU + UK + Switzerland area covered) than cropland areas of the EU + UK + Switzerland (29% of EU + UK + Switzerland area covered) (Table 2).

Although the data depicted in Figure 3 and Table 2 all represent the reported changes in SOC for the topsoil, the exact sampling depths vary between 5 and 30 cm, and the results are thus not directly comparable. Additionally, the data are collected between 1955 and 2024, and thus also reflect differences in both sampling techniques, laboratory methods, agricultural practices, and policies, despite representing the most recently available information for the given region or country.

3.3 | SOC Stock Changes

Both increasing and decreasing SOC stock changes have been reported for cropland and grassland (Figure 4), ranging from a loss of −0.59 Mg C ha^{-1}year^{-1} (cropland full profile; larger values from The Netherlands are not statistically significant) to a gain of 0.52 Mg ha^{-1}year^{-1} (grassland topsoil). Two studies reported SOC stock change for the combined agricultural land use class, which are of approximately the same magnitude but opposing directions. None of the negative SOC stock rates for grasslands were statistically significant. Furthermore, the non-significant rates of change were also found in studies where the total SOC stock was larger as compared to the other studies reporting SOC stock (Figure S1).

For studies with multiple depths, the direction of the rate of change in SOC stock was typically the same for both soil layers (Figure 4), however, the subsoil SOC stock change was typically larger than that of the topsoil. In Denmark, the subsoil rate of change was positive between 2009 and 2019, while the topsoil rate of change in the same time period was negative; this is the only case of disagreement between topsoil and subsoil dynamics; however, subsoil is less frequently studied across SMNs.

3.4 | SOC Content Changes

Increasing and decreasing SOC contents are found in all land use classes (Figure 5) ranging from −1.0 g C kg^{-1}year^{-1} (grassland topsoil) to 0.36 g C kg^{-1}year^{-1} (topsoil for cropland). Loss of SOC content is more frequently observed in studies reporting on cropland as compared to agricultural land and grassland. The largest rates of SOC content loss are reported from grasslands in England and Wales. These large SOC content losses also correspond to the regions with the highest SOC content (Figure S2).

SOC content is rarely reported for the subsoil layers. Only the Netherlands reported SOC content in the subsoil, and the rate of change was slightly larger in magnitude and in the same direction as the topsoil (Figure 5).

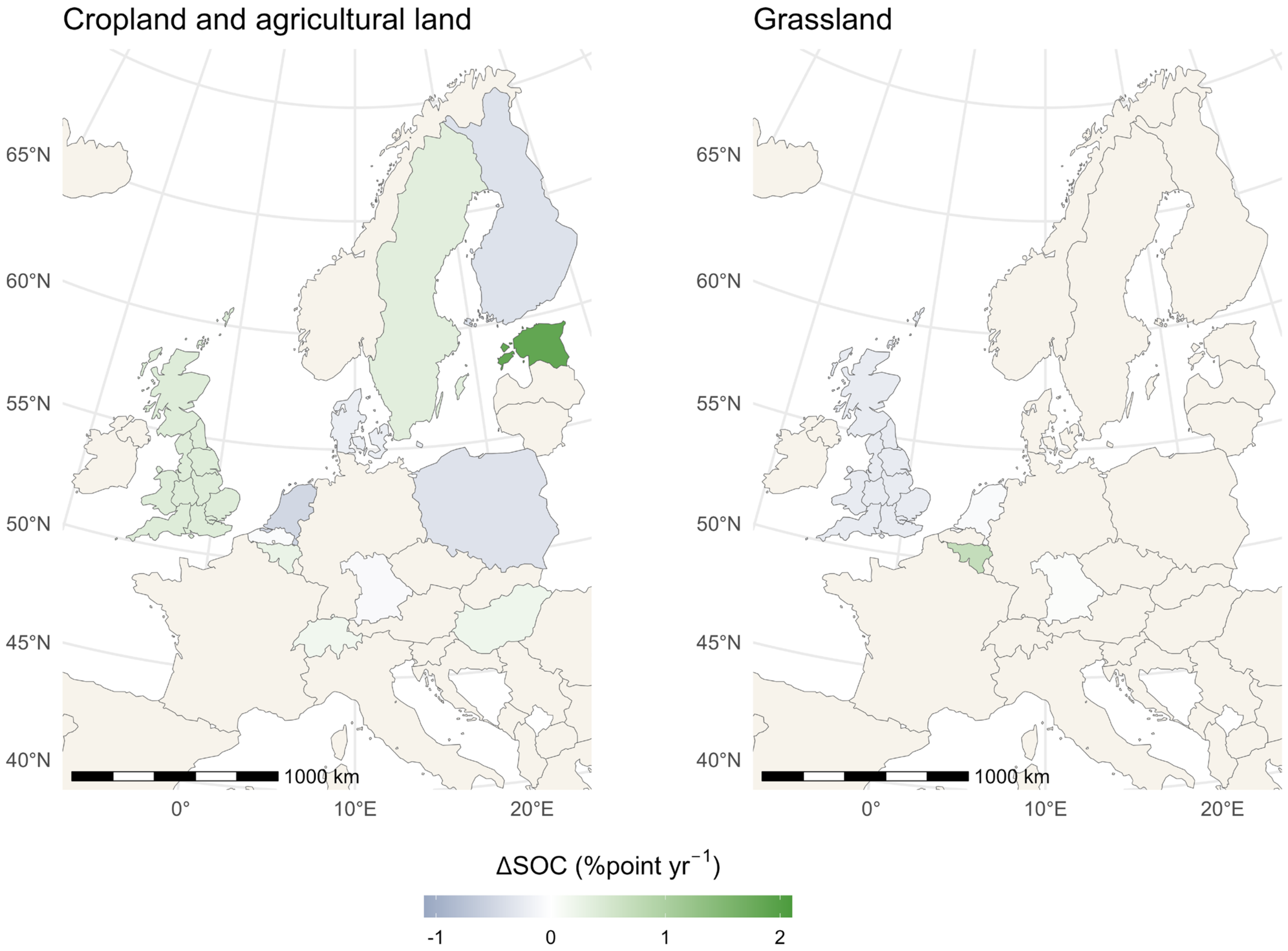

FIGURE 3 | Map of the reported relative change in SOC in the topsoil (converted to percentage points per year) by land use class from the most recent study of each country or region where the relative change of SOC change was available directly in the text or through calculations. Note that the reporting period of each country or region varies (Figure 1, Figure 2). Countries without reported relative SOC change information or not included in the review are depicted in beige.

TABLE 2 | Total area (km^2) and percentage (%) of the regions and countries included in this review by direction of SOC change in the topsoil, by specific land use and for the total agricultural area; agricultural area of the EU + UK + Switzerland not covered by a SMN with repeated sampling included at the bottom. If multiple SOC changes are reported for a given land use and area, the newest data were used. Area is derived from EUROSTAT and is from 2018.

	Agricultural and Cropland		**Grassland**		**Total**	
	Total area (km^2)	**1,041,287**	**Total area (km^2)**	**820,495**	**Total area (km^2)**	**1,861,782**
	Area covered	**Percent**	**Area covered**	**Percent**	**Area covered**	**Percent**
Tendency	**km^2**	**%**	**km^2**	**%**	**km^2**	**%**
Increase	122,243	12	27,449	3	149,692	8
Stable	23,186	2	28,567	3	51,752	3
Decrease	1,598,880	15	95,847	12	255,727	14
Not covered	739,822	71	678,834	82	1,418,656	76

Note: Area of Switzerland originates from the Swiss statistical office and covers the period 2013–2018. Non-significant changes in SOC are treated as stable.

3.5 | Multi-Tendency SOC Changes

Four regions (Denmark, Great Britain, Poland, Slovakia) have quantified SOC changes from more than two sampling campaigns. While consistent SOC content loss was found for both croplands and grasslands in Great Britain across the first three sampling campaigns (Figure 5 and Figure S2), increases were found in the most recent survey of croplands. Similarly,

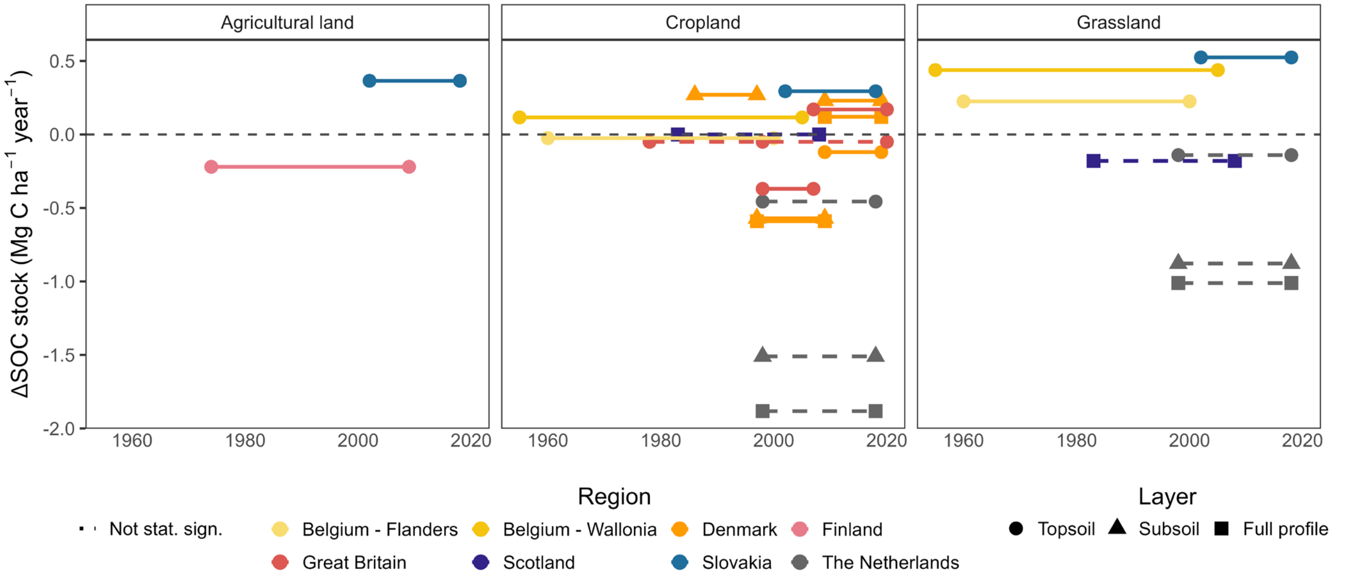

FIGURE 4 | Reported rate of change in SOC stock (converted to Mg C ha^{-1} year^{-1}), by sampling years, land use category, regions (colors), and sampling depths (circles for topsoil, triangles for subsoil, and squares from full profiles). Dashed lines represent non-significant changes in SOC.

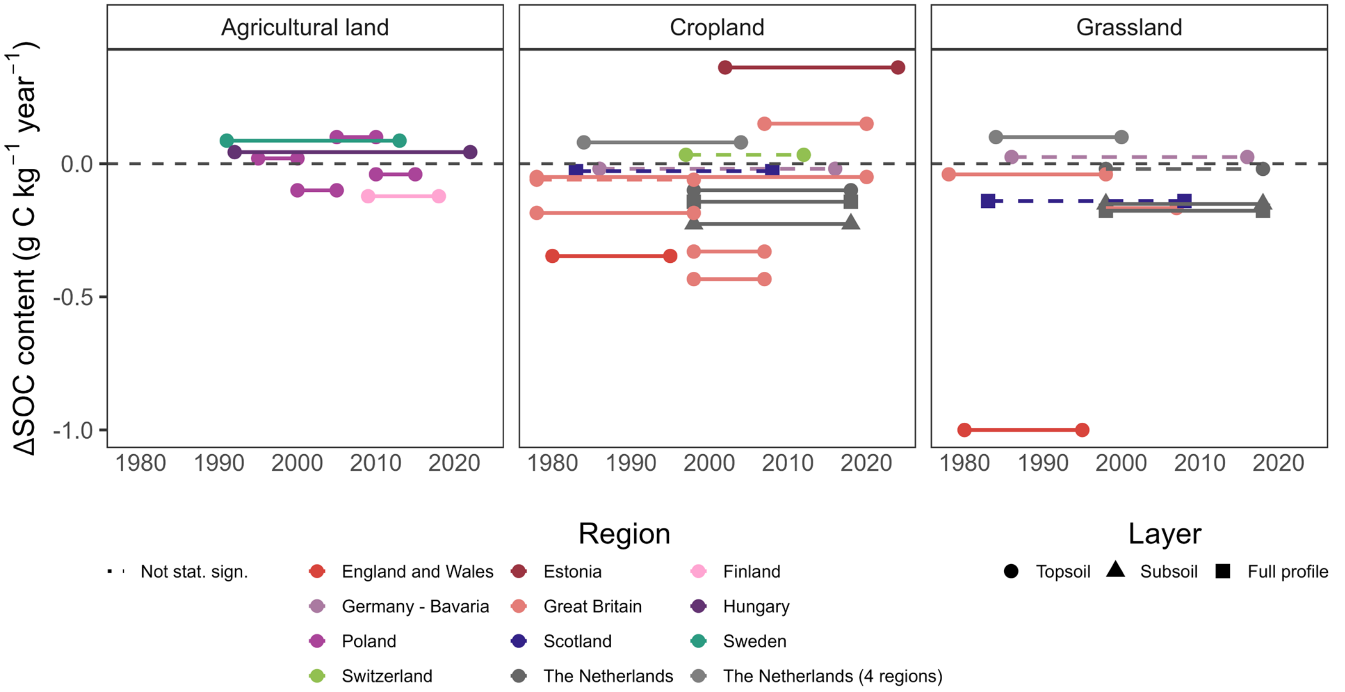

FIGURE 5 | Reported rate of change in SOC content (converted to g C kg^{-1} year^{-1}), by sampling years, land use category, regions (colors) and sampling depths (circles for topsoil, triangles for subsoil and squares for full profiles). Dashed lines represent non-significant changes in SOC content. Great Britain is represented by two different studies (Reynolds et al. 2013; Bentley et al. 2025) for the same time periods, as the datasets are not directly comparable; see Bentley et al. (2025) for elaboration.

the temporal pattern in SOC change was inconsistent for both Poland and Denmark (Figures 4 and 5, Figures S1 and S2). In Denmark, losses were found more frequently in the topsoil as compared to the subsoil. Results from Slovakia show consistent increases in SOC content (data reported as trend due to split by soil types).

4 | Discussion

4.1 | SOC Loss Prevails Across Europe

It has been argued that soils, including agricultural soils, can sequester substantial amounts of carbon and thereby potentially mitigate climate change or offset greenhouse gas emissions from other sectors (Chabbi et al. 2017; Minasny et al. 2017; Paustian et al. 2019; Rumpel et al. 2020; Bellassen et al. 2022). The results of this review indicate that agricultural areas frequently have been losing SOC in many regions and countries in Europe over a 50-year period; based on the most recent data from the reported regions and countries, twice as much agricultural land is reported to lose SOC as compared to the proportion of land with increasing SOC (Table 2) and SOC loss is reported to occur at greater rates than SOC increase (Figures 2, 4, and 5). As such, a reversal of the current trend across Europe would be required to achieve, for example, the stated goal of 4‰ per year increase suggested by the 4per1000 initiative (Minasny et al. 2017).

For the more recent sampling campaigns (2000—now) in particular, the change in SOC is more frequently negative than positive across land uses, suggesting current agricultural management practices in Europe are not sufficient to maintain SOC stocks under changing climate conditions (Figures 2, 4, and 5). However, as agricultural policies and practices are continuously evolving, the next sampling campaigns in European SMNs may show if the current political and scientific focus on promoting soil health-improving land management (Lal 2016; Veerman et al. 2020; Janzen et al. 2021; Heller et al. 2023; Thorsøe et al. 2023; Bouma 2025; Janzen 2024) and carbon sequestration (Oldfield et al. 2022; Don et al. 2023; EU 2024a, 2024b; Oldfield et al. 2024; Dupla et al. 2024) will be reflected in the SOC changes. In fact, some of the most recent results included in this study (e.g., Great Britain; Bentley et al. 2025) show increasing SOC change for annual croplands and link this change to a rising implementation of sustainable land management practices; however, this finding has been viewed with some skepticism (Kirk et al. 2025).

As the regions included in this study vary greatly in both total area, mineral soil proportion, as well as area under the investigated land uses, the comparison of SOC change rates between regions is not a direct indication of the total carbon uptake from or emissions to the atmosphere from the agriculture-related proportion of the land use, land use change and forestry sector. Thus, while the correlation between generally higher SOC levels and larger SOC losses (Figures S1 and S2) does indicate that high-SOC regions are losing carbon faster than low-SOC areas and areas where SOC is increasing, the total acreage of these land uses must be considered to get the total carbon balance from agricultural areas in Europe. However, scaling up the calculated SOC change rates weighted by land use-relevant area must consider multiple local factors, such as matching the assessed land use to the appropriate area and soil types (e.g., assessing proportion of organic soils), which is beyond the scope of this review.

While this review synthesizes information from 16 regions and countries in Europe, a majority of the EU + UK + Switzerland (76%) is not represented. In particular, southern and eastern Europe is sparsely covered, and large parts of central Europe are also unaccounted for, and as such, the warmer and drier regions of Europe (e.g., Mediterranean and Balkan) are underrepresented by national and regional SMNs with repeated sampling campaigns. The overall low SMN coverage is in part due to timing; for example, both France and Germany [accounting for 27% of cropland and 26% of grassland in the EU, respectively (Eurostat 2025)] are currently undertaking their second sampling campaigns (Jolivet et al. 2022; Thünen Institute 2024), and data regarding SOC change for these countries will thus likely become available in the near future.

4.2 | Comparability of the Data

In this study, data from 23 studies, datasets and reports are included. This consequently means that data has been collected, analyzed and reported in 23 different ways. While differences in sampling procedure, lab procedure and data analysis may inhibit direct comparison of the reported SOC changes, the general tendency across regions and countries is deemed reliable, as all the included studies and reports deal with SOC change for agricultural soils in a European country or region from repeated sampling campaigns. However, as Europe moves towards increased need for information on soil health, including SOC dynamics, to comply with legislation regarding climate change mitigation, nature restoration and soil resilience (EU 2024a, 2024b) and due to the knowledge demand of the growing carbon certificate trading market (Oldfield et al. 2022; EU 2024a, 2024b), the need for inter-comparable data on SOC change is increasing rapidly.

As reported by both Cornu et al. (2023) and Mason et al. (2025), there are many soil-related datasets available for Europe, but there is a substantial need for harmonization of the data before it can be used efficiently. Froger et al. (2024) provide a comprehensive insight into the methodologies and extent of currently established soil monitoring networks, a comparison with the EU-wide soil monitoring network LUCAS Soil as well as a detailed discussion on the potential paths forward for preservation and utilization of the current knowledge and data from the national SMNs while enabling comparisons across regions, nations and monitoring networks. While the LUCAS Soil dataset can elucidate some dynamics at the continental scale, it is not currently possible to use this dataset at national or regional level, due to the need for greater sampling density within soil districts to comply with the proposed soil monitoring criteria (Mason et al. 2025); additionally, substantial differences in SOC between national SMNs and LUCAS have been found (Froger et al. 2024), and national SMNs are still necessary to cover counties and regions in sufficient detail (Meurer et al. 2024). Furthermore, Jandl et al. (2014) have provided a list of generalized challenges to soil monitoring, most of which remain unsolved more than 10 years after publication, for example, uneven spatial distribution of information pertaining to SOC and standardization of soil depth for reporting of SOC and SOC changes.

In this review, cross-regional and -national comparisons were complicated by differences in the design of the SMNs, particularly with regards to sampling depths and intervals, as well as land use definitions. While the latter may be difficult to standardize as the land use definitions can be influenced by local conditions and agricultural management practices and must be meaningful under local conditions, the sampling depth may be possible to coordinate across Europe; not necessarily in terms of the specific sampling depth, but rather in terms of including multiple soil depths in the SMNs. Recent studies show that a significant proportion of the SOC dynamics occur in the subsoil (Harbo et al. 2023; Pries et al. 2023; Skadell et al. 2023). If the subsoil was included in more of the European SMNs, research into temporal and spatial dynamics of subsoils would be greatly facilitated. Moreover, subsoil SOC dynamics did not always follow the topsoil tendencies or were of different magnitude (Figures 4 and 5), impacting the total greenhouse gas emissions from agricultural soil when the subsoil is considered.

The temporal aspect of the articles and reports included in this study is a facet of SOC monitoring that must be considered when comparing the presented SOC changes. Firstly, the time between sampling differs widely in the included datasets (5–50 years), which can affect both the magnitude of the observed SOC change as well as the drivers of the SOC changes. Averaged SOC changes over long periods reflect the cumulative changes in SOC that have occurred in between sampling periods. For datasets collected with a large time gap, the average change in SOC can thus not be directly attributed to the (likely comparably larger number of) changes in agricultural practices, effects of climate change and shifts in agricultural policies, as it is not possible to differentiate these effects of these drivers. Furthermore, changes in SOC from sampling campaigns closer in time may reflect short-term variability and spatial variability rather than long-term SOC dynamics influenced by climate, agricultural practices and policies. Secondly, laboratory methodologies evolve over time, both in terms of what is measured (e.g., SOM vs. SOC as in Estonia) as well as accuracy of the laboratory equipment. Conversion and comparison between SOM-based results and SOC-based results is complicated by variations in conversion approaches, and increases in analytical accuracy mean that smaller changes may be observed when using newer equipment.

In the majority of the studies and reports included in this review, the statistical significance associated with the change in SOC is not reported, and any SOC change values reported must be assumed to be statistically significant unless stated otherwise. While this is an assumption that might be questioned, given that it is often not reported if, let alone how, the significance is tested statistically, it is necessary to make this assumption which relies on the further assumption that the authors of the peer-reviewed articles and reports have undertaken the necessary statistical analyses to correctly and accurately report SOC changes in their respective regions. Yet, given that some of the SOC changes are near-zero, it might be the case that the significance was not tested or not reported, and the rates of change were also not significant, which remains speculative.

4.3 | Explanatory Factors

Various explanations for the observed change in SOC have been reported in the studies included in this review. However, not all studies provide analyses or reflections of the observed SOC changes, and the analyses of such drivers of change are therefore limited both in geographical and temporal scope. Additionally, the discussed drivers and factors affecting the changes in SOC are likely highly affected by local conditions, such as policies, agricultural practices and traditions, as well as the scientific zeitgeist at the time of publication. As such, the discussions of factors and drivers of SOC change are unlikely to be directly comparable across the studies and would require a meta-analysis or substantial amounts of additional data to sufficiently investigate broader drivers of SOC change at the continental scale of Europe over such a long time period as is covered by the studies included in this review.

4.4 | Perspectives for Increased Comparability

To enable comparison between studies and soil monitoring networks, core information regarding the sampling approach should be included in the description of the dataset. This core information includes (i) the number of sites included in the network/study, how the sites were selected (e.g., fixed sampling grid, etc.) and how much area a site (on average) represents, (ii) the (average) years between sampling and the sampling years, (iii) definition of the land use(s) included in the study, and (iv) the sampling depth(s). While this information may be provided post hoc to the collection of samples in the SMN, improvements to comparability across SMNs may only be implemented going forward. However, it has proven difficult to determine whether the SMNs are expecting further sampling campaigns where any changes could be implemented. Furthermore, recent additions to EU legislation pertaining to soil monitoring may require additional changes to SMNs to be compliant with legislative requirements. As such, substantial changes may be expected for European SMNs in the near future, presenting an opportunity both for clarity in methodology as well as alignment of SMN protocols across large parts of Europe.

Calculating changes in SOC based on digital soil mapping or advanced statistics is becoming increasingly common (see list in Table S2; de Rosa et al. (2024)). However, as the approaches to such modelling of SOC changes vary greatly in terms of both the input data to the underlying models as well as the model themselves, direct comparison between studies is complicated. While modelling can be necessary to ensure that estimates for SOC levels and SOC changes are available for regions not directly sampled or at a spatial and temporal resolution beyond the sampling scale, modelling is also associated with a degree of uncertainty due to extrapolation risk, lack of good-quality reference data across space, model artefacts and model uncertainty. However, digital soil mapping of SOC-parameters is under continuous improvement and may be aided further by data from SMNs across Europe.

5 | Conclusion

Across countries and regions in Europe included in this review, SOC losses are observed on 14% of the agricultural area of the EU + UK + Switzerland, corresponding to 56% of the agricultural area covered by this review. SOC increases were observed on 7% of the agricultural area of the EU + UK + Switzerland, corresponding to 29% of the area covered in this review. Loss of SOC is observed on 70% of the grassland area and 52% of the cropland area included in the review. As such, the studied mineral soils under agricultural use are likely currently net sources of greenhouse gas emissions at the European scale; however, 76% of the agricultural land of the EU + Switzerland is not currently covered by national or regional SMNs with repeated sampling campaigns, leaving great potential for further study of SOC changes in Europe.

The currently available data regarding SOC changes from national or regional repeated soil monitoring networks in Europe is relatively limited in space and does not represent the full climatic, pedogenic, or agricultural gradients of Europe. In particular, Southern and Eastern regions, drier and warmer climates, as well as mountainous regions are under-represented in the current dataset. While more data is expected to become available soon, the inter-comparability between the soil monitoring networks and combined use of the data, as well as comparability to other studies, is hindered by differences in sampling and reporting standards. Harmonization in sampling practices across Europe and inclusion of subsoil layer can likely improve the use of the information gathered in SMNs, further benefiting from the effort and resources allocated to soil monitoring.

Author Contributions

Laura Sofie Harbo: methodology, data curation, investigation, formal analysis, visualization, writing – original draft, writing – review and editing. **Evelin Pihlap:** data curation, resources, writing – review and editing. **Gabriela Barančíková:** data curation, resources, writing – review and editing. **Axel Don:** writing – review and editing, conceptualization. **Florian Schneider:** conceptualization, writing – review and editing. **Christopher Poeplau:** conceptualization, writing – review and editing.

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Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** Reported SOC stock (converted to Mg C ha-1), by sampling years, land use category, regions (colors) and sampling depths (circles for topsoil, triangles for subsoil and squares from full profiles). Dashed lines represent non-significant differences in SOC stock. Note that not all observations from Figure 4 have corresponding observations in this figure as not all studies report both initial and final SOC stock values alongside changes in SOC stock. **Figure S2:** Reported SOC content (converted to g C kg-1), by sampling years, land use category, regions (colors) and sampling depths (circles for topsoil, triangles for subsoil and squares from full profiles). Dashed lines represent non-significant differences in SOC content. Note that not all observations from Figure 5. have corresponding observations in this figure as not all studies report both initial and final SOC content values alongside changes in SOC content. **Table S1:** Overview of the included studies and reports. **Table S2:** Overview of regional and national studies and reports of SOC change that did not satisfy the requirements for inclusion in this review.