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# Review of Soil Threats and Soil-Related Ecosystem Services European Maps: Can We Use Them to Study Their Relationships?

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## ABSTRACT

The scientific concepts of soil threats (STs) and soil-related ecosystem services (SESs) are gaining importance and are fueling the debate on natural resources management and decision-making within the EU. The literature reports numerous assessments of individual STs and SESs at the European scale. However, a comprehensive overview of the patterns emerging from the relationships between STs and SESs is still lacking, which restricts the ability to limit soil degradation and its impact on SESs. In this article, we provide an in-depth analysis of existing European maps for three STs (soil organic carbon loss, erosion, and compaction) and four SESs (climate regulation and carbon sequestration, hydrological control, biomass production, and erosion control) and the feasibility of combining them to study their relationships. At the EU-level, 37 maps for these STs and 17 for these SESs were encountered. With the notable exception of erosion, these maps differ considerably in their conceptualization of STs and SESs, and in the indicators, methods, and databases used to assess them. In the current situation, the combination of individual maps of STs and SESs to study their relationships is rarely possible. Besides these limitations, we identify possible combinations and provide recommendations aimed at improving the compatibility between different STs/SESs maps. We conclude that there is a need for a more robust framework for conceptualizing STs/SESs and for systematically and precisely specifying the chosen indicators.

## 1 | Introduction

Approximately 60%–70% of soils are currently in poor health in the EU, resulting in an associated cost of €50 billion per year (Panagos et al. 2024, 2018). Indeed, soils are affected by numerous threats (STs) that consist of "processes that could degrade (some of) the functions of soils and the services that soils provide" (Weninger et al. 2024). These services have been addressed in the literature under a large number of overlapping terms, such as soil ecosystem services (e.g., Pereira et al. 2018), soil-related ecosystem services (e.g., Paul et al. 2021), soil-based ecosystem services (e.g., Drobnik et al. 2018), soil contribution to ecosystem services (e.g., McBratney et al. 2017) and have also been estimated to be worth $11.4 trillion at the global scale

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**Summary**

- Analysis of the potential of ST/SES maps to be combined to study their relationships.
- To be combined ST/SES maps need to share the same conceptualization, indicator type and data.
- There is no agreement on soil ST/SES conceptualization, indicators and assessment methods and data sources.
- Criteria underlying the choice of indicators for STs/SESs should be explained more systematically.

(McBratney et al. 2017). In this study, we adopted the terminology proposed by Paul et al. (2021), which defines soil-related ecosystem services (SESs) as the subset of ecosystem services provided by soils and their chemical, physical, and biological properties, processes, and functions.

The costs and benefits contribute, among other factors, to the growing attention to STs and SESs. As a consequence, research on STs and SESs at the EU level has increased considerably, as evidenced by the funding of numerous mapping projects over the last decade (Maes et al. 2020; Vihervaara et al. 2019; Vrebos, Staes, et al. 2018; Vrebos, Bampa, et al. 2018; Stolte et al. 2015; Zulian et al. 2014). This work has resulted in numerous mappings, sometimes with very different perspectives. Moreover, most of these studies have considered STs and SESs individually, although it is known that they exhibit complex relationships (Kiessé et al. 2024; Medina-Roldán et al. 2024; Obiang-Ndong et al. 2020). Understanding these relationships is important because they need to be considered when implementing remediation measures or designing management strategies to reduce soil degradation and ensure the provision of SESs. In this regard, studies have called for increased attention to developing theoretical knowledge on the multiple relationships among ecosystem services (Carpenter et al. 2009; Bennett et al. 2009). Some rare studies have started exploring this approach by combining existing ST maps at EU extent, as was done recently for STs by Prăvălie et al. (2024).

In this work, we aimed to understand the causes of discrepancies between existing European ST/SES maps and to assess the feasibility of constructing maps of several STs or SESs based on the existing individual ones. For this purpose, we selected three STs (soil organic carbon (SOC) loss, erosion, and compaction) and four SESs (climate regulation and carbon sequestration, hydrological control, biomass production, and erosion control), being considered the most important by stakeholders from 16 European Member States (Foldal et al. 2022), and carried out a systematic literature review on how their estimation was conducted focusing particularly on: (i) the indicators chosen for the different STs/SESs, an indicator being a single variable or a set of variables representative of the STs/SESs in question (Kandziora et al. 2013), (ii) the methods, and (iii) the databases used to estimate the indicators. Based on our analysis, we propose combinations of preferences (concept and indicator type) that can be used to determine ST/SES relationships and identify potentially combinable maps according to these criteria for the ST and SES considered.

## 2 | Materials and Methods

### 2.1 | Definition of the Selected STs and SESs

Several definitions and classifications for individual SES and ST exist in the literature. The definitions of the STs/SESs included in this study are based on the main classifications of STs (Blum 2005) and SESs (CICES, Haines-Young and Potschin 2018), partly taken up by Paul et al. (2021) and their simplification proposed by Weninger et al. (2024) and Foldal et al. (2022), for STs and SESs, respectively (Tables 1 and 2). These definitions were validated by stakeholders from 16 different EU countries, including researchers, practitioners, policy-makers, farmers, and industry representatives (Weninger et al. 2024).

### 2.2 | Literature Search

We conducted a systematic literature search following the ROSES framework (Haddaway et al. 2018). This search was performed in Web of Science, Scopus, and Google Scholar on April 25, 2024, with a query for each ST/SES considered (see Table S1 for the exact queries). The queries were built based on two components: (i) one common to all STs and SESs targeting mapping approaches with keywords such as "mapping" or "modelling" or "assessment" and for European to global extent (Table S1); and (ii) the other specific to each of the STs and SESs considered with, for erosion for example, keywords such as "soil loss*", "sediment loss*" or "erosion" for the ST erosion. These queries identified 1526 articles for STs and 1123 for SESs, respectively. The titles and abstracts of the identified articles were reviewed. Only articles whose title and abstract suggested the production of a map of at least one of the selected STs/SESs at the EU extent were retained (Figure 1). Then, a text analysis verified that the collected documents estimated and mapped a ST or a SES and removed the articles that had no direct relation to STs and/or SESs. Eight technical reports found in Google Scholar were also considered, five on SESs and three on STs. In total, we collected 37 documents for STs and 17 for SESs.

Most of the documents contained the estimation of only one of the selected STs (≈85%) and SESs (≈60%). Finally, for the considered STs and SESs, we obtained 47 and 33 estimations/mappings, respectively (Table 3).

### 2.3 | Information Extracted and Database Building

From each document, we extracted: (i) the STs and/or SESs considered, (ii) the indicators used for the different STs or SESs as well as (iii) the methods and (iv) databases used to estimate them. All this information was gathered in an Excel file sheet (Supporting Information). Both methods and databases were further classified.

Indeed, both ST and or SES indicators can be measured or estimated using expert knowledge or numerical modelling, aligning with previous classifications of these approaches (Montagne et al. 2025; Englund et al. 2017; Greiner et al. 2017; Andrew et al. 2015) (Table 4). We also included an "assessed by others" category to classify documents that did not assess

**TABLE 1** | Comparison Foldal et al. (2022), with CICES v4.3 (Haines-Young and Potschin 2018) and Paul et al. (2021) classification systems: Provisioning and regulating and maintenance services.

| SES name | Definition of Foldal et al. (2022) | Corresponding CICES section | Corresponding CICES division | Corresponding CICES group | Corresponding CICES class | Comparisons with Paul et al. (2021) |
|---|---|---|---|---|---|---|
| Climate regulation and carbon sequestration | The capacity of a soil to reduce the amount of GHG emissions in the atmosphere (i.e., carbon dioxide, methane and nitrous oxide). Carbon sequestration is the soil capability and integrated system of anthropogenic measures to increase soil C stock in individual horizon/whole soil profile. | Regulation & Maintenance (Biotic/Biophysical) | Regulation of physical, chemical, biological conditions | Atmospheric composition and conditions | Regulation of chemical composition of atmosphere and oceans, including maintaining rainfall patterns through evapotranspiration at the sub-continental extent. | Equal |
| Hydrological control | The capacity of a soil to receive, store, conduct and supply water for subsequent use while minimising the effects of prolonged droughts, flooding and erosion. | Regulation and Maintenance (Biotic/Biophysical) | Regulation of baseline flows and extreme events | All | All except wind and fire protection. | Compared to Paul et al. (2021) we added Regulation of baseline flows and extreme events for water |
| Biomass production | The capacity of soils to supply humans with food, feed, fibre, fuel, wood, pharmaceuticals and biochemical. | Provisioning (Biotic/Biophysical) | Biomass | All | All | Compared to Paul et al. (2021) we aggregated the biomass production indicators. |
| Erosion control | Control of erosion rates is the reduction in the loss of soil material by virtue of the stabilising effects of the presence of plants and animal that mitigates or prevents potential damage to human use of the environment or human health and safety. | Regulation & Maintenance (Biotic/Biophysical) | Regulation of baseline flows and extreme events | Erosion control | All | Paul et al. (2021) also grouped the two classes for erosion control for example, grouped erosion control for wind and water |

**TABLE 2** | Soil threats defined by Foldal et al. (2022).

| ST name | Definition of Foldal et al. (2022) |
|---|---|
| Soil organic carbon loss | Soil organic carbon loss is defined as a process of decreasing soil organic carbon stocks or content of specific soil layers. |
| Erosion | Soil erosion is a soil degradation process consisting of the detachment, disintegration and transport of soil particles by erosive agents, such as water (water erosion), wind (wind erosion), ploughing (erosion by tillage) or ice (glacial erosion). |
| Compaction | The densification and distortion of soil by which total and air-filled porosity are significantly reduced, causing deterioration or loss of one or more soil functions. |

the indicators themselves but adapted pre-existing maps of the considered indicators to reinterpret them within the STs/SESs framework.

At last, a vast variety of data sources is used for ST/SES assessments. We have classified them, as Andrew et al. (2015), according to the nature of the data (soil, climate, topography, land use and land cover (LULC), agricultural practices, biomass, and parent material data) but also by separating non-spatially exhaustive databases from spatially exhaustive ones. Non-spatially exhaustive databases contain discontinuous or discrete data that are measured in specific locations (e.g., LUCAS point measurements). Spatially exhaustive databases contain data for continuous areas offering complete spatial coverage (e.g., climate and EUROSTAT NUTS1 statistics).

## 3 | Results: A Snapshot of the Existing Assessments at the European Extent of the Most Important STs/SESs

### 3.1 | Indicators Used to Estimate STs and SESs at EU Extent

Numerous indicators were used for EU-wide mapping of the considered STs/SESs (Figures 2 and 3). For most of the considered STs/SESs, there is no consensus on the indicator to use, with the same indicator being used at best by two to five studies (Figures 2a,c and 3a,b,d). In the worst case, each study defined its own indicator (e.g., for biomass production; Figure 3c). Erosion is a notable exception as it is estimated from soil loss by water in 61% of the cases (Figure 2b). This lack of consensus reflects the author's different preferences on at least one of the following five aspects:

1. The ST/SES used in the mapping assessment is either potential (capacity) or actual (flow) (Tables 5 and 6).
2. Different parts of the ecosystem are considered when assessing STs or SESs. This is very clear for SESs, as seen for example for climate regulation and carbon sequestration estimated either by considering only the soil system (soil carbon storage), or by considering both the plant and soil systems (greenhouse gas (GHG) fluxes; Figure 3a). The same applies to biomass production, assessed by the biomass production itself in five out of six cases (i.e., at the agroecosystem scale) or by the ability of the soil to produce biomass (Figure 3c) in the latter case. Finally, erosion control is assessed either by the presence of vegetation protecting the soil, or by erosion avoided as a result of the interaction between vegetation and soil (Figure 3d).
3. The STs are assessed at different steps of the Diver-Pressure-State-Impact-Response (DPSIR) or different levels of the cascade frameworks for SESs (Niemeijer and de Groot 2008; Potschin-Young et al. 2018). This is particularly the case of soil compaction, assessed either by a balance between pressure (stress) and state (soil strength), or by a state alone (soil strength), or by the resulting compaction accumulated over time (impact), or by the consequence of compaction on yield (Figure 2c).
4. The indicators targeted specific, but different components of a threat (erosion) or SES (hydrological control). Indeed, hydrological control can consist of flood regulation (more than half of the documents), drought, or excess water, which are estimated using different indicators (Figure 3b). Similarly, erosion results from several processes, such as erosion by natural agents—primarily by water (diffused or concentrated in rills and gullies, most studies), but also wind erosion, or a combination of both (Figure 2b)—or by soil management practices (two studies), such as tillage (one study) and harvesting (one study). More rarely, some studies consider a combination of natural and human processes (Figure 2b).
5. The ST indicator characterises either the process constituting the threat or the resulting soil condition. As an example, SOC loss was characterised by negative SOC changes in five out of eight documents (i.e., SOC loss process), while it was quantified as a SOC stock or content (i.e., soil condition) in the remaining three documents (Figure 2a).

Variability in preferences (described above) and associated indicators results in very different assessments and maps for a given ST/SES, as demonstrated by the example of climate regulation and carbon sequestration estimated either by the GHG fluxes based on net ecosystem productivity (NEP) (Figure 4a; Paracchini et al. 2011) or by SOC stock (change in SOC, Figure 4b; Vrebos, Staes, et al. 2018). While high values of net ecosystem productivity and SOC storage are expected to indicate high levels of climate regulation and carbon sequestration, the two maps appear inverted, with areas of high storage in one being areas of low storage in the other. On the other hand, the same spatial structures are found in both maps (Figure 4a,b), which is less clear when examining the maps of potential and actual wind erosion (Figure 4c,d).

### 3.2 | Methods Used to Assess ST/SES Indicators

Indicators can be calculated either based on point data and then spatialized (e.g., by spatial interpolation) or directly

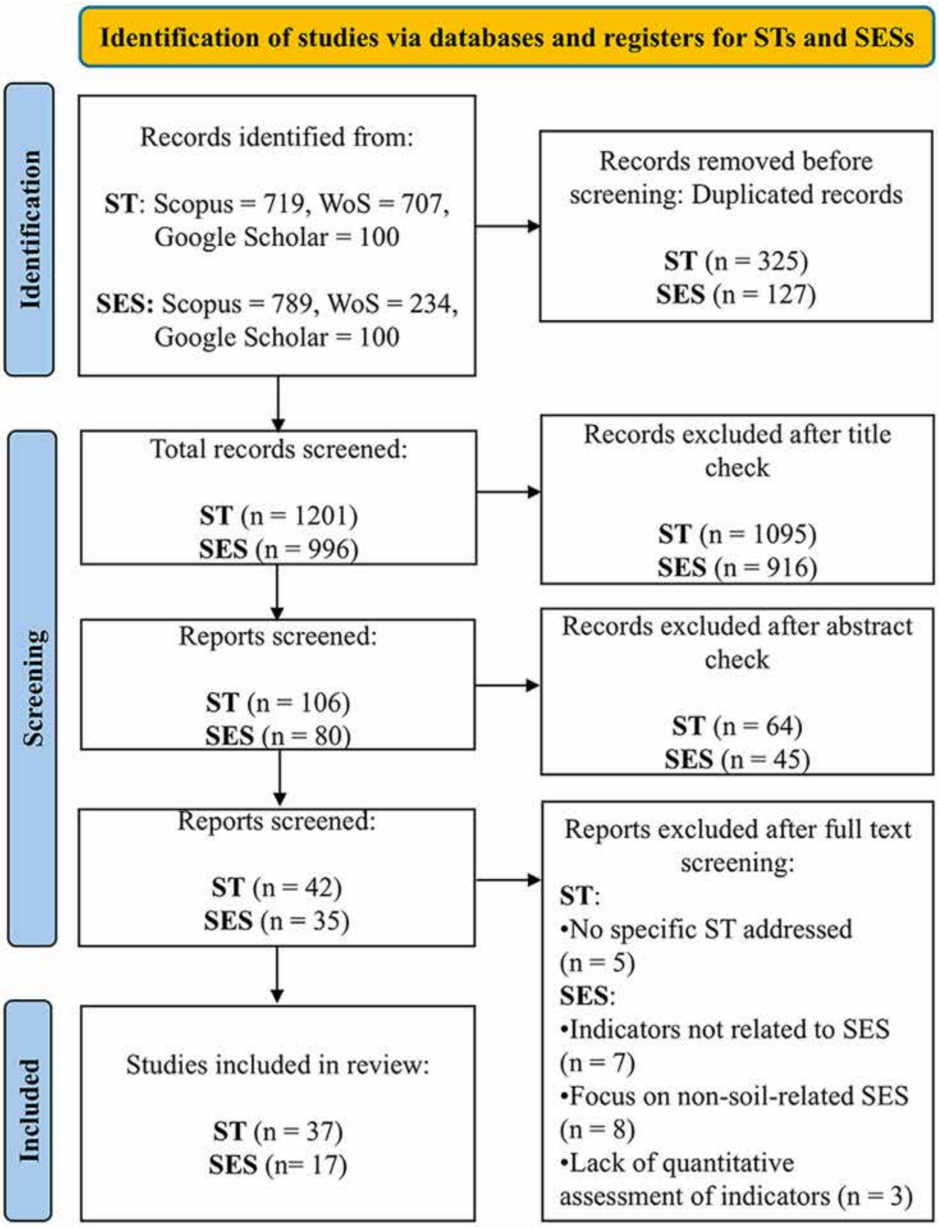


**FIGURE 1** | PRISMA flow diagram illustrating the selection process adopted in the review. This flowchart was realized following Page et al. (2021). The authors pre-identified that only the first 100 records from Google Scholar would be screened, following guidance in Rethlefsen and Page (2022). WoS stands for Web of Science.

**TABLE 3** | Number of documents and date of the first publication for the considered STs/SESs.

| ST/SES | | First publication date | Total number of documents estimating/mapping the considered ST/SES[a] | Total number of documents analysed |
|---|---|---|---|---|
| ST | Soil organic carbon loss | 2014 | 8 | 37 |
| | Soil erosion | 1991 | 31 | |
| | Soil compaction | 1991 | 8 | |
| SES | Climate regulation and carbon sequestration | 2002 | 9 | 17 |
| | Hydrological control | 2011 | 7 | |
| | Biomass production | 2006 | 10 | |
| | Erosion control | 2012 | 7 | |

[a]The total number of STs/SESs is larger than the total number of documents for STs/SESs since one document may assess several STs/SESs.

**TABLE 4** | Classification of the methods used to estimate the STs/SESs.

| Type of method | Used when | Categories | Principle |
|---|---|---|---|
| Expert knowledge | Compensate for the absence of empirical data | | Approach relying on an accumulated expertise and biophysical knowledge to infer the potential distribution of STs/SESs. |
| Numerical modelling | When numerical data are available | Rule-based models | The expertise and biophysical knowledge are used to create decision rules to assess semi-quantitative ST/SES indicators (Burkhard and Maes 2017). |
| | | Statistical and empirical approaches | These types of approaches range from statistical relationships between known explanatory variables (soil properties and climate; Wainwright and Mulligan 2012) to empirical equations as the well-known Revised Universal Soil Loss Equation (RUSLE; Burkhard and Maes 2017). |
| | | Process-based models | A mechanistic approach that simulates the biophysical processes occurring in the soil ecosystem to estimate STs/SESs (Wainwright and Mulligan 2012). |

calculated on spatialized data. These two options correspond to what has been considered in the literature as mapping-first or mapping-last approaches (Angelini et al. 2023; Styc and Lagacherie 2019), although the two stages are sometimes intertwined. A critical analysis of spatialization methods, however, is beyond the scope of this paper as numerous reviews on this topic already exist in the literature (Englund et al. 2017; Andrew et al. 2015; Malinga et al. 2015; Crossman et al. 2013; Martínez-Harms and Balvanera 2012). Therefore, we only considered here the methods used to estimate indicators without considering the spatialisation step. In some cases, the indicators were estimated in previous studies and reinterpreted with the ST/SES framework; the assessment method was therefore not considered in this section. Consequently, the methods used were only analysed for 34 ST and 21 SES indicators, respectively (Figure 5).

ST/SES indicators were primarily estimated (using statistical, rule-based, and process-based modelling) and, to a lesser extent, using expert knowledge or direct measurements (Figure 5). Indeed, only three of the four SESs considered (climate regulation and carbon sequestration, biomass production, and erosion control) and only one ST (erosion) were sometimes directly measured, while this was never the case for SOC loss, compaction, and hydrological control at the EU extent (Figure 5). SES indicators were mainly obtained through modelling approaches, including rule-based and process-based modelling, but also statistical modelling to a lesser extent (Figure 5).

Nevertheless, the frequency of use of the different assessment methods varies considerably among STs/SESs. Climate regulation and carbon sequestration, as well as hydrological control, were mainly assessed using process-based models, erosion using statistical models, and biomass production using rule-based models (Figure 5). The other STs and SESs, namely erosion control, SOC loss, and compaction, were assessed using a wider range of methods (Figure 5). Such differences in the assessment methods used for different STs and SESs are likely due to a legacy of past research efforts that eventually resulted in the emergence of "easier" or even "natural" methods, as already observed by Czúcz et al. (2020) for indicator selection. This is undoubtedly the case for assessments of biomass production dominated by rule-based models (e.g., Tóth et al. 2013) and sheet and rill erosion mainly obtained by statistical models (i.e., RUSLE), whose development dates back several decades, or sometimes even a century, for the assessment of soil suitability for agricultural production (Figure 5). Similarly, the considerable efforts made to mechanistically model the dynamics of SOC or soil water fluxes explain why process-based models are so often used to assess SOC loss, climate regulation, and carbon sequestration, or hydrological control (Figure 5).

When different methods were used to assess the same ST or SES, they were generally used to estimate different indicators. This is particularly the case for the compaction assessment for which rule-based models have been used to assess the soil strength (Houšková and Montanarella 2008; Jones et al. 2003), process-based models to assess the balance between stress and soil strength (Lamandé et al. 2018; Schjønning et al. 2015), expert knowledge to assess the actual state of compaction (Oldeman et al. 1991), and statistical models to assess the consequences of soil compaction (Sonderegger and Pfister 2021; Stoessel et al. 2018). Furthermore, rule-based modelling, as a static approach (Greiner et al. 2017), has been mainly used to estimate potential ST/SES indicators (Tables 5 and 6), while process-based modelling, as a dynamic approach (Greiner et al. 2017), has often been used to assess processes and consequently actual STs or SESs. Statistical modelling is a simple

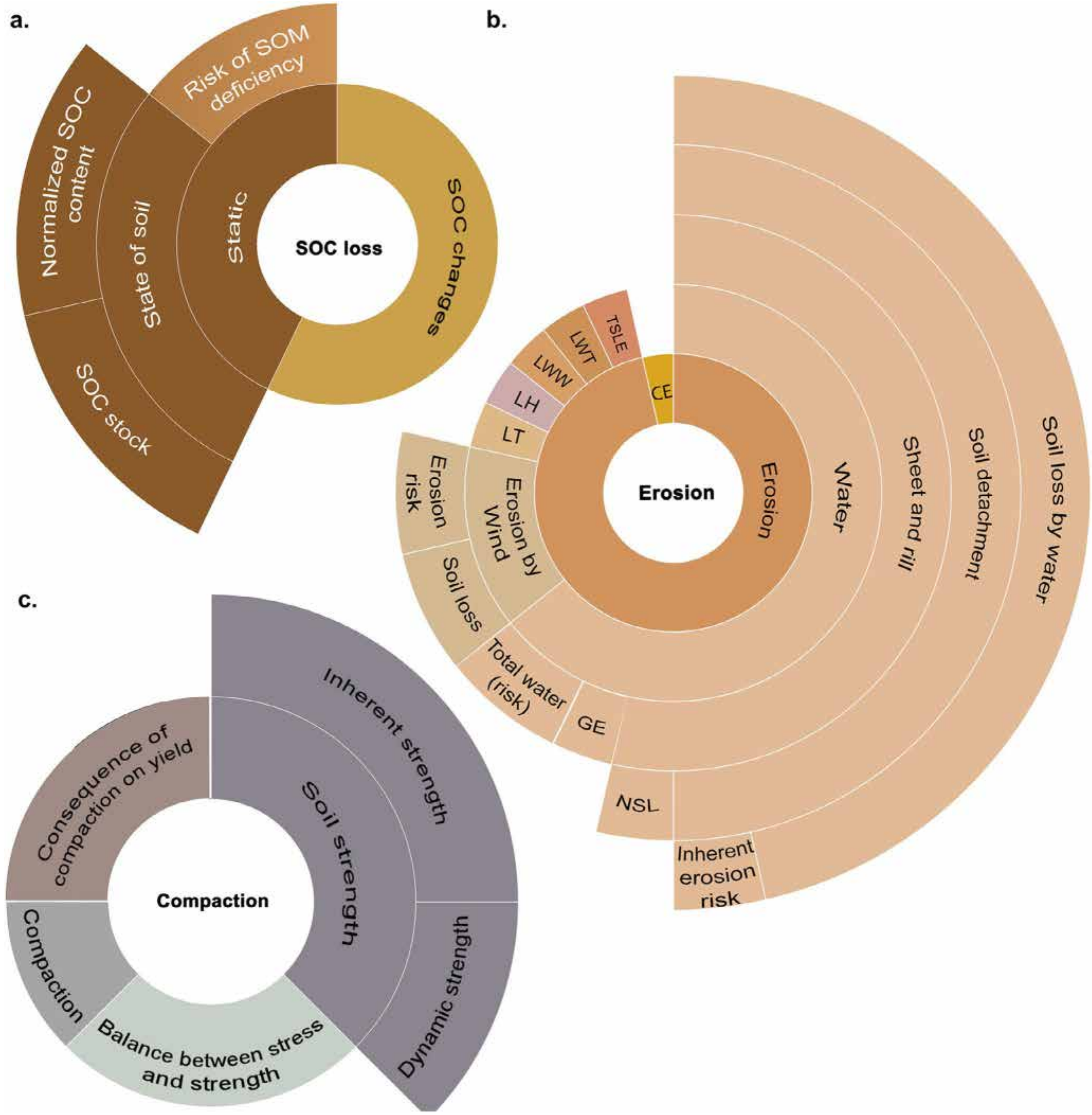


**FIGURE 2** | ST indicators: (a) SOC loss; (b) erosion; (c) compaction. The colours in each graph represent different groups of indicators. NSL stands for net soil loss by water; GE for gully erosion, LT for loss by tillage, LH for loss by harvest, LWW for loss by water and wind, LWT for loss by water and tillage, TSLE for total soil loss by erosion, CE for consequences of erosion. References associated with each indicator are reported in the Supporting Information (Table S2).

alternative to estimate actual STs and SESs, especially for water erosion (Figure 2b) or for erosion control (avoided soil loss; Figure 3d).

## 3.3 | Sources of Information

The previous analysis highlighted the importance of data for ST/SES indicator assessments. Thus, we analyzed the data sources used for the different ST/SES indicators.

### 3.3.1 | Types of Data Used to Assess the Different ST/SES Indicators

The type of data used depends on the ST/SES and on the indicator considered, as well as on the method chosen to assess them. Soil data are used in all assessments for most of the STs and SESs considered, with the notable exceptions of some assessments of erosion control and biomass production (Figure 6). Climate and LULC data are also used in the calculation of most ST/SES indicators, with the exception of some indicators of biomass

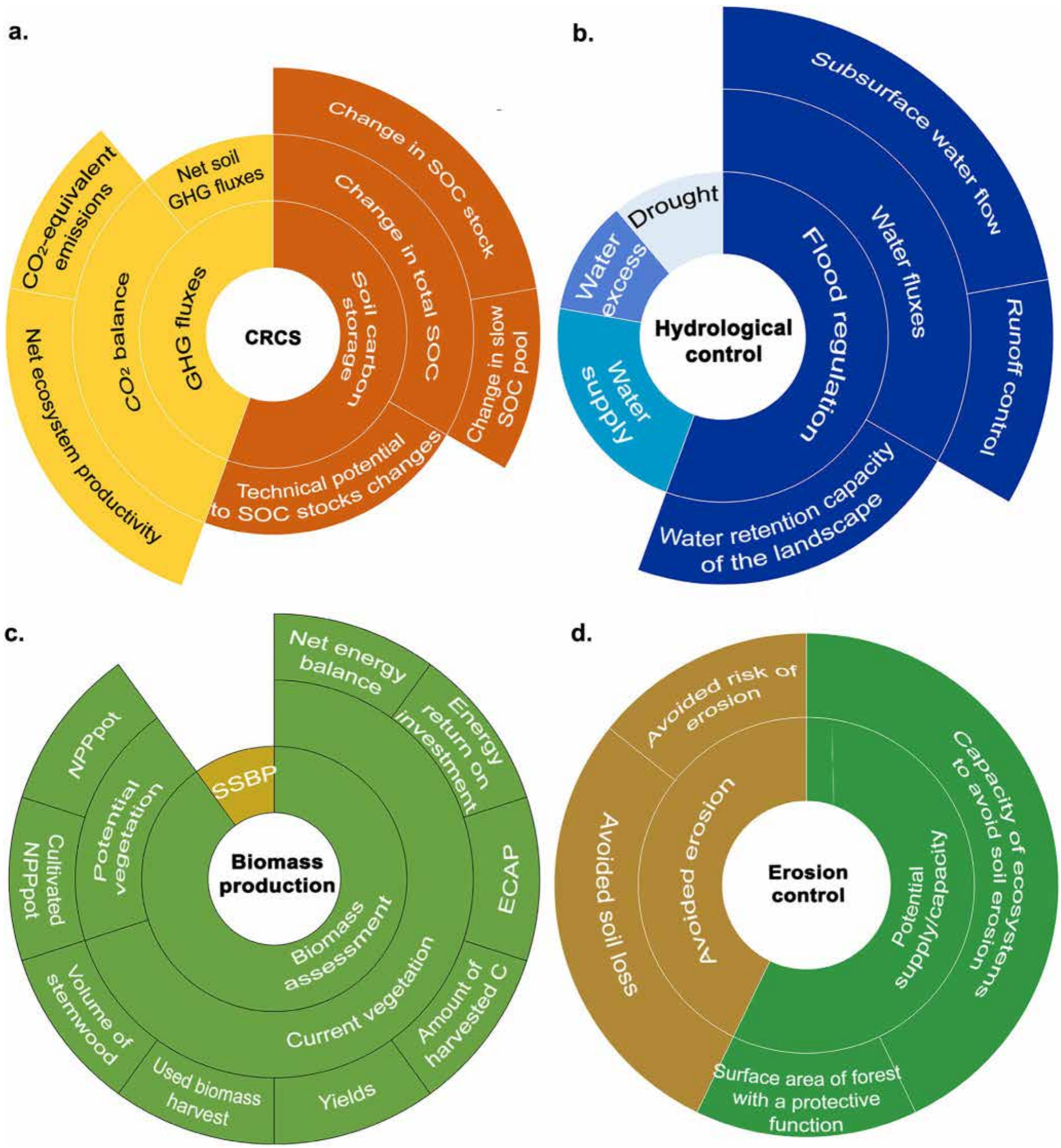


**FIGURE 3** | SES indicators: (a) Climate regulation and carbon sequestration; (b) hydrological control; (c) biomass production; (d) erosion control. The colours in each figure represent different groups of indicators. CRCS stands for climate regulation and carbon sequestration, NPPpot for potential net primary production, SSBP for soil suitability to biomass production, and ECAP for energy content of agricultural productions. References associated with each indicator are reported in the Supporting Information (Table S3).

production and soil compaction (the indicators "consequences of compaction on yield"—Sonderegger and Pfister 2021; Stoessel et al. 2018—and "balance between stress and strength"—Lamandé et al. 2018; Schjønning et al. 2015; Figure 2c—which are based solely on soil data and agricultural practices). Topography and agricultural practices data are mainly used to estimate erosion, but also, to a lesser extent, climate regulation and carbon sequestration for agricultural practices. Biomass data have been mainly used to estimate biomass production (Figure 6). Finally, parent material data have been used in one case for hydrological control (Trombetti et al. 2015).

### 3.3.2 | Sources of Data

For each data type (soil, climate, LULC, topography, agricultural practices, and biomass), different sources were used in the ST/SES assessments (Figure 7). The vast majority of datasets

**TABLE 5** | Combination of preference of the indicators used in the literature for mapping the different STs at the EU extent.

| ST | Actual | | | | Potential (sensitivity/risk) |
|---|---|---|---|---|---|
| | Process | State | Impact | Other | |
| Erosion | **Soil loss by water** (Borrelli, Ballabio, et al. (2022), Panagos et al. (2020), Borrelli et al. (2017), Bosco et al. (2015), Panagos et al. (2015), Podmanicky et al. (2011), van der Knijff et al. 2000, Baartman et al. (2022), Kirkby et al. (2008), Cerdan et al. (2010), Englund et al. 2020, Prăvălie, Patriche, et al. (2021), Van Oost et al. 2009, Wuepper et al. (2020)) **Net soil loss by water** (Borrelli et al. (2018)) **Soil loss by wind erosion** (Englund et al. (2020), Chappell et al. (2019)) **Loss by tillage** (Van Oost et al. (2009)) **Loss by harvest** (Panagos et al. (2019)) **Loss by water and wind** (Englund et al. (2020)) **Loss by water and tillage** (Van Oost et al. (2009)) **Total loss by erosion** (Borrelli, Panagos, et al. (2022)) | **Gully erosion** (Borrelli, Ballabio, et al. 2022) | **Consequence of erosion** (Sonderegger and Pfister (2021)) | | **Inherent erosion risk** (van der Knijff et al. (2000)) **Erosion risk by wind** (Borrelli, Lugato, et al. (2016), Borrelli, Panagos, et al. (2016), Borrelli et al. (2014), Oldeman et al. 1991) **Total water (risk)** (Le Bissonnais et al. (2002), Oldeman et al. (1991)) |
| Compaction | | **Compaction** (Oldeman et al. (1991)) | **Consequence of compaction on yield** (Stoessel et al. (2018), Sonderegger and Pfister (2021)) | **Balance between stress and strength** (Lamandé et al. (2018), Schjønning et al. (2015)) | **Inherent strength** (Houšková and Montanarella (2008), Jones et al. 2003); **Dynamic strength** (Jones et al. (2003)) |
| SOC loss | **SOC change** (Poeplau and Dechow (2023); Padarian et al. (2022), Prăvălie, Patriche, et al. (2021), Prăvălie, Nita, et al. (2021), Sanderman et al. (2017)) | **SOC stock** (Lugato, Panagos, et al. (2014)); Normalized SOC content (Englund et al. (2020)) | | | **Risk of SOM deficiency** (Hijbeek et al. (2017)) |

*Note:* Indicators were classified according to a combination of preferences at two levels (Niemeijer and de Groot 2008). The first level distinguishes between actual and potential states. The second level categorised the indicator depending on its ability to represent a process (mechanisms driving degradation), a soil condition, an impact (consequences of STs), or something else (others).

**TABLE 6** | Combination of preference of the indicators used in the literature for mapping the different SESs at the EU extent.

| Provider | Soil system | | Soil–plant system | | Socio-system |
|---|---|---|---|---|---|
| **Component** | **Capacity** | **Flow** | **Capacity** | **Flow** | **Flow** |
| Climate regulation and carbon sequestration | **Technical potential to SOC stocks changes** (Lugato, Bampa, et al. (2014), Vleeshouwers and Verhagen (2002)) | **SOC stocks changes** (De Rosa et al. (2023), Vrebos, Staes, et al. (2018)) **Change in slow SOC pool** (Vrebos, Bampa, et al. (2018)) **Net soil GHG fluxes** (Lugato et al. (2018)) | | **Net ecosystem productivity** (Schulp et al. (2012), Paracchini et al. (2011)) **$CO_2$ equivalent emissions** (Vrebos et al. (2019)) | |
| Hydrological control | | | **Water retention capacity of the landscape** (in areas sensitive to flood) (Trombetti et al. (2015), Schulp et al. (2012)) | **Subsurface water flow** (Liquete et al. (2011), Paracchini et al. (2011)) **Runoff control** (Stürck et al. (2014)) **Drought** (Vrebos et al. (2019)) **Water excess** (Waterlogging) (Vrebos et al. (2019)) | |
| Biomass production | **Soil suitability to biomass production** (Tóth et al. (2013)) | | **Cultivated potential Net Primary Procution (NPPpot)** (Schulp et al. (2012)) **Potential net primary productivity** (Mayer et al. (2021)) | | **Volume of stemwood** (Nabuurs et al. (2007)) **Net energy balance** (Pérez-Soba et al. (2015)) **Energy return on investment** (Pérez-Soba et al. (2015)) **Used biomass harvest** (Mayer et al. (2021)) **Current yields** (Schulp et al. (2012)) **Amounts of harvested C** (Vrebos, Staes, et al. (2018)) **Energy content of agricultural productions** (Pérez-Soba et al. (2015)) |

(Continues)

**TABLE 6** | (Continued)

| Provider | Soil system | | Soil–plant system | | Socio-system |
|---|---|---|---|---|---|
| **Component** | **Capacity** | **Flow** | **Capacity** | **Flow** | **Flow** |
| Erosion control | | | **Capacity of ecosystem to avoid soil erosion** (Trombetti et al. (2015), Rendon et al. (2022), Schulp et al. (2012)) **Surface area of forest with a protective function** (Trombetti et al. (2015)) | **Avoided risk of erosion** (Schulp et al. (2012)) **Avoided soil loss** (Trombetti et al. (2015), Rendon et al. (2022)) | |

*Note:* The indicators are classified according to the combination of preferences used (provider and component). The indicators were classified according to the combination of preferences at two levels: The first level considered the provider (i.e., soil system, the soil–plant system, or the socio-ecosystem), while the second considered the component that represents the specific aspect of the service (i.e., capacity and flow) (Van Oudenhoven et al. 2012).

used are spatially exhaustive (Figure 7), with the exception of SPADE and LUCAS datasets for soil and land cover.

For soil data (Figure 7a), the spatially exhaustive ESDAC European Soil Database is the most frequently used to assess the STs and SESs considered, with the exception of biomass production and erosion control, which were most often estimated using the FAO Global Soil Database (FAO/IIASA/ISRIC/ISS-CAS/JRC 2009). This is likely because these latter assessments were conducted in Eastern European countries and published in 2012 (Schulp et al. 2012; Figure 7a), when these countries were not yet included in the European Soil Database. Two other spatially exhaustive soil databases, SoilGrids and Open Landmark, are regularly used, especially for recent global assessments, replacing the FAO Soil Database, which is no longer used in recent work. Finally, 30% of the ST/SES assessments, mainly those based on process-based modelling, used point measurements databases such as LUCAS Soil or SPADE, depending on the type of data needed (e.g., bulk density was not available in LUCAS Soil before 2019). LUCAS Soil is also used for gully erosion (Borrelli, Poesen, et al. 2022), as it is the only database providing this information.

For climate data (Figure 7b), three of the six data sources were most frequently used: the JRC European Climate Database (notably MARS), the most frequently used from 2000 to 2017; the European Climate Assessment and Dataset (E-OBS), which began its use in 2015 and is currently the most widely used. The Climate Research Unit (CRU) database is typically used in global-scale studies (Poeplau and Dechow 2023) or when Eastern European countries, not fully included in E-OBS until recently, are considered (Schulp et al. 2012), as well as in studies published before 2015. Additionally, WorldClim data have been used for scenarios in global-scale analyses (Borrelli, Ballabio, et al. 2022).

For LULC (Figure 7c), 11 databases were used; one of them is non-spatially exhaustive (LUCAS), but provides information on crop types (Lugato et al. 2018). The CORINE land cover database is one of the most widely used. However, for assessment and mapping at the global scale (Padarian et al. 2022) and/or covering Eastern European countries (Schulp et al. 2012), recently integrated into CORINE land cover, the GlobCover database has been preferred, especially for the assessment of erosion control. The databases are also sometimes used in combination: CORINE land cover with Eurostat (Panagos et al. 2020; Panagos et al. 2015) or FAOSTAT with MODIS–MOD13A2 (Borrelli et al. 2017; Borrelli, Lugato, et al. 2016; Borrelli, Panagos, et al. 2016). Finally, remote sensing data from different satellites (SPOT, LANDSAT, NOAA AVHRR, MODIS–MOD13A2) are also used, especially for SOC loss (Poeplau and Dechow 2023; Padarian et al. 2022).

For topography (Figure 7d), four of the six identified data sources are used more frequently: the Shuttle Radar Topography Mission (SRTM), the European Digital Elevation Model (EU-DEM), the Global 30 Arc-Second Elevation (GTOPO30), and its derivative, the Global 30 s Arc-Second Hydrologic One Kilometre Elevation (HYDRO1k). GTOPO30 has been used to assess STs only in Eastern European countries (Schulp et al. 2012), or at the global level in its most recent version (Global Multi-resolution Terrain Elevation Data 2010, GMTED2010) (Padarian et al. 2022). HYDRO1k specifically provides topographically derived datasets, including streams and drainage basins, needed in some of

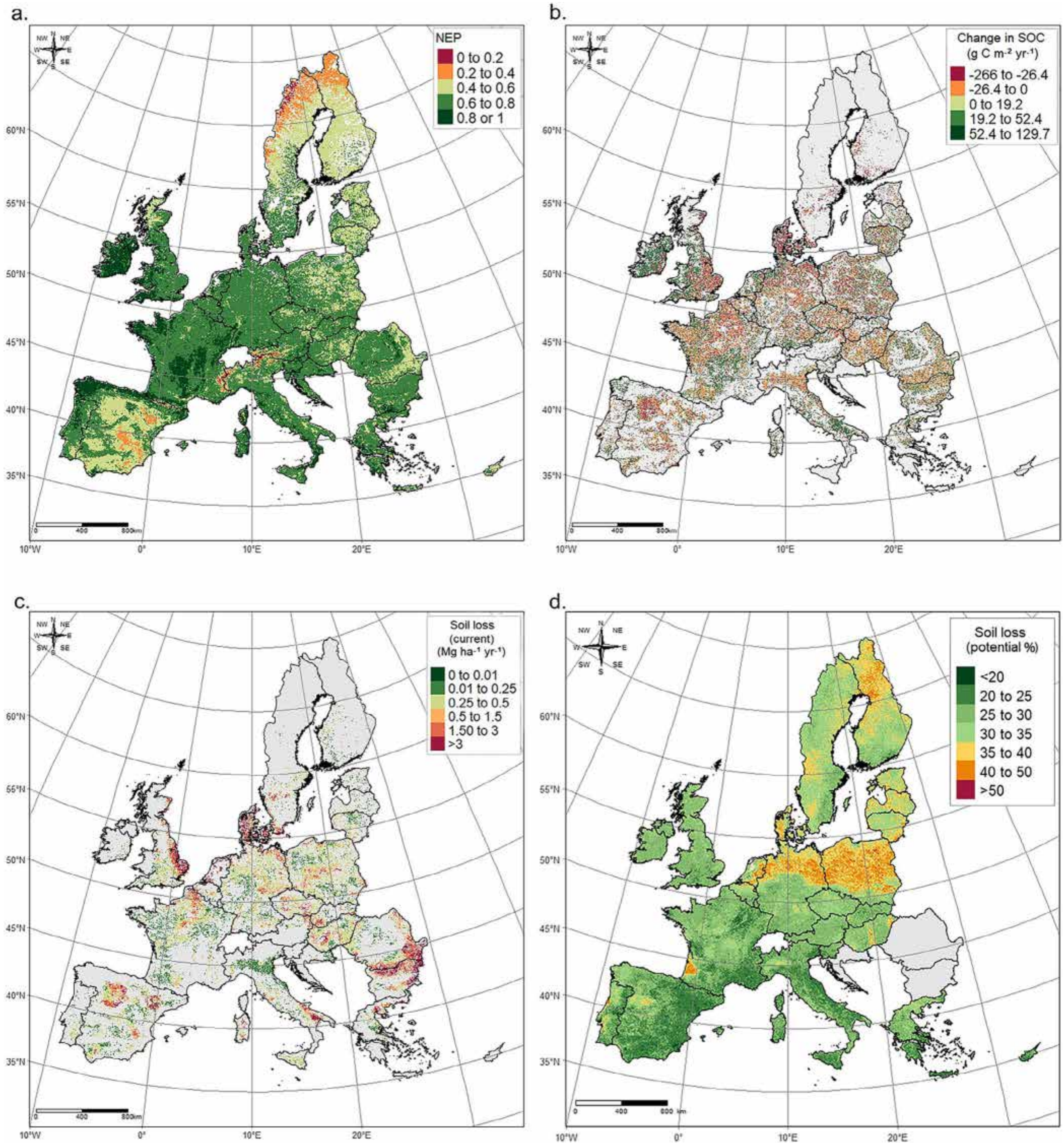


**FIGURE 4** | Impact of the choice of indicator on the ST/SES maps. Upper row—impact of the part of the ecosystem considered when assessing the SES "climate regulation and carbon sequestration": (a) GHG fluxes using net ecosystem productivity focusing on the soil–plant system (data from Paracchini et al. 2011, Data sources: ESDAC); (b) SOC stock (change in SOC) focusing only on the soil system (Data sources: Vrebos Dirk). Lower row—Mapping potential versus actual ST indicator for wind erosion (Data sources: ESDAC): (c) actual (data from Borrelli, Lugato, et al. 2016), (d) potential (data from Borrelli et al. 2014).

the erosion assessments (Le Bissonnais et al. 2002) and hydrological control (Stürck et al. 2014) indicators.

The MAPSPAM, EUROSTAT, and FAOSTAT databases are the most used for estimating agricultural practices and biomass (Figure 7e,f). In addition to these three main databases, CAPRI model outputs are also used for biomass estimation (Figure 7f).

## 4 | Discussion: Analysis of the Potential of Existing ST/SES Estimations at the EU Extent for Building ST/SES Relationships

Most existing work has considered STs (≈85%) and SESs (≈60%) individually, and those assessing more than two STs/SESs have not examined their relationships, although, as mentioned in the

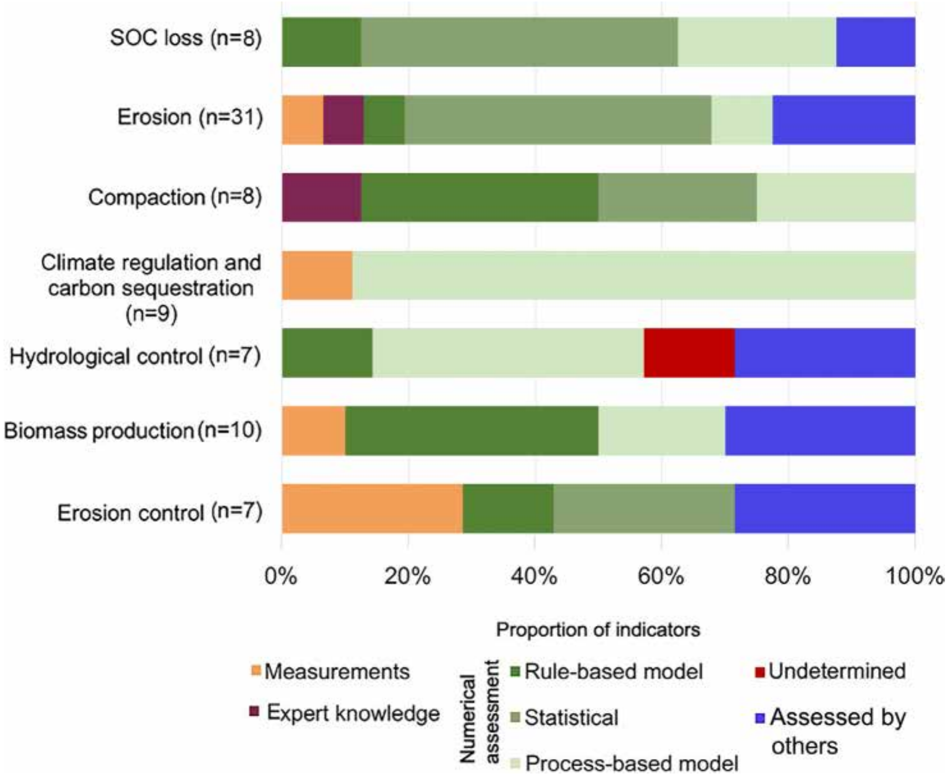


**FIGURE 5** | Methods used to assess ST and SES indicators at EU extent from 1990 to 2022. Numbers in brackets represent the number of assessments encountered in the literature for each ST/SES.

introduction, STs and SESs are known to have complex relationships (Kiessé et al. 2024; Medina-Roldán et al. 2024; Obiang-Ndong et al. 2020) that often involve trade-offs and synergies (Bennett et al. 2009). Thus, knowledge of these relationships could guide the adaptation of remediation measures or the design of management strategies aimed at reducing soil degradation and ensuring SES supply. Yet, to the best of our knowledge, only one study has assessed the co-occurrence of STs at the EU level (Prăvălie et al. 2024), and the interactions between SESs have been largely neglected.

As we have seen, existing EU-wide assessments of STs and SESs present a wide variety of ST/SES indicators, with different combinations of preferences, assessment methods, and databases used as input data. For example, an average of four indicators is currently mapped at the EU level for each of the most important STs and SESs, resulting in very different maps for a given ST or SES.

Currently, defining EU-wide ST/SES relationships based on the reuse of pre-existing maps of individual ST and SES faces a number of challenges and pitfalls due to the wide variety of preferences observed in the literature. Mapping ST/SES relationships based on existing individual ST/SES maps at the EU level requires careful selection of compatible indicators, assessment methods, and databases, as outlined below.

### 4.1 | Selection of the Indicators Used to Make the ST/SES Relationships

Ecological indicators have long been recognised as boundary objects (Turnhout 2009). This means that indicators are not only purely objective science-based tools useful for assessing objects of interest such as STs or SESs, but also the vectors of selective preferences about what STs and SESs are or should be (Turnhout 2009). Regarding SESs, their indicators can represent the soil system itself, the soil–plant system, or integrate elements from the socio-ecosystem (Table 6). The focus on a particular component of the preferences combination governing STs among risk, process, soil state, or impact (Table 5; Niemeijer and de Groot 2008), or the process of delivering SESs between capacity or flow (Van Oudenhoven et al. 2012), is also part of these preferences. Reflecting specific combinations of preferences, different indicators of the same ST/SES are not systematically interchangeable. Therefore, before establishing ST/SES relationships, indicators must be carefully selected to ensure the compatibility of preferences specific to each indicator. Such a selection, far from simple because the preference systems associated with the indicators are often insufficiently explicit, if not simply false (Czúcz et al. 2020), is further complicated by its dependence on the type of relationships to be constructed.

In the case of multi-ST or multi-SES relationships, each particular combination of preferences is likely to be of interest. However, for a given relationship, all indicators must share the same combination of preferences. Given the current state of knowledge at the European scale, such complete alignment of preferences cannot be achieved for SESs (Table 6) and for STs only if sensitivity or the actual soil condition is considered (Table 5). As a result, it is not surprising that the EU-wide studies of ST/SES relationships mixed indicators reflecting several combinations of preferences. For instance, Prăvălie

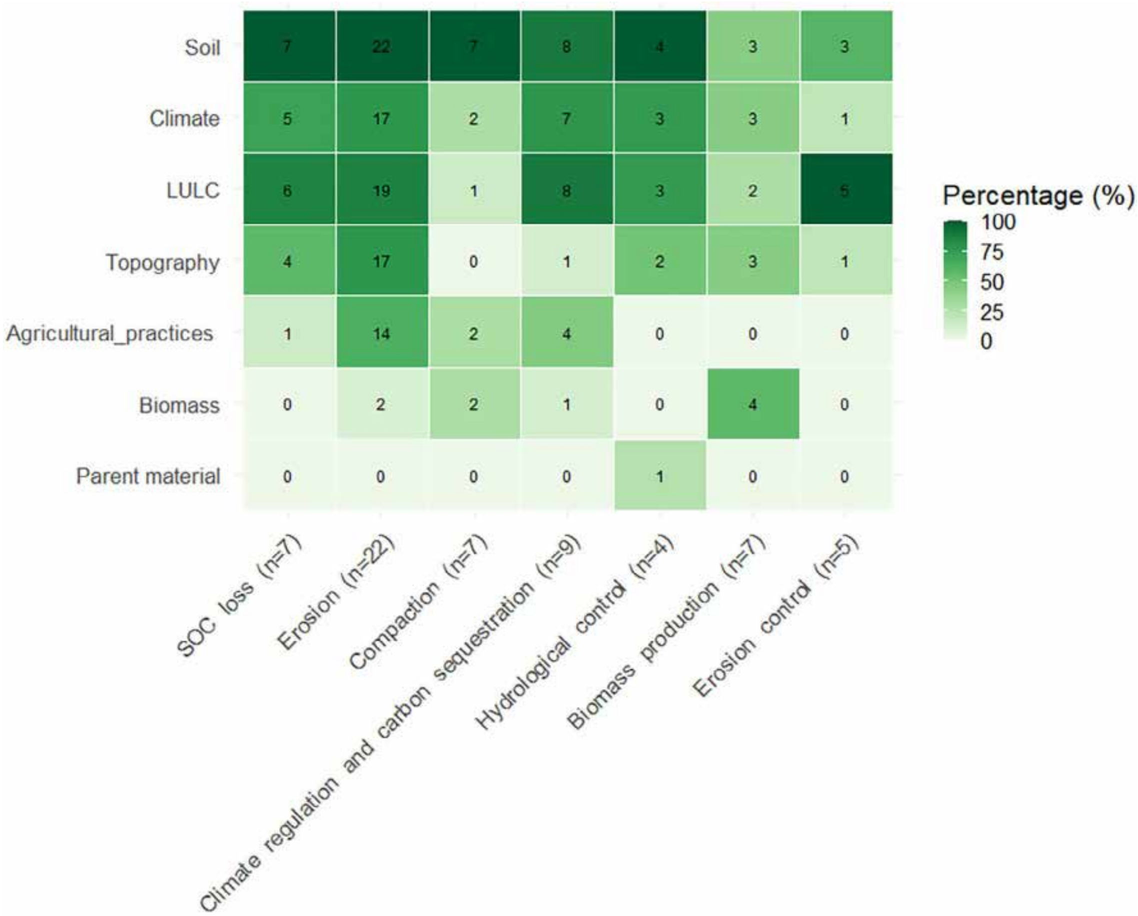


**FIGURE 6** | Type of data used in the literature for the evaluation of the considered STs and SESs at the EU extent. The number of indicators assessed in the considered documents using the different data types is reported in brackets (indicators assessed by expert knowledge or "assessed by others" were excluded from this analysis).

et al. (2024) mixed pressure indicators for aridity; process indicators for water and wind erosion, soil organic carbon loss, vegetation decline, or groundwater decline; current soil condition indicators for salinization, acidification, and trace metal and metalloid pollution; risk or sensitivity indicators for compaction and pesticide pollution; and finally, a combination of process and condition indicators for nutrient imbalances. A further step could also be to map soils that are either (i) susceptible to degradation (risk indicators); (ii) currently threatened (process indicators); or (iii) degraded (condition indicators). Reusing existing ST/SES maps would be facilitated if the combination of preferences underlying each indicator were clearly explained in the published documents. In addition, there are two to five times more SES indicators in the literature than those used at the European level (Czúcz et al. 2020; Boerema et al. 2016). Therefore, there is significant room for improvement in the various types of ST and SES assessments at the European level, which could address the current limitations in the development of ST/SES relationship studies, particularly for SESs.

In the case of a single ST or SES, characterising the relationships between indicators that differ only in one of the preferences mentioned above (Tables 5 and 6) is of great interest, as demonstrated by comparing the potential (capacity) and the actual (flow) supply of SES (all other preferences being similar) to assess the sustainability (when the flow is lower than the capacity) or the unsustainability (when the flow is higher than the capacity) of the SES uptake (Baró et al. 2016; Schröter et al. 2014). At the EU level, the study of such relationships is rare and mainly limited to the comparison of the potential and actual supply of a few SESs, such as biomass production (Mayer et al. 2021; Schulp et al. 2012) or erosion control (Rendon et al. 2022; Trombetti et al. 2015; Schulp et al. 2012). Based on the existing EU-wide SES maps, the comparison of the potential and the actual supply could be extended to the regulation of climate and carbon sequestration by comparing the technical potential of SOC storage (Lugato, Bampa, et al. 2014; Vleeshouwers and Verhagen 2002) with the actual SOC storage (De Rosa et al. 2023; Lugato et al. 2018; Vrebos, Staes, et al. 2018; Vrebos, Bampa, et al. 2018) or to hydrological control by comparing the water storage capacity (Trombetti et al. 2015; Schulp et al. 2012) with subsurface water flow (Liquete et al. 2011; Paracchini et al. 2011). For STs, various comparisons of sensitivity, process, condition, or impact indicators for SOC loss, erosion, and compaction are, at least partially, feasible (Figure 2) and could be helpful to identify situations where soils are simultaneously sensitive, threatened, or degraded.

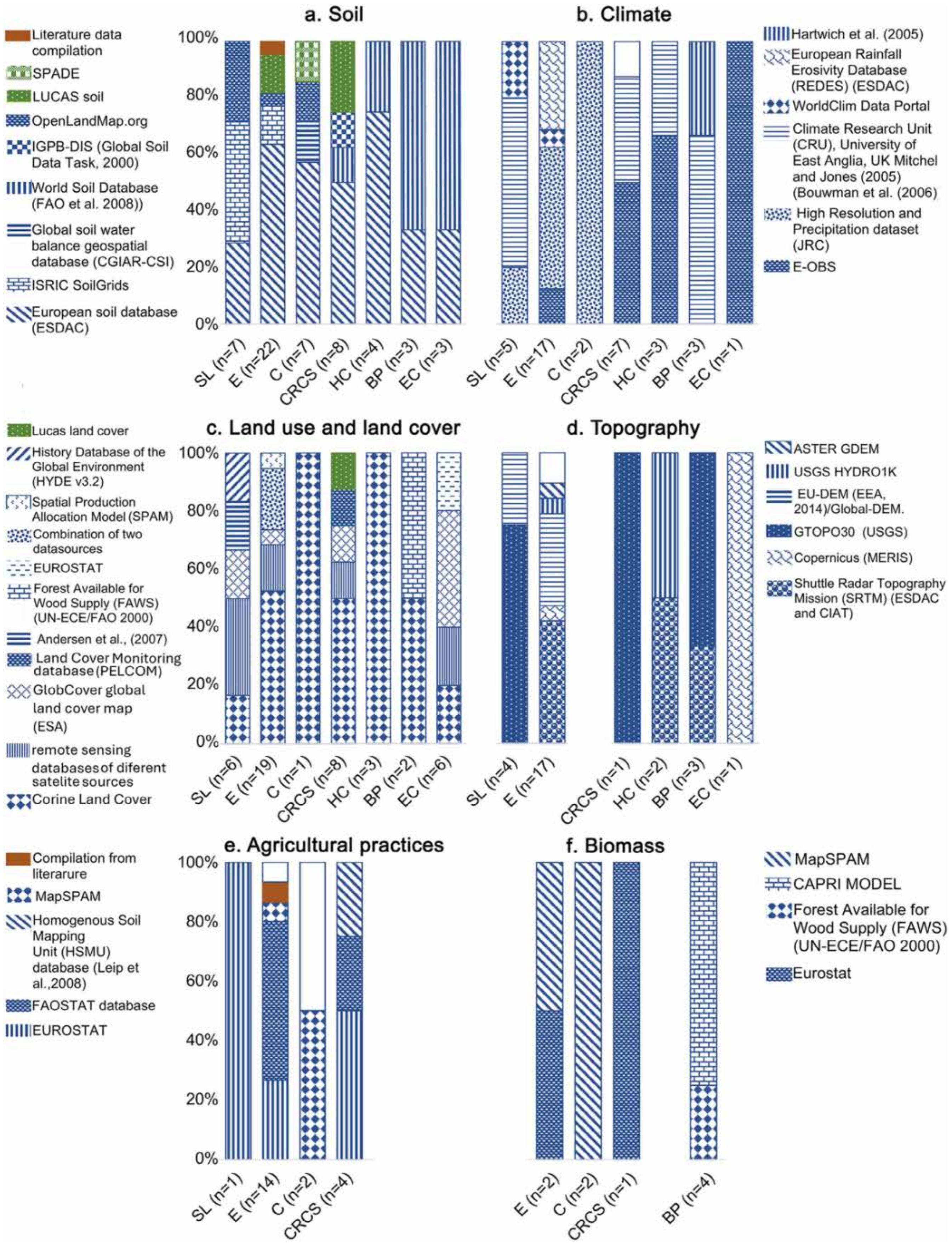


**FIGURE 7** | Legend on next page.

**FIGURE 7** | Databases used in the assessment of STs/SESs for: (a) soil, (b) climate, (c) LULC, (d) topography, (e) agricultural practices and (f) biomass. The numbers in brackets refer to ST/SES assessments by data type (see Figure 6). Colours indicate dataset type: Blue = spatially exhaustive, green = point data, brown = literature, white = no source information. SL = SOC Loss; E = Erosion; C = Compaction; CRCS = Climate Regulation and Carbon Sequestration; HC = Hydrological Control; BP = Biomass Production; EC = Erosion Control.

### 4.2 | Rigorous Examination of the Method Employed to Estimate the Indicators

The different methodologies used to quantify STs/SESs, often closely linked to specific indicators, have specific advantages and limitations. Expert knowledge can be a very effective method to provide an overview of multiple STs/SESs in space, while process-based modelling is necessary to understand how management influences STs/SESs or to predict the consequences of unprecedented climate or management scenarios (Grêt-Regamey et al. 2015; Schröter et al. 2016). However, the assessment methods also have specific and sometimes mutually exclusive areas of application. Measurement-based assessments, although regularly requested, are not feasible for every ST and SES. As shown in our study, measurements have only been used for a limited number of indicators for erosion (Borrelli, Poesen, et al. 2022—Gully; Cerdan et al. 2010), erosion control (Trombetti et al. 2015), and climate regulation and carbon sequestration (De Rosa et al. 2023). With the exception of erosion control, process-based models have been proven particularly popular in studies to quantify ST/SES indicators. While these models are effective in assessing various SESs in deep, homogeneous, and well-drained soils, they are not effective in marginal soils characterised by significant waterlogging, extreme acidity, or strong textural differentiation (Choquet et al. 2021). In contrast, rule-based models have been shown to be usable for a wider variety of soil conditions, but at the cost of increased uncertainty (Choquet et al. 2021).

While combining methodologies can be an effective approach to increase the diversity of STs/SESs incorporated into relationships, it also entails additional limitations and uncertainties specific to each methodology used. Such combinations of limitations and uncertainties are problematic because the conditions for which the available methodologies perform well and the uncertainties associated with such methodologies are rarely known due to the lack of comparative and validation studies.

### 4.3 | Alignment of Datasets for a Given Type of Data

As with methods, the choice of input data used has a significant impact on ST/SES maps (Ellili-Bargaoui et al. 2023; Scammacca et al. 2023; Bagstad et al. 2018). Thus, when jointly assessing STs/SESs, indicators should ideally be estimated from the same database for a given data type. Our review of the datasets used to assess available ST/SES indicators has shown that this is rarely, and even then, only partially, the case. For STs, the assessment of (i) SOC loss by Hijbeek et al. (2017); (ii) soil erosion by Kirkby et al. (2008), van der Knijff et al. (2000) or Podmanicky et al. (2011); and finally, (iii) soil compaction by Jones et al. (2003) is all based on the ESDAC and JRC MARS datasets for soil and climate data respectively (Table 7). However, none of these indicators have been assessed using the same database for LULC and topography (Table 7). Not all SES considered have ever been assessed with a similar dataset (Table 8), except for those that were assessed by the same authors. This is, for example, the case of Schulp et al. (2012) for climate regulation and carbon sequestration, biomass production and erosion control, or Vrebos, Staes, et al. (2018), Vrebos, Bampa, et al. (2018), and Vrebos et al. (2019) for climate regulation and carbon sequestration and hydrological control (Table 8).

In recent years, intensive work has been carried out to compare existing soil databases and assess the impact of their use on the assessment of soil indicators in order to identify solutions to manage this diversity, through the use of transfer or scoring functions to obtain comparable values (Froger et al. 2024; Cornu et al. 2023). While this work has the merit of raising the question of the origin of the data on the results produced and of proposing some initial solutions, it only concerns the harmonisation of different soil databases to assess unmeasured soil properties. This is a much simpler problem than the assessment of ST/SES indicators requiring the combination of different types of data, each likely to have multiple origins/sources (Cornu et al. 2023).

### 4.4 | Shaping the Future of Studies on ST/SES Interactions at the EU Extent

Although limited, the set of ST/SES maps currently available at the European level offers several opportunities for combinations. Some of them have already been exploited, such as the simple addition of the soil loss due to different types of erosion to assess the total soil loss by erosion (Borrelli, Panagos, et al. 2022). Others still await exploration, such as the comparison of different ST/SES components. However, due to the lack of a set of indicators sharing a common preference combination (Section 4.1), a proper characterisation of ST/SES relationships is generally impossible. Several complementary steps can be proposed to develop such approaches.

In the short term, European ST/SES maps could be recomputed using similar input data. Thus, for instance, the recalculation of potential SOC stocks of Lugato, Panagos, et al. (2014), based on JRC-MARS climate data rather than CRU data (Table 7), would allow for fully aligning input data (ESDAC for soil, JRC-MARS for climate and CORINE for LULC) of a first set of indicators for the three most important STs for stakeholders, using the potential SOC stocks by Lugato, Panagos, et al. (2014), the soil loss by water by Podmanicky et al. (2011), and the dynamic soil strength by Jones et al. (2003) (Table 8).

Improving the consistency of methodologies used is much more complex, as no model integrating a realistic representation of

**TABLE 7** | Combination of EU-wide data sources used for estimation of actual indicators for the three considered STs.

| ST | Indicator | References | SOIL data | Climate data | LULC | Topography | Agricultural Practices | Biomass |
|---|---|---|---|---|---|---|---|---|
| SOC loss | Change in SOC | Poeplau and Dechow (2023) | OpenLandMap.org | CRU | Remote sensing databases[a] | | | |
| | | Padarian et al. (2022) | ISRIC SoilGrids | WorldClim | Remote sensing databases[a] | GTOPO30 | | |
| | | Prăvălie, Patriche, et al. (2021) | Global Soil Data collection[b] | | | | | |
| | | Prăvălie, Nita, et al. (2021) | ISRIC SoilGrids | | ESA[c] | | | |
| | | Sanderman et al. (2017) | ISRIC SoilGrids | CRU | HYDE v3.2[d] | Global EarthEnv-DEM | | UNEP-WCMC |
| | SOC stock | Lugato, Panagos, et al. (2014) | ESDAC | CRU | CORINE | | | |
| | Risk of SOM | Hijbeek et al. (2017) | ESDAC | JRC-MARS | Andersen et al. (2007) | GTOPO30 | | |
| Soil erosion | Soil loss by water | Baartman et al. (2022) | ESDAC | E-OBS | CORINE | SRTM | | |
| | | Borrelli, Ballabio, et al. (2022) | ISRIC SoilGrids | WorldClim | GlobCover | SRTM | FAOSTAT | |
| | | Panagos et al. (2020) | LUCAS soil | REDES | European LULC datasets[e] | EU-DEM | EUROSTAT | |
| | | Borrelli et al. 2017 | ISRIC SoilGrids | REDES | European LULC datasets[e] | ASTER GDEM | FAOSTAT | |
| | | Bosco et al. (2015) | ESDAC | E-OBS | CORINE | SRTM | Literature[f] | |
| | | Panagos et al. (2015) | LUCAS soil | REDES | European LULC datasets[e] | EU-DEM | EUROSTAT | |
| | | Podmanicky et al. (2011) | ESDAC | JRC-MARS | CORINE | SRTM | FAOSTAT | |
| | | Van Oost et al. 2009 | ESDAC | | Corine Land Cover | SRTM | FAOSTAT | |
| | | Kirkby et al. (2008) | ESDAC | JRC-MARS | Remote sensing data[a] | SRTM | FAOSTAT | |
| | | Borrelli et al. (2018) | ESDAC | REDES | CORINE | EU-DEM | EUROSTAT | |
| | | Borrelli, Poesen, et al. (2022) | LUCAS soil | | | | | |
| | Wind erosion | Chappell et al. (2019) | ISRIC SoilGrids | GLDAS, v2.1 | | | | MODIS[g] |
| | Loss by tillage | Van Oost et al. (2009) | ESDAC | | Corine Land Cover | SRTM | FAOSTAT | |
| | Loss by harvest | Panagos et al. (2019) | ESDAC | | Corine Land Cover | EU-DEM | | Eurostat |
| | Consequences of erosion | Sonderegger and Pfister (2021) | OpenLandMap.org | REDES | SPAM | SRTM | MAPSPAM | MAPSPAM |

(Continues)

**TABLE 7** | (Continued)

| ST | Indicator | References | SOIL data | Climate data | LULC | Topography | Agricultural Practices | Biomass |
|---|---|---|---|---|---|---|---|---|
| Compaction | Soil strength | Houšková and Montanarella (2008) | ESDAC | | Corine Land Cover | | | |
| | | Jones et al. (2003) | ESDAC | JRC-MARS | Corine Land Cover | | | |
| | Balance between stress and strength | Lamandé et al. (2018) | SPADE | | | | | |
| | | Schjønning et al. (2015) | ESDAC | | | | | |
| | Consequences of compaction on yield | Sonderegger and Pfister (2021) | OpenLandMap.org | | | | MAPSPAM | MapSPAM |
| | | Stoessel et al. (2018) | CGIAR-CSI | | | | MAPSPAM | MapSPAM |

[a]Remote sensing data of different satellite sources (SPOT, LANDSAT, NOAA AVHRR, MODIS–MOD13A2).
[b]Global Soil Data collection: Hengl et al. (2018); ISRIC; USDA National Cooperative Soil Characterisation Database, Africa Soil Profiles Database, LUCAS.
[c]ESA Climate Change Initiative time series at 300 m.
[d]HYDE v3.2: History Database of the Global Environment.
[e]European LULC datasets: CORINE-Eurostat, FAOSTAT and MODIS–MOD13A2 datasets.
[f]Literature compilation.
[g]MODIS-derived vegetation indices.

soils is currently available to quantify a wide range of SESs on land uses ranging from forest to arable land (Choquet et al. 2021). Two complementary and non-exclusive approaches could be considered depending on the diversity of STs/SESs and land uses to be considered. Several models specifically dedicated to the assessment of individual ST/SES could be combined, provided that these models are of similar complexity (a set of rule-based, statistical, or process-based models) to better control the usage conditions, benefits, and uncertainties specific to each method type (Choquet et al. 2021). Such an approach is unavoidable because most STs, but also some SESs, such as erosion control, can only be modelled using specific tools. As most STs and SESs have been mapped at the EU level using all different method types (Figure 5), this approach seems relatively quick and easy to implement. A second approach would be to map and characterise the relationships of several STs or SESs using a single model. Such an approach has already been applied at the local (Ellili-Bargaoui et al. 2021), regional (Choquet et al. 2021; Obiang-Ndong et al. 2020), and national levels (Therond et al. 2017), but rarely at the EU level (Vrebos, Staes, et al. 2018; Vrebos, Bampa, et al. 2018; Vrebos et al. 2019). While effective in terms of methodological consistency, this type of approach is, so far, limited to arable land, a narrow but relevant set of SESs including biomass production, hydrological control, as well as climate regulation and carbon sequestration. In this type of approach, the consideration of other land uses and a broader range of STs/SESs is a more distant objective that will require the development of specific modelling capacities (Choquet et al. 2021).

Finally, the EU-wide mapping of new ST/SES indicators would allow the analysis of the ST/SES relationship based on sets of indicators sharing consistent representations (or combinations of preferences). Regarding STs, a pressing need concerns the assessment of the degree of compaction (soil condition) and of its evolution over time (process). The integration of bulk density in most national soil databases in EU countries, sometimes for years (Cornu et al. 2023), its (partial) integration in the LUCAS Soil database from the 2018 campaign (Orgiazzi et al. 2018), and potentially in the future Soil Monitoring Law are all tools that could support the mapping of this indicator (i.e., soil compaction expressed as a variation in bulk density change). Regarding SESs, the most advanced type of indicators is defined at the soil–plant system level (Table 6), which is consistent with the emerging definition of SESs as the subset of ecosystem services directly controlled by soil properties, processes, or functions (Paul et al. 2021). According to Table 6, two main indicators need to be developed to obtain a comprehensive set of indicators at the soil–plant system level: (i) a capacity indicator for climate regulation and carbon sequestration and (ii) a flow (actual) indicator for biomass production. The former should reflect the capacity of the soil–plant system to store carbon. Among other possibilities, it could be based, for the plant compartment, on the net primary productivity of the plant cover that would prevail in the absence of human intervention (Mayer et al. 2021) and, for the soil compartment, on the assessment of the soil organic carbon sequestration potential (Chen et al. 2018; Angers et al. 2011). The latter should reflect the total amount of below- and aboveground biomass produced, rather than just the harvested fraction. It could be assessed, for example, by the net primary productivity of the currently prevailing vegetation (Mayer et al. 2021; Haberl et al. 2014).

**TABLE 8** | Combination of EU-wide data sources used for the estimation of actual indicators for the four considered SESs.

| SES | Indicator | References | Soil data | Climate data | LULC | Topography | Agricultural practices | Biomass |
|---|---|---|---|---|---|---|---|---|
| Climate regulation and carbon sequestration | Soil carbon storage | Vleeshouwers and Verhagen (2002) | | | | | FAOSTAT | |
| | | Vrebos, Staes, et al. (2018) | ESDAC | E-OBS | CORINE | | | |
| | | De Rosa et al. (2023) | LUCAS | | | | | |
| | | Vrebos, Bampa, et al. (2018) | ESDAC | E-OBS | CORINE | | | |
| | GHG fluxes | Lugato et al. (2018) | LUCAS | E-OBS | Lucas land cover | | EUROSTAT | EUROSTAT |
| | | Lugato, Bampa, et al. (2014) | | | | | EUROSTAT | |
| | | Vrebos et al. (2019) | ESDAC | E-OBS | CORINE | | | |
| | | Paracchini et al. (2011) | | | Remote sensing data | | | |
| | | Schulp et al. (2012) | World Soil Database | CRU | GlobCover | GTOPO30 | | |
| Hydrological control | Flood regulation estimated by water fluxes | Stürck et al. (2014) | World Soil Database | CRU | CORINE | HYDRO1K | | |
| | Water excess | Vrebos et al. (2019) | ESDAC | E-OBS | CORINE | | | |
| | Drought | Vrebos et al. (2019) | ESDAC | E-OBS | CORINE | | | |
| Biomass production | Current vegetation | Pérez-Soba et al. (2015) | | | | | | CAPRI |
| | | Schulp et al. (2012) | World Soil database | CRU | | GTOPO30 | | |
| Erosion control | Avoid soil loss | Trombetti et al. (2015) | | | EUROSTAT | | | |
| | | Schulp et al. (2012) | World Soil Database | | GlobCover | | | |

It is difficult to precisely assess, from existing studies, which harmonisation step (input data, methods or a consistent set of indicators) will have the greatest impact on the quality of the assessment of the ST/SES relationships. However, a trade-off probably exists between ease of implementation and impact on the quality of these relationships. The harmonisation of input data, which is relatively easy to implement but will probably have a more limited impact than harmonisation of methods or improvement of indicator consistency (in terms of preferences), will have a deeper impact but are more difficult to implement.

## 5 | Conclusions

This research aimed to assess the feasibility of reusing existing EU-wide ST or SES maps to characterise relationships between the three STs and four SESs, considered most important by stakeholders from 16 European countries. Despite the first EU-wide ST or SES maps being published decades ago, the possibilities of developing studies on ST/SES relationships from the combination of existing maps are limited by the number of available EU-wide maps. They are also limited by the heterogeneity of the conceptualisation of each ST/SES, the combination of preferences used to define the different indicators, the methods and the input data used to assess them, all of which have an impact on the levels of ST/SES and their spatial distribution.

Despite these limitations, the set of currently available maps offers several possibilities for combinations, notably (i) for SES, a more systematic characterisation of the interactions between the capacity and the flow of each SES, in order to assess the (un)sustainability of the uptake of each SES, and (ii) for STs, a combination of sensitivity, process and state indicators, in order to identify situations where soils are simultaneously sensitive, threatened, or degraded by a particular threat. The characterisation of the relationships between several SESs or STs, with a better harmonisation of indicators, methods, and input data, will require several stages of development, ranging from the recalculation of already existing indicators with similar input data for the development and mapping of new indicators. Although difficult, improving the consistency of input data, methodologies, and indicators is essential to limit methodological biases in the assessment of ST/SES relationships and, ultimately, to decision-making for the management of STs and SESs. For instance, managing threatened but not degraded soils requires preventive actions, while managing degraded soils (whether threatened or not) requires remediation actions. In the meantime, we urge the community to systematically specify the combination of preferences considered for each indicator to identify the need for developing new indicators and to facilitate the selection of coherent sets of indicators.

### Author Contributions

**Jessica Reyes-Rojas:** data curation, visualization, writing – original draft, methodology, investigation, writing – review and editing. **David Montagne:** conceptualization, methodology, data curation, formal analysis, writing – original draft, investigation, supervision, writing – review and editing. **Nicolas P. A. Saby:** writing – review and editing, data curation. **João Augusto Coblinski:** writing – review and editing. **Sylwia Pindral:** writing – review and editing. **Eduardo Medina-Roldán:** writing – review and editing. **Romina Lorenzetti:** writing – review and editing. **Ottone Scammacca:** writing – review and editing. **Chiara Piccini:** writing – review and editing. **Luboš Borůvka:** writing – review and editing. **Sophie Cornu:** data curation, conceptualization, formal analysis, visualization, writing – original draft, methodology, investigation, supervision, writing – review and editing.

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### Conflicts of Interest

The authors declare no conflicts of interest.

### Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

### References

Andersen, E., B. Elbersen, F. Godeschalk, and D. Verhoog. 2007. "Farm Management Indicators and Farm Typologies as a Basis for Assessments in a Changing Policy Environment." *Journal of Environmental Management* 82: 353–362. https://doi.org/10.1016/j.jenvman.2006.04.021.

Andrew, M. E., M. A. Wulder, T. A. Nelson, and N. C. Coops. 2015. "Spatial Data, Analysis Approaches, and Information Needs for Spatial Ecosystem Service Assessments: A Review." *GIScience & Remote Sensing* 52: 344–373. https://doi.org/10.1080/15481603.2015.1033809.

Angelini, M. E., G. B. M. Heuvelink, and P. Lagacherie. 2023. "A Multivariate Approach for Mapping a Soil Quality Index and Its Uncertainty in Southern France." *European Journal of Soil Science* 74: e13345. https://doi.org/10.1111/ejss.13345.

Angers, D. A., D. Arrouays, N. P. A. Saby, and C. Walter. 2011. "Estimating and Mapping the Carbon Saturation Deficit of French Agricultural Topsoils." *Soil Use and Management* 27, no. 4: 448–452. https://doi.org/10.1111/j.1475-2743.2011.00366.x.

Baartman, J. E. M., J. P. Nunes, H. van Delden, R. Vanhout, and L. Fleskens. 2022. "The Effects of Soil Improving Cropping Systems (SICS) on Soil Erosion and Soil Organic Carbon Stocks Across Europe: A Simulation Study." *Land* 11: 943. https://doi.org/10.3390/land11060943.

Bagstad, K. J., E. Cohen, Z. H. Ancona, S. G. McNulty, and G. Sun. 2018. "The Sensitivity of Ecosystem Service Models to Choices of Input Data and Spatial Resolution." *Applied Geography* 93: 25–36. https://doi.org/10.1016/j.apgeog.2018.02.005.

Baró, F., I. Palomo, G. Zulian, P. Vizcaino, D. Haase, and E. Gómez-Baggethun. 2016. "Mapping Ecosystem Service Capacity, Flow and Demand for Landscape and Urban Planning: A Case Study in the Barcelona Metropolitan Region." *Land Use Policy* 57: 405–417. https://doi.org/10.1016/j.landusepol.2016.06.006.

Bennett, E. M., G. D. Peterson, and L. J. Gordon. 2009. "Understanding Relationships Among Multiple Ecosystem Services." *Ecology Letters* 12, no. 12: 1394–1404. https://doi.org/10.1111/j.1461-0248.2009.01387.x.

Blum, W. E. 2005. "Functions of Soil for Society and the Environment." *Reviews in Environmental Science and Bio/Technology* 4, no. 3: 75–79. https://doi.org/10.1007/s11157-005-2236-x.

Boerema, A., A. J. Rebelo, M. B. Bodi, K. J. Esler, and P. Meire. 2016. "Are Ecosystem Services Adequately Quantified?" *Journal of Applied Ecology* 54, no. 2: 358–370. https://doi.org/10.1111/1365-2664.12696.

Borrelli, P., C. Ballabio, P. Panagos, and L. Montanarella. 2014. "Wind Erosion Susceptibility of European Soils." *Geoderma* 232: 471–478. https://doi.org/10.1016/j.geoderma.2014.06.008.

Borrelli, P., C. Ballabio, J. E. Yang, D. A. Robinson, and P. Panagos. 2022. "GloSEM: High-Resolution Global Estimates of Present and Future Soil Displacement in Croplands by Water Erosion." *Scientific Data* 9: 406. https://doi.org/10.1038/s41597-022-01489-x.

Borrelli, P., E. Lugato, L. Montanarella, and P. Panagos. 2016. "A New Assessment of Soil Loss due to Wind Erosion in European Agricultural Soils Using a Quantitative Spatially Distributed Modelling Approach." *Land Degradation & Development* 28: 335–344. https://doi.org/10.1002/ldr.2588.

Borrelli, P., P. Panagos, C. Alewell, et al. 2022. "Policy Implications of Multiple Concurrent Soil Erosion Processes in European Farmland." *Nature Sustainability* 6: 103–112. https://doi.org/10.1038/s41893-022-00988-4.

Borrelli, P., P. Panagos, C. Ballabio, E. Lugato, M. Weynants, and L. Montanarella. 2016. "Towards a Pan-European Assessment of Land Susceptibility to Wind Erosion." *Land Degradation & Development* 27, no. 4: 1093–1105. https://doi.org/10.1002/ldr.2318.

Borrelli, P., J. Poesen, M. Vanmaercke, et al. 2022. "Monitoring Gully Erosion in the European Union: A Novel Approach Based on the Land Use/Cover Area Frame Survey (LUCAS)." *International Soil and Water Conservation Research* 10: 17–28. https://doi.org/10.1016/j.iswcr.2021.09.002.

Borrelli, P., D. A. Robinson, L. R. Fleischer, et al. 2017. "An Assessment of the Global Impact of 21st Century Land Use Change on Soil Erosion." *Nature Communications* 8: 2013. https://doi.org/10.1038/s41467-017-02142-7.

Borrelli, P., K. van Oost, K. Meusburger, C. Alewell, E. Lugato, and P. Panagos. 2018. "A Step Towards a Holistic Assessment of Soil Degradation in Europe: Coupling On-Site Erosion With Sediment Transfer and Carbon Fluxes." *Environmental Research* 161: 291–298. https://doi.org/10.1016/j.envres.2017.11.009.

Bosco, C., D. de Rigo, O. Dewitte, J. Poesen, and P. Panagos. 2015. "Modelling Soil Erosion at European Scale: Towards Harmonization and Reproducibility." *Natural Hazards and Earth System Sciences* 15: 225–245. https://doi.org/10.5194/nhess-15-225-2015.

Burkhard, B., and J. Maes, eds. 2017. *Mapping Ecosystem Services*. Pensoft Publishers. https://doi.org/10.3897/ab.e12837.

Carpenter, S. R., H. A. Mooney, J. Agard, et al. 2009. "Science for Managing Ecosystem Services: Beyond the Millennium Ecosystem Assessment." *Proceedings of the National Academy of Sciences of The United States of America* 106, no. 5: 1305–1312. https://doi.org/10.1073/pnas.0808772106.

Cerdan, O., G. Govers, Y. le Bissonnais, et al. 2010. "Rates and Spatial Variations of Soil Erosion in Europe: A Study Based on Erosion Plot Data." *Geomorphology* 122: 167–177. https://doi.org/10.1016/j.geomorph.2010.06.011.

Chappell, A., N. P. Webb, J. F. Leys, C. M. Waters, S. Orgill, and M. J. Eyres. 2019. "Minimising Soil Organic Carbon Erosion by Wind Is Critical for Land Degradation Neutrality." *Environmental Science & Policy* 93: 43–52. https://doi.org/10.1016/j.envsci.2018.12.020.

Chen, J., M. Heiling, C. Resch, M. Mbaye, R. Gruber, and G. Dercon. 2018. "Does Maize and Legume Crop Residue Mulch Matter in Soil Organic Carbon Sequestration?" *Agriculture, Ecosystems & Environment* 265: 123–131. https://doi.org/10.1016/j.agee.2018.06.005.

Choquet, P., B. Gabrielle, M. Chalhoub, et al. 2021. "Comparison of Empirical and Process-Based Modelling to Quantify Soil-Supported Ecosystem Services on the Saclay Plateau (France)." *Ecosystem Services* 50: 101332. https://doi.org/10.1016/j.ecoser.2021.101332.

Cornu, S., S. Keesstra, A. Bispo, et al. 2023. "National Soil Data in EU Countries, Where Do We Stand?" *European Journal of Soil Science* 74, no. 4: e13398. https://doi.org/10.1111/ejss.13398.

Crossman, N. D., B. Burkhard, S. Nedkov, et al. 2013. "A Blueprint for Mapping and Modelling Ecosystem Services." *Ecosystem Services* 4: 4–14. https://doi.org/10.1016/j.ecoser.2013.02.001.

Czúcz, B., R. Haines-Young, M. Kiss, et al. 2020. "Ecosystem Service Indicators Along the Cascade: How Do Assessment and Mapping Studies Position Their Indicators?" *Ecological Indicators* 118: 106729. https://doi.org/10.1016/j.ecolind.2020.106729.

De Rosa, D., C. Ballabio, E. Lugato, M. Fasiolo, A. Jones, and P. Panagos. 2023. "Soil Organic Carbon Stocks in European Croplands and Grasslands: How Much Have We Lost in the Past Decade?" *Global Change Biology* 30: e16992. https://doi.org/10.1111/gcb.16992.

Drobnik, T., L. Greiner, A. Keller, and A. Grêt-Regamey. 2018. "Soil Quality Indicators—From Soil Functions to Ecosystem Services." *Ecological Indicators* 94: 151–169. https://doi.org/10.1016/j.ecolind.2018.06.052.

Ellili-Bargaoui, Y., C. Walter, B. Lemercier, R. Armand, S. Selim, and D. Michot. 2023. "The Accuracy of Soil Information Influences Assessment of Soil Ecosystem Services in Brittany, France." *Geoderma Regional* 34: e00704. https://doi.org/10.1016/j.geodrs.2023.e00704.

Ellili-Bargaoui, Y., C. Walter, B. Lemercier, and D. Michot. 2021. "Assessment of Six Soil Ecosystem Services by Coupling Simulation Modelling and Field Measurement of Soil Properties." *Ecological Indicators* 121: 107211. https://doi.org/10.1016/j.ecolind.2020.107211.

Englund, O., G. Berndes, and C. Cederberg. 2017. "How to Analyse Ecosystem Services in Landscapes—A Systematic Review." *Ecological Indicators* 73: 492–504. https://doi.org/10.1016/j.ecolind.2016.10.009.

Englund, O., P. Börjesson, G. Berndes, et al. 2020. "Beneficial Land Use Change: Strategic Expansion of New Biomass Plantations Can Reduce Environmental Impacts From EU Agriculture." *Global Environmental Change* 60: 101990. https://doi.org/10.1016/j.gloenvcha.2019.101990.

FAO/IIASA/ISRIC/ISS-CAS/JRC. 2009. *Harmonized World Soil Database (Version 1.1)*. FAO. https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/ru/.

Foldal, C., K. Oorts, R. Antón, et al. 2022. "Soil Threats and Soil Ecosystem Services of Interest in SERENA (SERENA Deliverable No. D2.2)."

Froger, C., E. Tondini, D. Arrouays, et al. 2024. "Comparing LUCAS Soil and National Systems: Towards a Harmonized European Soil Monitoring Network." *Geoderma* 449: 117027. https://doi.org/10.1016/j.geoderma.2024.117027.

Global Soil Data Task. 2000. "Global Soil Data Products CD-ROM (IGBP-DIS)." International Geosphere–Biosphere Programme – Data and Information Services. from the ORNL Distributed Active Archive Center, Oak Ridge National Laboratory, Oak Ridge, TN, USA http://www.daac.ornl.gov/.

Greiner, L., A. Keller, A. Grêt-Regamey, and A. Papritz. 2017. "Soil Function Assessment: Review of Methods for Quantifying the Contributions of Soils to Ecosystem Services." *Land Use Policy* 69: 224–237. https://doi.org/10.1016/j.landusepol.2017.06.025.

Grêt-Regamey, A., B. Weibel, F. Kienast, S. E. Rabe, and G. Zulian. 2015. "A Tiered Approach for Ecosystem Services Mapping." *Mapping Ecosystem Services* 13: 211–215. https://doi.org/10.1016/j.ecoser.2014.10.008.

Haberl, H., K.-H. Erb, and F. Krausmann. 2014. "Human Appropriation of Net Primary Production: Patterns, Trends, and Planetary Boundaries." *Annual Review of Environment and Resources* 39, no. 2014: 363–391. https://doi.org/10.1146/annurev-environ-121912-094620.

Haddaway, N. R., B. Macura, P. Whaley, and A. S. Pullin. 2018. "ROSES RepOrting Standards for Systematic Evidence Syntheses: Pro Forma, Flow-Diagram and Descriptive Summary of the Plan and Conduct of Environmental Systematic Reviews and Systematic Maps." *Environmental Evidence* 7: 7. https://doi.org/10.1186/s13750-018-0121-7.

Haines-Young, R., and M. B. Potschin. 2018. *Common International Classification of Ecosystem Services (CICES) V5.1 and Guidance on the Application of the Revised*. Fabis Consulting Ltd. https://cices.eu/content/uploads/sites/8/2018/01/Guidance-V51-01012018.pdf.

Hartwich, R., R. Baritz, M. Fuchs, D. Krug, and S. Thiele. 2005. *Erläuterungen Zur Bodenregionenkarte der Europäischen Union and ihrer Nachbarstaaten 1: 5,000,000 (version 2.0)*. Bundesanstalt für Geowissenschaften und Rohstoffe (BGR).

Hengl, T., M. G. Walsh, J. Sanderman, I. Wheeler, S. P. Harrison, and I. C. Prentice. 2018. "Global Mapping of Potential Natural Vegetation: An Assessment of Machine Learning Algorithms for Estimating Land Potential." *PeerJ* 6: e5457.

Hijbeek, R., A. Cormont, G. Hazeu, et al. 2017. "Do Farmers Perceive a Deficiency of Soil Organic Matter? A European and Farm Level Analysis." *Ecological Indicators* 83: 390–403. https://doi.org/10.1016/j.ecolind.2017.08.023.

Housková, B., and L. Montanarella. 2008. "The Natural Susceptibility of European Soils to Compaction." In *Threats to Soil Quality in Europe*, edited by G. Tóth, L. Montanarella, and E. Rusco, 23–35. Join Research Centre. https://doi.org/10.2788/8647.

IGBP. 2000. "Global Soil Data Task (IGBP-DIS, ISO-Image of CD)." https://doi.org/10.1594/PANGAEA.869912.

Jones, R. J. A., G. Spoor, and A. J. Thomasson. 2003. "Vulnerability of Subsoils in Europe to Compaction: a Preliminary Analysis." *Soil and Tillage Research* 73: 131–143. https://doi.org/10.1016/S0167-1987(03)00106-5.

Kandziora, M., B. Burkhard, and F. Müller. 2013. "Interactions of Ecosystem Properties, Ecosystem Integrity and Ecosystem Service Indicators—A Theoretical Matrix Exercise." *Ecological Indicators* 28: 54–78. https://doi.org/10.1016/j.ecolind.2012.09.006.

Kiessé, T. S., B. Lemercier, M. S. Corson, Y. Ellili-Bargaoui, J. Afassi, and C. Walter. 2024. "Assessing Dependence Between Soil Ecosystem Services as a Function of Weather and Soil: Application of Vine Copula Modeling." *Environmental Modelling & Software* 172: 105920. https://doi.org/10.1016/j.envsoft.2023.105920.

Kirkby, M. J., B. J. Irvine, R. J. A. Jones, and G. Govers. 2008. "The PESERA Coarse Scale Erosion Model for Europe. I.—Model Rationale and Implementation." *European Journal of Soil Science* 59: 1293–1306. https://doi.org/10.1111/j.1365-2389.2008.01072.x.

Lamandé, M., M. H. Greve, and P. Schjønning. 2018. "Risk Assessment of Soil Compaction in Europe—Rubber Tracks or Wheels on Machinery." *Catena* 167: 353–362. https://doi.org/10.1016/j.catena.2018.05.015.

Le Bissonnais, Y., J. Daroussin, A. Lecour, et al. 2002. "Soil Erosion Risk Assessment in Europe Data (MESALES model)—Dataset." https://esdac.jrc.ec.europa.eu/ESDB_Archive/serae/GRIMM/erosion/inra/europe/analysis/maps_and_listings/web_erosion/index.html.

Leip, A., G. Marchi, R. Koeble, M. Kempen, W. Britz, and C. Li. 2008. "Linking an Economic Model for European Agriculture With a Mechanistic Model to Estimate Nitrogen and Carbon Losses From Arable Soils in Europe." *Biogeosciences* 5: 73–94. https://doi.org/10.5194/bg-5-73-2008.

Liquete, C., J. Maes, A. la Notte, and G. Bidoglio. 2011. "Securing Water as a Resource for Society: An Ecosystem Services Perspective." *Ecohydrology and Hydrobiology* 11: 247–259. https://doi.org/10.2478/v10104-011-0044-1.

Lugato, E., F. Bampa, P. Panagos, L. Montanarella, and A. Jones. 2014. "Potential Carbon Sequestration of European Arable Soils Estimated by Modelling a Comprehensive Set of Management Practices." *Global Change Biology* 20: 3557–3567. https://doi.org/10.1111/gcb.12551.

Lugato, E., A. Leip, and A. Jones. 2018. "Mitigation Potential of Soil Carbon Management Overestimated by Neglecting $N_2O$ Emissions." *Nature Climate Change* 8: 219–223. https://doi.org/10.1038/s41558-018-0087-z.

Lugato, E., P. Panagos, F. Bampa, A. Jones, and L. Montanarella. 2014. "A New Baseline of Organic Carbon Stock in European Agricultural Soils Using a Modelling Approach." *Global Change Biology* 20: 313–326. https://doi.org/10.1111/gcb.12292.

Maes, J., A. Teller, M. Erhard, et al. 2020. *Mapping and Assessment of Ecosystems and Their Services: An EU Ecosystem Assessment, EUR 30161 EN*. Publications Office of the European Union, ISBN 978–92–76-17833-0. https://doi.org/10.2760/757183.

Malinga, R., L. J. Gordon, G. Jewitt, and R. Lindborg. 2015. "Mapping Ecosystem Services Across Scales and Continents–A Review." *Ecosystem Services* 13: 57–63. https://doi.org/10.1016/j.ecoser.2015.01.006.

Martínez-Harms, M. J., and P. Balvanera. 2012. "Methods for Mapping Ecosystem Service Supply: A Review." *International Journal of Biodiversity Science, Ecosystems Services & Management* 8: 17–25. https://doi.org/10.1080/21513732.2012.663792.

Mayer, A., L. Kaufmann, G. Kalt, et al. 2021. "Applying the Human Appropriation of Net Primary Production Framework to Map Provisioning Ecosystem Services and Their Relation to Ecosystem Functioning Across the European Union." *Ecosystem Services* 51: 101344. https://doi.org/10.1016/j.ecoser.2021.101344.

McBratney, A. B., C. L. S. Morgan, and L. E. Jarrett. 2017. "The Value of Soil's Contributions to Ecosystem Services." In *Global Soil Security, Progress in Soil Science*, edited by D. J. Field, C. L. S. Morgan, and A. B. McBratney, 227–235. Springer International Publishing. https://doi.org/10.1007/978-3-319-43394-3_20.

Medina-Roldán, E., R. Lorenzetti, C. Calzolari, and F. Ungaro. 2024. "Disentangling Soil-Based Ecosystem Services Synergies, Trade-Offs, Multifunctionality, and Bundles: A Case Study at Regional Scale (NE Italy) to Support Environmental Planning." *Geoderma* 448: 116962. https://doi.org/10.1016/j.geoderma.2024.116962.

Mitchell, T., and P. Jones. 2005. "An Improved Method of Constructing a Database of Monthly Climate Observations and Associated High-Resolution Grids." *International Journal of Climatology* 25, no. 6: 693–712. https://doi.org/10.1002/joc.1181.

Montagne, D., O. Scammacca, C. walter, and I. Cousin. 2025. "The Concept of Ecosystem Services and Its Application to Soil: Between Promises and Reality." In *Agricultural Soil Science: Sustainable Soil Management of Agricultural Soils*, edited by Y. Coquet and J. Michelin, 161–209. ISTE Ltd. https://doi.org/10.1002/9781394361809.ch7.

Nabuurs, G. J., A. Pussinen, J. van Brusselen, and M. J. Schelhaas. 2007. "Future Harvesting Pressure on European Forests." *European Journal of Forest Research* 126: 391–400. https://doi.org/10.1007/s10342-006-0158-y.

Niemeijer, D., and R. S. de Groot. 2008. "A Conceptual Framework for Selecting Environmental Indicator Sets." *Ecological Indicators* 8: 14–25. https://doi.org/10.1016/j.ecolind.2006.11.012.

Obiang-Ndong, G., O. Therond, and I. Cousin. 2020. "Analysis of Relationships Between Ecosystem Services: A Generic Classification and Review of the Literature." *Ecosystem Services* 43: 101120. https://doi.org/10.1016/j.ecoser.2020.101120.

Oldeman, L. R., R. T. A. Hakkeling, and W. G. Sombroek. 1991. *World Map of the Status of Human-Induced Soil Degradation, GLASOD Project ISRIC ISSS FAO ITC Staring Centre*. ISRIC ISSS FAO ITC Staring Centre.

Orgiazzi, A., C. Ballabio, P. Panagos, A. Jones, and O. Fernández-Ugalde. 2018. "LUCAS Soil, the Largest Expandable Soil Dataset for Europe: A Review." *European Journal of Soil Science* 69, no. 1: 140–153. https://doi.org/10.1111/ejss.12499.

Padarian, J., U. Stockmann, B. Minasny, and A. B. McBratney. 2022. "Monitoring Changes in Global Soil Organic Carbon Stocks From Space." *Remote Sensing of Environment* 281: 113260. https://doi.org/10.1016/j.rse.2022.113260.

Page, M. J., J. E. McKenzie, P. M. Bossuyt, et al. 2021. "The PRISMA 2020 Statement: An Updated Guideline for Reporting Systematic Reviews." *BMJ* 372: n71. https://doi.org/10.1136/bmj.n71.

Panagos, P., C. Ballabio, J. Poesen, et al. 2020. "A Soil Erosion Indicator for Supporting Agricultural, Environmental and Climate Policies in the European Union." *Remote Sensing* 12: 1365. https://doi.org/10.3390/rs12091365.

Panagos, P., P. Borrelli, A. Jones, and D. A. Robinson. 2024. "A 1-Billion-Euro Mission: A Soil Deal for Europe." *European Journal of Soil Science* 75: e13466. https://doi.org/10.1111/ejss.13466.

Panagos, P., P. Borrelli, J. Poesen, et al. 2015. "The New Assessment of Soil Loss by Water Erosion in Europe." *Environmental Science & Policy* 54: 438–447. https://doi.org/10.1016/j.envsci.2015.08.012.

Panagos, P., P. Borrelli, and J. Poesen. 2019. "Soil Loss due to Crop Harvesting in the European Union: A First Estimation of an Underrated Geomorphic Process." *Science of the Total Environment* 664: 487–498. https://doi.org/10.1016/j.scitotenv.2019.02.009.

Panagos, P., G. Standardi, P. Borrelli, E. Lugato, L. Montanarella, and F. Bosello. 2018. "Cost of Agricultural Productivity Loss due to Soil Erosion in the European Union: From Direct Cost Evaluation Approaches to the Use of Macroeconomic Models." *Land Degradation and Development* 29: 471–484. https://doi.org/10.1002/ldr.2879.

Paracchini, M., G. Zulian, and J. Maes. 2011. "A European Assessment of the Provision of Ecosystem Services–Towards an Atlas of Ecosystem Services." Publications Office, LU. Joint Research Centre, Institute for Environment and Sustainability, Publications Office of the European Union. https://data.europa.eu/doi/10.2788/63557.

Paul, C., K. Kuhn, B. Steinhoff-Knopp, P. Weißhuhn, and K. Helming. 2021. "Towards a Standardization of Soil-Related Ecosystem Service Assessments." *European Journal of Soil Science* 72: 1543–1558. https://doi.org/10.1111/ejss.13022.

Pereira, P., I. Bogunovic, M. Muñoz-Rojas, and E. C. Brevik. 2018. "Soil Ecosystem Services, Sustainability, Valuation and Management." *Current Opinion in Environmental Science & Health* 5: 7–13. https://doi.org/10.1016/j.coesh.2017.12.003.

Pérez-Soba, M., B. Elbersen, M. Kempen, et al. 2015. *Agricultural Biomass as Provisioning Ecosystem Service: Quantification of Energy Flows*. Publications Office, LU. https://doi.org/10.2788/679096.

Podmanicky, L., K. Balázs, M. Belényesi, C. Centeri, D. Kristóf, and N. Kohlheb. 2011. "Modelling Soil Quality Changes in Europe. An Impact Assessment of Land Use Change on Soil Quality in Europe." *Ecological Indicators* 11: 4–15. https://doi.org/10.1016/j.ecolind.2009.08.002.

Poeplau, C., and R. Dechow. 2023. "The Legacy of One Hundred Years of Climate Change for Organic Carbon Stocks in Global Agricultural Topsoils." *Scientific Reports* 13: 7483. https://doi.org/10.1038/s41598-023-34753-0.

Potschin-Young, M., R. Haines-Young, C. Görg, U. Heink, K. Jax, and C. Schleyer. 2018. "Understanding the Role of Conceptual Frameworks: Reading the Ecosystem Service Cascade." *Ecosystem Services* 29: 428–440. https://doi.org/10.1016/j.ecoser.2017.05.015.

Prăvălie, R., P. Borrelli, P. Panagos, et al. 2024. "A Unifying Modelling of Multiple Land Degradation Pathways in Europe." *Nature Communications* 15: 3862. https://doi.org/10.1038/s41467-024-48252-x.

Prăvălie, R., I. A. Nita, C. Patriche, et al. 2021. "Global Changes in Soil Organic Carbon and Implications for Land Degradation Neutrality and Climate Stability." *Environmental Research* 201: 111580. https://doi.org/10.1016/j.envres.2021.111580.

Prăvălie, R., C. Patriche, P. Borrelli, et al. 2021. "Arable Lands Under the Pressure of Multiple Land Degradation Processes. A Global Perspective." *Environmental Research* 194: 110697. https://doi.org/10.1016/j.envres.2020.110697.

Rendon, P., B. Steinhoff-Knopp, and B. Burkhard. 2022. "Linking Ecosystem Condition and Ecosystem Services: A Methodological Approach Applied to European Agroecosystems." *Ecosystem Services* 53: 101387. https://doi.org/10.1016/j.ecoser.2021.101387.

Rethlefsen, M. L., and M. J. Page. 2022. "PRISMA 2020 and PRISMA-S: Common Questions on Tracking Records and the Flow Diagram." *Journal of the Medical Library Association: JMLA* 110, no. 2: 253–257. https://doi.org/10.5195/jmla.2022.1449.

Sanderman, J., T. Hengl, and G. J. Fiske. 2017. "Soil Carbon Debt of 12,000 Years of Human Land Use." *Proceedings of the National Academy of Sciences* 114, no. 36: 9575–9580. https://doi.org/10.1073/pnas.1706103114.

Scammacca, O., O. Sauzet, J. Michelin, et al. 2023. "Effect of Spatial Scale of Soil Data on Estimates of Soil Ecosystem Services: Case Study in 100 Km 2 Area in France." *European Journal of Soil Science* 74: e13359. https://doi.org/10.1111/ejss.13359.

Schjønning, P., J. J. H. van den Akker, T. Keller, et al. 2015. "Driver-Pressure-State-Impact-Response (DPSIR) Analysis and Risk Assessment for Soil Compaction—A European Perspective." In *Advances in Agronomy*, 183–237. Elsevier. https://doi.org/10.1016/bs.agron.2015.06.001.

Schröter, M., C. Albert, A. Marques, et al. 2016. "National Ecosystem Assessments in Europe: A Review." *Bioscience* 66: 813–828. https://doi.org/10.1093/biosci/biw101.

Schröter, M., D. N. Barton, R. P. Remme, and L. Hein. 2014. "Accounting for Capacity and Flow of Ecosystem Services: A Conceptual Model and a Case Study for Telemark, Norway." *Ecological Indicators* 36: 539–551. https://doi.org/10.1016/j.ecolind.2013.09.018.

Schulp, C. J. E., R. Alkemade, K. Klein Goldewijk, and K. Petz. 2012. "Mapping Ecosystem Functions and Services in Eastern Europe Using Global-Scale Datasets." *International Journal of Biodiversity Science, Ecosystem Services & Management* 8: 156–168. https://doi.org/10.1080/21513732.2011.645880.

Sonderegger, T., and S. Pfister. 2021. "Global Assessment of Agricultural Productivity Losses From Soil Compaction and Water Erosion." *Environmental Science & Technology* 55: 12162–12171. https://doi.org/10.1021/acs.est.1c03774.

Stoessel, F., T. Sonderegger, P. Bayer, and S. Hellweg. 2018. "Assessing the Environmental Impacts of Soil Compaction in Life Cycle Assessment." *Science of the Total Environment* 630: 913–921. https://doi.org/10.1016/j.scitotenv.2018.02.222.

Stolte, J., M. Tesfai, L. Øygarden, et al. 2015. *Soil Threats in Europe*. Publications Office LU. https://doi.org/10.2788/828742.

Stürck, J., A. Poortinga, and P. H. Verburg. 2014. "Mapping Ecosystem Services: The Supply and Demand of Flood Regulation Services in Europe." *Ecological Indicators* 38: 198–211. https://doi.org/10.1016/j.ecolind.2013.11.010.

Styc, Q., and P. Lagacherie. 2019. "What Is the Best Inference Trajectory for Mapping Soil Functions: An Example of Mapping Soil Available Water Capacity Over Languedoc Roussillon (France)." *Soil Systems* 3: 34. https://doi.org/10.3390/soilsystems3020034.

Therond, O., M. Tichit, A. Tibi, et al. 2017. "Volet 'écosystèmes Agricoles' de l'Evaluation Française des Ecosystèmes et des Services Ecosystémiques. Rapport d'étude, Inra (France)." https://doi.org/10.15454/PRMV-WC85.

Tóth, G., C. Gardi, K. Bódis, et al. 2013. "Continental-Scale Assessment of Provisioning Soil Functions in Europe." *Ecology and Society* 2: 32. https://doi.org/10.1186/2192-1709-2-32.

Trombetti, M., E. Ivits, I. Vandecasteele, et al. 2015. "Mapping and Assessment of Ecosystems and Their Services: Trends in Ecosystems and Ecosystem Services in the European Union Between 2000 and 2010." Joint Research Centre, Institute for Environment and Sustainability, Publications Office of the European Union. https://data.europa.eu/doi/10.2788/341839.

Turnhout, E. 2009. "The Effectiveness of Boundary Objects: The Case of Ecological Indicators." *Science and Public Policy* 36, no. 5: 403–412. https://doi.org/10.3152/030234209X442007.

UNECE/FAO. 2000. "Forest Resources of Europe, CIS, North America, Australia, Japan and New Zealand." UN-ECE/FAO Contribution to the Global Forest Resources Assessment 2000 (Geneva Timber and Forest Study Papers No. 17).

van der Knijff, J. M., R. J. A. Jones, and L. Montanarella. 2000. "Soil Erosion Risk Assessment in Europe. European Soil Bureau Research Report EUR 19044 EN." pp. 34.

Van Oost, K., O. Cerdan, and T. A. Quine. 2009. "Accelerated Sediment Fluxes by Water and Tillage Erosion on European Agricultural Land." *Earth Surface Processes and Landforms* 34: 1625–1634. https://doi.org/10.1002/esp.1852.

Van Oudenhoven, A. P. E., K. Petz, R. Alkemade, L. Hein, and R. S. de Groot. 2012. "Framework for Systematic Indicator Selection to Assess Effects of Land Management on Ecosystem Services." *Ecological Indicators* 21: 110–122. https://doi.org/10.1016/j.ecolind.2012.01.012.

Vihervaara, P., A. Viinikka, L. Brander, F. Santos-Martín, L. Poikolainen, and S. Nedkov. 2019. "Methodological Interlinkages for Mapping Ecosystem Services–From Data to Analysis and Decision-Support." *One Ecosystem* 4: e26368. https://doi.org/10.3897/oneeco.4.e26368.

Vleeshouwers, L. M., and A. Verhagen. 2002. "Carbon Emission and Sequestration by Agricultural Land Use: A Model Study for Europe." *Global Change Biology* 8: 519–530. https://doi.org/10.1046/j.1365-2486.2002.00485.x.

Vrebos, D., F. Bampa, R. Creamer, et al. 2018. "Scenarios Maps: Visualising Optimised Scenarios Where Supply of Soil Functions Matches Demands D 4.3 (No. 4.3)." https://landmarkproject.eu/work-package/work-package-4/.

Vrebos, D., A. Jones, E. Lugato, et al. 2019. "Spatial Evaluation and Trade-Off Analysis of Soil Functions Through Bayesian Networks." *European Journal of Soil Science* 72: 1575–1589. https://doi.org/10.1111/ejss.13039.

Vrebos, D., J. Staes, R. P. O. Schulte, et al. 2018. "Soil Function Supply Maps." https://landmarkproject.eu/work-package/work-package-4/.

Wainwright, J., and M. Mulligan, eds. 2012. *Environmental Modelling: Finding Simplicity in Complexity*. 2nd ed. Wiley.

Weninger, T., D. Ramler, G. Bondi, et al. 2024. "Do We Speak One Language on the Way to Sustainable Soil Management in Europe? A Terminology Check via an EU-Wide Survey." *European Journal of Soil Science* 75: e13476. https://doi.org/10.1111/ejss.13476.

Wuepper, D., P. Borrelli, and R. Finger. 2020. "Countries and the Global Rate of Soil Erosion." *Nature Sustainability* 3, no. 1: 51–55. https://doi.org/10.1038/s41893-019-0438-4.

Zulian, G., C. Polce, and J. Maes. 2014. "ESTIMAP: A Gis-Based Model to Map Ecosystem Services in the European Union." *Annals of Botany* 4: 1–7. https://doi.org/10.4462/annbotrm-1180.

**Supporting Information**

Additional supporting information can be found online in the Supporting Information section. **Data S1:** Supporting Information.