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From Soil Threats to Soil Health: Prevention or Remediation

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ABSTRACT

While soil threats and soil health are two interrelated, sometimes confused, concepts, we demonstrated here that a clear separation between these two concepts associated to a mapping of both soil threats and soil health is necessary. Soil threats are commonly defined as processes that may degrade the soil properties, functions or services, while soil health describes the state of the soil at a given moment in time. As a consequence, an unhealthy soil is a soil which is degraded compared to a reference. Mapping soil threats or soil health results then in different but complementary views of the situation. Mapping soil threats informs actions to prevent soil degradation, while mapping soil health indicates the capacity of soils to provide functions and places where remediation is needed. In this study, we demonstrated the differences between these concepts by comparing projection maps for 2050 of soil threats and soil health by considering soil compaction and loss of soil organic carbon (SOC) as soil threats and bulk density and SOC stock as basic soil properties to evaluate both soil threat and soil health in terms of the above-mentioned two soil descriptors. These maps were produced by digital soil mapping, taking into account changes in climate and land use in the European Union (EU). Soil threats were mapped using soil property change between 1980 and 2050 as indicators, that is, a decrease in SOC stocks for SOC loss and increase in soil bulk density for compaction. For soil health assessment, as references are needed, we defined soil areas that could be considered as homogeneous by combining soil, climate and land use information and defined for each area a threshold for soil health based on a quantiles approach. As a result, the obtained soil threat and health maps were very different, as healthy soils can be under threat but not have crossed the threshold yet, while unhealthy soils may not be under threat anymore if no more degradation occurs. These results demonstrate that reading a map requires a good prior understanding of the meaning of the indicators used in order to be able to interpret it in terms of threat or health and to be able to select appropriate metrics, which will not be the same in both cases. Indeed, while soil health maps identify degraded areas where the soil lost part or all its capacity to provide functions and that need remediation, soil threat maps offer vital information about potential vulnerabilities and areas requiring intervention or management strategies.

1 | Introduction

Soil is a vital and dynamic component of our planet's ecosystem, and plays a fundamental role in sustaining life by supporting biodiversity and a large range of ecosystem services (Paul et al. 2020). The increasing pressures of human activities and climate change have led to the emergence of soil threats that jeopardize the delicate balance of this essential

Highlights

1. Soil health is the soil condition, while soil threats are processes that will likely alter the soil condition.
2. The differences between these concepts were demonstrated by comparing projection maps for 2050 for soil compaction and loss of soil organic carbon.
3. Generated soil threat and health maps are very different.
4. Disentangling those two concepts has a political impact in terms of protection and restoration of soils.

resource (Rinot et al. 2019; Guo 2021). The Status of the World's Soil Resources report (FAO and ITPS 2015), published by The United Nations Food and Agriculture Organization (UNFAO), identified ten major soil threats across the globe. This list includes threats such as soil erosion, compaction, acidification, contamination, sealing, salinization, waterlogging, nutrient imbalance, losses of soil organic carbon (SOC) and losses of soil biodiversity. A recent report emphasized that a significant proportion, ranging from 60% to 70%, of soils within the European Union (EU) are currently degraded with respect to one or more soil health metrics (Veerman et al. 2020; Panagos 2006; Panagos et al. 2024; Arias-Navarro et al. 2024). To address this extensive soil degradation, the EU commission has set out a soil strategy for 2030, aiming at achieving healthy soils by 2050 through concrete measures (Panagos et al. 2024), and a Soil Monitoring and Resilience Directive (European Parliament 2025) recently adopted by the EU Member States. This directive is intended to establish a common framework for monitoring soil health and provide a legal framework for the monitoring and regeneration of degraded soils, making sustainable soil management the norm in the EU.

While soil threats are defined as dynamic processes that cause the degradation of soil health (Stolte et al. 2016), embodying a spectrum of challenges that collectively pose a substantial risk to overall soil health (Montanarella et al. 2016), a definition agreed on by many EU stakeholders (Weninger et al. 2024), soil health reflects “the capacity [at a given time] of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health” (Doran and Zeiss 2000). Thus, it's crucial to distinguish between soil threats (an ongoing process of soil degradation) and soil health, which denotes the overall state or condition of the soil, with an unhealthy soil being considered a degraded soil. For instance, soils in arid and semi-arid regions can be under the threat of salinization caused by improper irrigation and climate aridification (Daliakopoulos et al. 2016) but remain healthy as they do not have too high salinity yet. This soil, while not currently degraded, faces the risk of being compromised in the future, whereas once-salinized soils are no longer considered healthy even if the process of salinization (soil threats) is no longer active. Similarly, healthy soils in peri-urban areas face threats from urbanization and city expansion, which can lead to soil sealing, contamination, and loss of valuable ecosystem services (Ihenetu et al. 2024). From this example, we can highlight three important points:

1. the soil health concept aims at identifying soils whose condition is degraded or not, and possibly requires corrective measures, whereas the soil threat concept depicts an on-going process (or its absence) ultimately leading to a degraded state of the soils, which requires proactive measures to avoid reaching this state;
2. for the evaluation of soil health and soil threats, the same soil properties are used:
3. as a dynamic process, the concept of soil threat refers to a difference between two states of the soil in time (i.e., two values of a soil property), whereas the concept of soil health refers to thresholds for a combination of soil properties beyond which the soil is no longer considered in good health. These thresholds for the different soil properties depend on environmental parameters, such as soil type, climate and land use (Matson et al. 2024). Some of these thresholds are proposed at the EU scale in the recently accepted Soil Monitoring and Residence Directive (European Parliament 2025).

Therefore, assessing distinctly both soil threats and soil health holds paramount importance as it directly influences the formulation of targeted strategies for both prevention and remediation. However, in the literature as well as in the Soil Monitoring and Resilience Directive (European Parliament 2025) indicators of soil states are sometimes used as indicators of soil threats as demonstrated by Reyes-Rojas et al. (2025).

In this study, we demonstrate through a cartographic approach at the European scale and through two examples the importance of clearly separating these two complementary concepts for sustainable soil management. The chosen soil threats are SOC loss and soil compaction, and SOC stock and bulk density are the associated soil properties, whose values express soil health, and whose value evolution in time indicates soil threats. We selected these soil threat and soil health indicators because many confusions are encountered in the literature for these two soil threats as shown by Reyes-Rojas et al. (2025). The methodology used here is generic and can therefore be applied to the other soil threats (based on other soil indicators). However, we note that if a more complex soil health assessment is required (i.e., based on more than one soil indicator), then a methodology for combining several separate soil health indicators is required (Hannam et al. 2025).

2 | Materials and Methods

2.1 | Soil Threats Assessment for 2050

Soil threats are assessed by indicators that are numerous in the literature (Montagne et al. 2023; Reyes-Rojas et al. 2025). For the two soil threats considered—SOC loss and soil compaction—we used the soil threat assessment developed by Coblinski et al. (2023) who selected the indicators proposed by Montagne et al. (2023) for the considered soil threats: (i) the temporal evolution of SOC stocks throughout the entire soil profile (or 1-m depth for deeper soil) to assess SOC loss and (ii) the temporal evolution of topsoil (0–30 cm) bulk density to assess soil compaction. They calculated changes in SOC stock and bulk density between 1980 and 2050, as presented in Equation (1):

$$\text{Soil threat}\,(\%) = \frac{\text{Property}_{2050} - \text{Property}_{1980}}{\text{Property}_{1980}} \times 100 \tag{1}$$

where soil threat is SOC stock loss or soil compaction; properties are estimates of SOC stock (used to evaluate SOC loss) or bulk density (used to evaluate soil compaction), considered for two dates, 1980 or 2050. Such an indicator provides an estimate of the soil threat intensity over a given time interval.

2.1.1 | Considered SOC Stocks and Bulk Density Maps for 1980

The analysis was performed for the 24 European countries that participate in the European Joint Programme on Agricultural Soils in which this work was conducted. The study area covers 3.97 million km^2.

Indicator calculation was performed using SoilGrids for 1980 soil data (Poggio et al. 2021), WorldClim for climate (Fick and Hijmans 2017), and Land Use-based Integrated Sustainability Assessment (LUISA) for 2012 and 2050 land use (Lavalle et al. 2017). 1980 was chosen as the reference date, since it corresponds to the median date of soil profile sampling carried out by ISRIC's World Soil Information Service (WoSIS) (Poggio et al. 2021).

Since the different databases have different spatial resolution, we used a common spatial resolution of 1 km used by the WorldClim. Since some databases are provided with a finer resolution, an aggregation step was applied. For LUISA (resolution of 100 m), we considered the proportion of each land use in the 1 km pixel. For SoilGrids (resolution of 250 m), the average value of the different soil properties was calculated.

SoilGrids provides SOC stocks for the following soil layers up to 2 m deep: 0–5; 5–15; 15–30; 30–60; 60–100; and 100–200 cm. Thus, SOC stocks were summed up to the soil depth provided by the ESDAC database (Panagos 2006) or up to one meter for deeper soils. For bulk density, the value of the 0–30 cm layer was used for practical reasons, as bulk density data are only measured for the surface layer in European monitoring systems such as LUCAS. Examples of environmental variables are shown in Figure S1.

2.1.2 | Projecting SOC Stocks and Bulk Density for 2050

For 2050 projections, we used the maps proposed by Coblinski et al. (2023) considering the SSP5-8.5 climate change scenario and the land use change projected by the LUISA model (Lavalle et al. 2017). These maps were obtained by a digital soil mapping (DSM) approach following two steps: (i) a DSM model was built on existing data for the reference date (1980) and (ii) climate and land use used as covariates in the model were replaced by their respective projections for 2050 to project soil properties by that date. This method, also known as space-for-time substitution (Blois et al. 2013), has been already used to create maps of SOC at European scale (Lugato et al. 2021).

For climate, an average of the projection of two downscaled global climate models (ACCESS-CM2 and HadGEM3-GC3-LL; Dix et al. 2019; Good 2019) for SSP5-8.5 climatic projections among those defined by the IPCC (Intergovernmental Panel on Climate Change) was used, representing a high-emission scenario driven by continued fossil fuel use and limited mitigation efforts with severe climate impacts. Hence, this scenario predicts the highest increase in temperature and cumulative CO_2 emissions (Wieder et al. 2015) and therefore probably has the highest impact on soil threats. For land use data, the projection for 2050 provided by the LUISA model was considered.

The DSM models were built up using the above-mentioned SOC stock and bulk density maps for 1980. A total of 40,000 pixels were selected from the maps to train in the first step a quantile random forest model in combination with environmental covariates (McBratney et al. 2003), including soil, relief, climate (Fick and Hijmans 2017), and land use type (Lavalle et al. 2017).

In the case of SOC, over a time range of 70 years (1980–2050), only a part of the SOC stock is likely to evolve, part of the SOC having a much longer residence time (Balesdent et al. 2018 among others). The proportions of these two fractions ($SOC_{<70\,years}$ and $SOC_{>70\,years}$) vary in depth (Balesdent et al. 2018). Two SOC stocks corresponding to these two SOC fractions were thus calculated. To do so, for each soil layer, the proportions proposed by Balesdent et al. (2018) for these two SOC fractions ($SOC_{>70\,years}$ and $SOC_{>70\,years}$) were used and the $SOC_{<70\,years}$ and $SOC_{>70\,years}$ stocks were obtained summing up the different layers. The DSM approach was thus applied on the sole $SOC_{<70\,years}$ stock, the rest of the stock ($SOC_{>70\,years}$) being considered as constant in time. The final SOC stock map for 2050 was obtained by adding the projected $SOC_{<70\,years}$ stock for 2050 to the current $SOC_{>70\,years}$ stock.

2.1.3 | Soil Threat Classes

Because of the various uncertainty sources associated with each step of the chosen approach, we did not consider values of changes as a continuous variable, but we classified changes into 3 classes as proposed by Coblinski et al. (2023) (Table 1). The soil threat maps were reported using these thresholds.

2.2 | Soil Health Assessment for 2050

Soil health was assessed for 2050 based on the separate projections of SOC stocks and bulk density described in the previous section. While soil health represents the ability of the soil to fulfil its function, it is generally estimated through a group of soil properties chosen to depict its condition, as proposed notably in the newly voted Soil Monitoring and Resilience Directive (European Parliament 2025). In addition, as mentioned above, soil health estimation requires the definition of threshold values that differ among soils for the considered soil characteristics. Indeed, soil characteristics are intricately linked to the specific combination of soil type and climate, but also anthropogenic impact (as land use and management). Identifying the threshold for soil health necessitates a preliminary stratification process to identify areas that can be considered as homogeneous (also called soil unit in the future Soil Monitoring and Resilience Directive—European Parliament 2025—term used hereafter), in order to be able to define thresholds for a given soil property or soil health indicator.

2.2.1 | Delineation of the Stratification of Homogeneous Soil Units

The stratification was performed using available spatial data on soil type, land use, and climate at the European scale, corresponding to 1980 as much as possible (see maps Figure S1). For soil types, we used the European soil database (King et al. 1994; Lambert et al. 2003) at a scale 1:1,000,000 for which we considered the first classification level of the Word Reference Base (WRB) that comprises 22 Reference Soil Groups for Europe and the dominant soil group per soil mapping unit. For the land use, we selected the map derived from the LUISA base map (Baranzelli et al. 2014). The seven classes of the first level of classification were considered: croplands, permanent croplands, livestock production, transitional woodland shrubs, natural vegetation, mature forests, and non-soil areas. For climate, we used the climate zone map developed by Metzger et al. (2005), which contains 13 environmental zones for Europe. A mask was applied for non-soil areas such as urban areas and glaciers to remove these from the final stratification map.

TABLE 1 | Considered soil threats and associated indicators and soil threat classes.

Soil threat	Soil threat indicator	Soil threat classes
SOC loss	Decrease in SOC stocks over the whole soil depth or 1 m for deeper soils	10%–40% decrease in 70 yrs.: significant SOC loss, 10% decrease or increase in 70 years: no significant SOC change (no soil threats) More than 10% increase in 70 years: no SOC loss
Compaction	Increase in topsoil bulk density	10 to 40% decrease in years: no compaction 10% increase or decrease in 70 years: non-significant change; 10% to 40% increase in 70 years.: moderate compaction (medium ST) > 40% increase in 70 years: strong compaction (strong ST)

All spatial databases were first combined in vector format and then were processed at 1 km pixel resolution to compute the stratification, leading to 1096 soil units representing unique combinations of land use, climate, and soil type. We kept only soil units larger than 1 km^2, resulting in 730 soil units (Figure S2). The eliminated (removed from map) units (less than 1 km^2) covered less than 0.5% of the total area, so their elimination did not affect the overall results.

2.2.2 | Threshold Identification

The threshold values for each soil health indicator (SOC stock and bulk density values in 2050) were defined following a distribution approach, one approach also proposed by Matson et al. (2024). Thus, the sample quantile values were computed for each soil unit. As the data are subject to uncertainties, these uncertainties must be taken into account when defining thresholds, particularly for soil units with very small ranges of variation in their properties. While in principle the population distribution approach does provide info on typical/atypical values, not explaining the why of atypical values, it is a classical assumption to consider that atypical values are caused by degradation (Drexler et al. 2022). In addition, in our case, selecting a distribution approach is rational in terms of the availability and quality of both soil data and soil-forming spatial factors. To get acquainted with other methods for setting targets and thresholds, we refer to Matson et al. (2024).

For SOC stock, as the range of stock variation (maximum value minus minimum value expressed as a percentage) differed a lot between soil units, the quantiles chosen to define the threshold were defined as a function of this range variation of SOC stock as reported in Table 2. For example, for a homogeneous soil unit with respect to SOC stock (i.e., variation range of 30%), only values of the extreme percentile of the distribution are considered as atypical due to the uncertainty on the stock estimation. On the opposite, for heterogenous soil units (i.e., variation range > 60%), 20th and 80th percentiles were used as done by Moebius-Clune et al. (2016). SOC values between the lower and

TABLE 2 | Percentile chosen as thresholds for soil health, respectively, to the SOC stock depending on the range of variation of the SOC stock of the considered soil unit delineated by intersecting soil type, land use, and climate as suggested in the newly voted Soil Monitoring and Resilience Directive.

Variation range of the SOC stock in % for a given soil unit	Threshold percentile	
	Lower	Upper
30%	1st	99th
30%–40%	5th	95th
40%–50%	10th	90th
50%–60%	15th	85th
> 60%	20th	80th

Note: A soil with a SOC stock lower than the lower threshold is considered unhealthy while above the upper threshold, the soil is healthy; in between the lower and upper thresholds, the soil is considered as "medium healthy."

upper thresholds were considered as "medium healthy," that is, these soils are neither extensively degraded nor are they benchmark examples of soil health. Note that the selected thresholds are arbitrary and serve to illustrate the distinction between soil health and soil threats but nevertheless correspond to an approach classically used in the literature (Matson et al. 2024). An example for both homogeneous and heterogeneous soil units in terms of SOC stocks is shown in Figure 1.

As the range of bulk density values was very narrow, we used threshold values based on the median values of the corresponding strata. These thresholds were calculated as (1) median −10% of the median and (2) median +10% of the median. Thus, we considered that a soil was healthy if its bulk density value was lower than the first threshold in the corresponding soil unit, and unhealthy if its bulk density value was higher than the second threshold. The soils in between the two thresholds were considered as neither healthy nor unhealthy.

3 | Results

3.1 | Soil Threats and Health Maps

The soils that are subjected to threats and the unhealthy soils in the 2050 projections differ in total area (for compaction) at the European scale (Figure 2) and both in spatial patterns (Figure 3). The projected SOC losses (threats) are located predominantly in northern areas, in Ireland, northern Germany and Poland, in the southern part of Sweden and Finland, and the Baltic states when degraded soils will be encountered in 2050 across the entire territory of Europe, with notable areas in Spain, Belgium, the Czech Republic, southern and central Poland, Portugal, southern Sweden, Lithuania and Estonia. It is to be noted that the threatened areas in terms of SOC loss are not always unhealthy in terms of SOC stock (e.g., northern Germany and Poland soils, Figure 2 top left). Regarding SOC loss, the surface of the threatened soils and unhealthy soils in terms of SOC stock is equivalent and represents about 20% of the European soils (Figure 2).

For compaction, the surface of soils under threat (5% of European soils) is considerably smaller than that of unhealthy soils based on the bulk density criteria (40% of European soils). In addition, areas of soils threatened by compaction and of unhealthy soils are not always the same. For example, healthy to medium healthy soils in Austria, in northern Finland or Sweden, or in southeast England are predicted to be moderately threatened by soil compaction in 2050 (Figure 3).

The comparison of the projection of soil threats and health across EU represents thus different perspectives of reality enabling to identify four distinct situations:

1. soils that are healthy and not under threat, the ideal case (65 and 50% of the EU soils for SOC and bulk density status respectively, Figure 4);
2. soils that are both unhealthy and under threat. About 3% of the EU lands are both under threat of SOC loss and unhealthy—degraded—with respect to its SOC status, whereas for bulk density this area is 19% (Figure 4).
3. soils that are still healthy but under threat. For SOC, this is the case for instance for soils of Ireland, Austria,

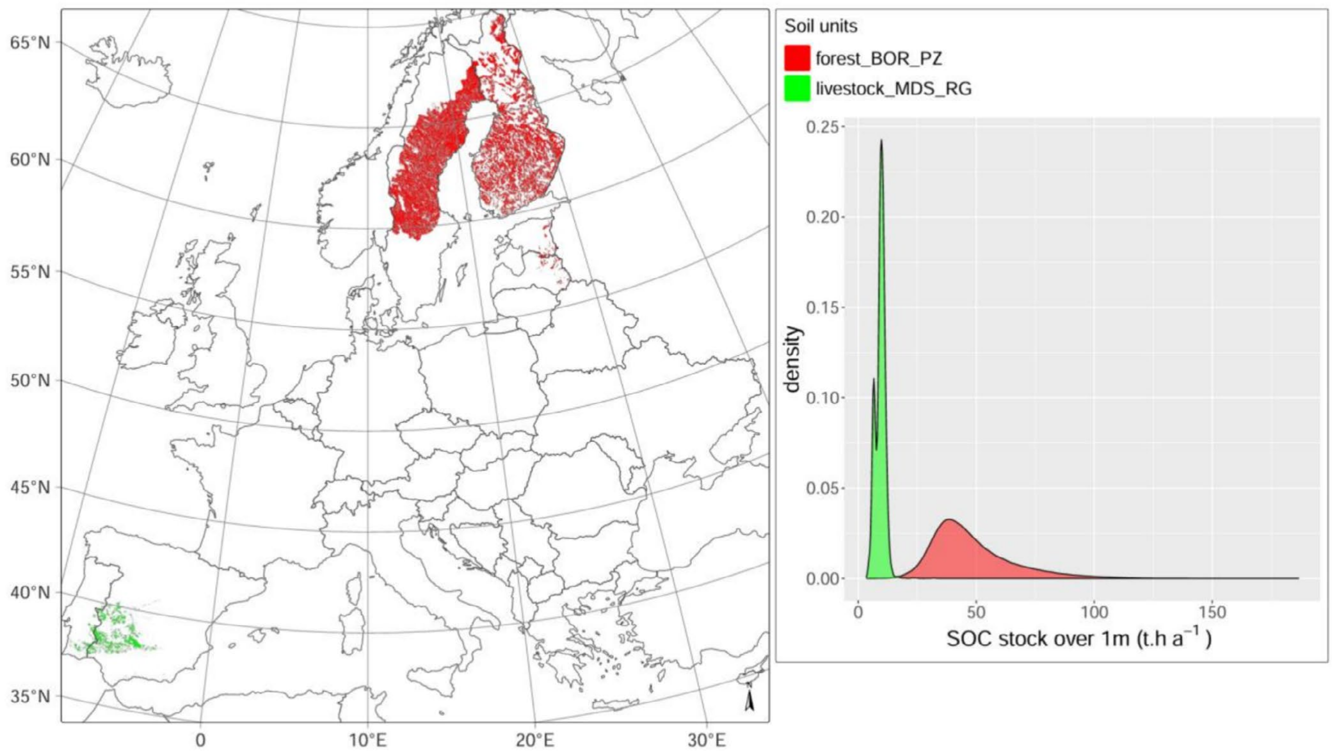

FIGURE 1 | Example of homogeneous and heterogeneous soil units in terms of SOC stocks: Maps of the localization and the corresponding SOC stock distribution.

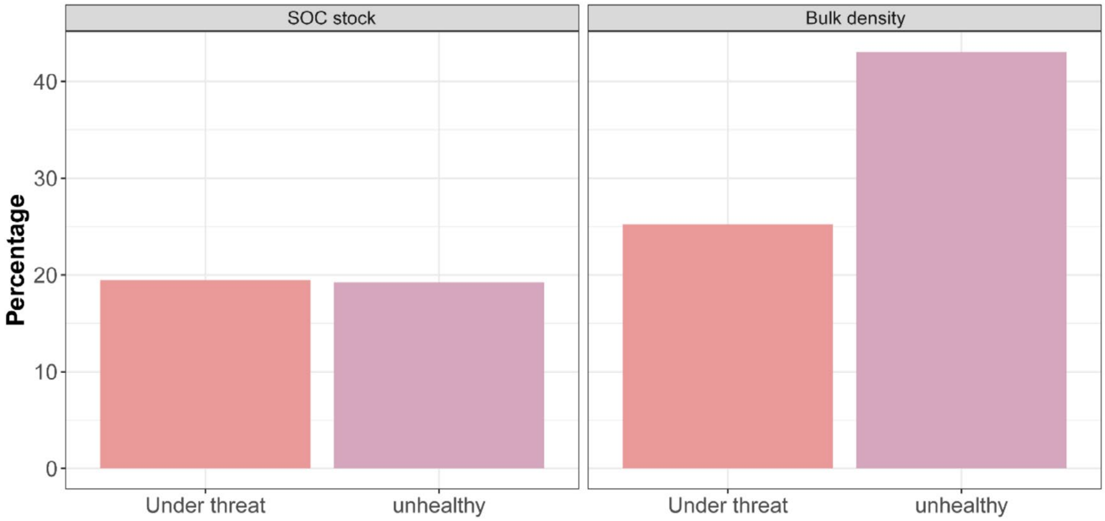

FIGURE 2 | The percentage of threatened and unhealthy EU soils in terms of SOC stocks and bulk density in the EU according to the selected scenario by 2050. For this figure, we considered as threatened the soils with a SOC loss larger than 10% per 70 years and a bulk density increase larger than 10% per 70 years and as healthy the soils from the categories healthy and medium healthy.

northern areas of Germany and Poland, the western part of Finland, and most of Latvia (Figure 5), representing about 18% of the soil surface in Europe (Figure 4). This situation represents 7% of EU soils for soil compaction (Figure 4).

4. soils that are unhealthy but not threatened anymore. This situation was clearly observed for both considered soil threats. For soil compaction it represents 25% of the soils (Figure 4), located in large areas in Hungary, Romania, Slovakia, Czech Republic, Bulgaria, and parts of Poland and Germany (Figure 5), and 17% of the soils for SOC (Figure 4).

4 | Discussion

4.1 | Soil Remediation or Prevention?

Distinguishing between soil health and soil threats in terms of remediation and prevention underscores the proactive versus reactive approaches needed for sustainable soil management. Remediation efforts are needed to restore soil health. It aims to revitalize degraded soils and improve their multifunctionality and resilience. These actions are generally relatively intrusive for the soil, as they are performed when the soil is already degraded. As an example, actions like subsoiling needed to decompact soils are extremely costly and destructive for the soil. This is even more expensive and difficult to manage for other forms of degradation, such as contamination, when the polluted area is removed and treated. Thus, the need for remediation should be avoided and one of the best approaches for that is to prevent soil degradation. Nevertheless, it has to be kept in mind that 60%–70% of European soils are already degraded and need remediation actions for most of them.

On the other hand, threats to soil necessitate primarily preventive measures, since the threat can lead to the deterioration of soil health in the future. While healthy soils are supposed to be more resilient (Lal 2015; Davis et al. 2023), many of them are under threat (Seybold et al. 1999); our results, for example, suggest that this applies to 18% of the soils when considering the SOC stock and 7% when considering soil bulk density. Prevention strategies aim to mitigate the underlying causes of soil degradation before they escalate into significant problems (Kraamwinkel et al. 2021). These efforts may involve implementing soil conservation practices, such as erosion control measures, proper land use planning, and pollution prevention measures.

While soil health remediation focuses on restoring degraded soils to a healthier state, prevention strategies aim to mitigate the risks and drivers of soil degradation (threats) before they manifest, thereby preserving soil health in the long term. These are two of the four operational phases proposed by Blum (1990) for soil protection. Prevention requires an initial investment and ongoing maintenance, resulting in lower costs and more predictability than the potentially high and variable costs of remediation (Girona-García et al. 2023; Panagos et al. 2024). However, both prevention and remediation require soil property monitoring. Such monitoring does not exist in all EU countries, what limits the proper definition of threshold values for identifying the boundary between healthy and unhealthy soils, and when existing, it is sometimes very specific to one or two soil properties (SOC, pH) or limited to the topsoil as notably the case of the EU-wide soil monitoring system LUCAS among others (Mason et al. 2025). Most monitoring efforts are recent and do not have several sampling campaigns available yet (Mason et al. 2025), preventing the estimation of soil threats as proposed here. In addition, Heuser (2022), after reviewing existing acts related to soil protection, indicated that the current EU legislation only partially covers some aspects of soil pollution and biological soil protection, providing soil protection only as a side effect. Furthermore, existing EU laws virtually do not include measures to prevent physical threats to soil, such as compaction or erosion. This situation should evolve in the coming years thanks to the recently voted Soil Monitoring and Residence Directive.

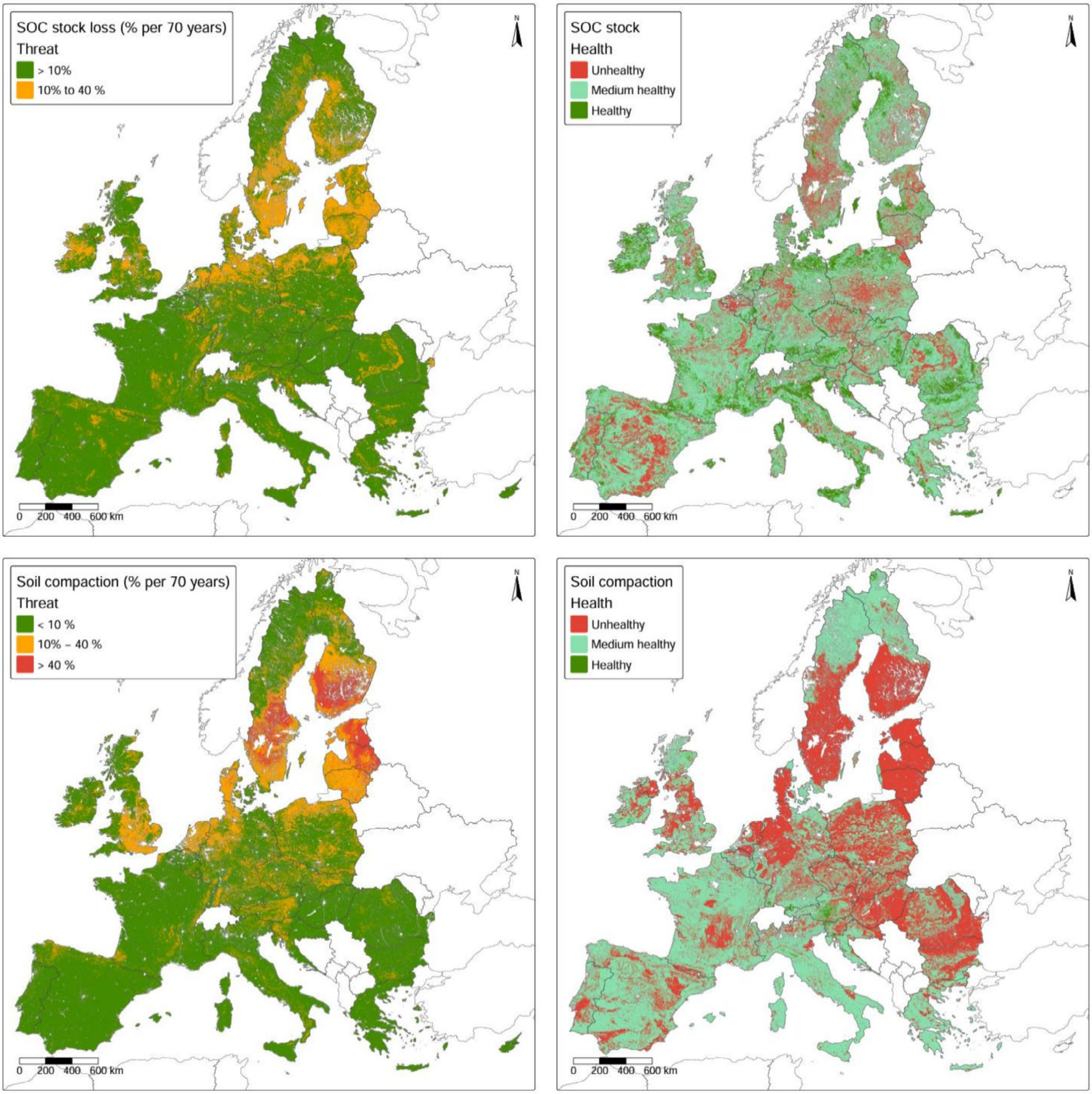

FIGURE 3 | Maps of: soil threats (left column) with SOC stock losses between 1980 and 2050 (top left) and of soil compaction (assessed as a change in bulk density, bottom left); soil health by 2050 (right column) considering SOC stocks (top right) and topsoil bulk density (bottom right).

Although it is meaningless to attempt to restore degraded soils that are under threats without mitigating the risks and threats to soil, by 2050, 17% of the soils in Europe regarding SOC loss and 25% regarding soil compaction will likely be degraded but no longer under threat. They could therefore be subject to remediation actions. Given the immensity of the task, it can be argued that natural regeneration should be preferred to active remediation techniques. This is notably exemplified in the case of abandoned croplands, where once-degraded soils, left fallow, have the prospect of remediation over time. The process of natural regeneration, often accompanied by ecological succession, can lead to the restoration of soil health and halt, for example, soil erosion or other negative processes (Cerdà 1997). Finally, threats to already degraded soils may be overlooked, especially when not considering new damage to soil that is already exposed to a different threat (Prăvălie et al. 2021). For instance, croplands under prolonged use without soil conservation practices are usually affected by the combined effect of compaction and carbon loss (Topa et al. 2021; Suleymanov et al. 2022), but at the same time may still be susceptible to issues such as contamination or acidification (Froger et al. 2023). In such cases, the cumulative impact of multiple threats can exacerbate soil degradation, posing a significant challenge to soil health and overall ecosystem resilience. Recognizing and addressing these layered threats becomes essential in devising comprehensive soil management strategies

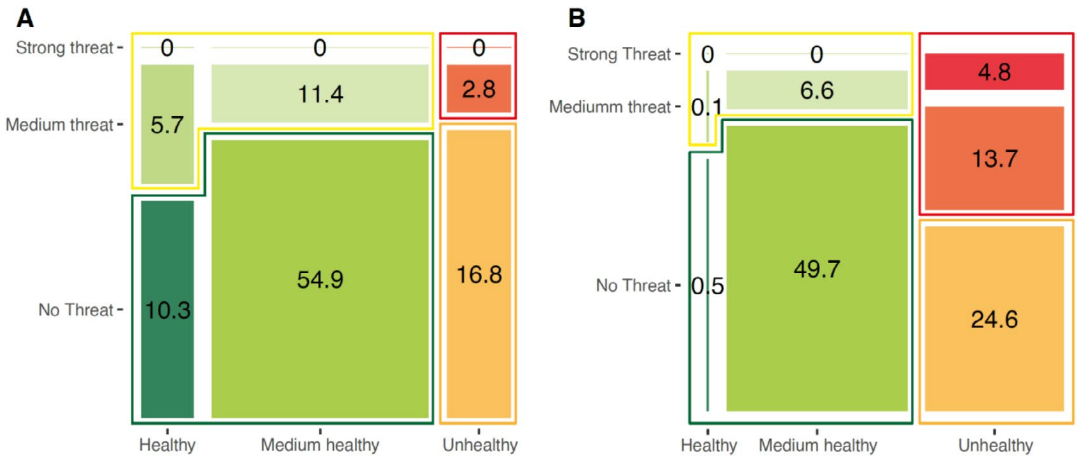

FIGURE 4 | Proportion of soil that are not threatened and healthy (green frame), threatened but still healthy (yellow frame), unhealthy but not threatened anymore (orange frame) and both threatened and unhealthy (red frame). For this figure we considered as threatened soils with a SOC stock change larger than 10% per 70 years (A) and a bulk density increase larger than 10% per 70 years (B) and as healthy the soils from the categories healthy and medium healthy.

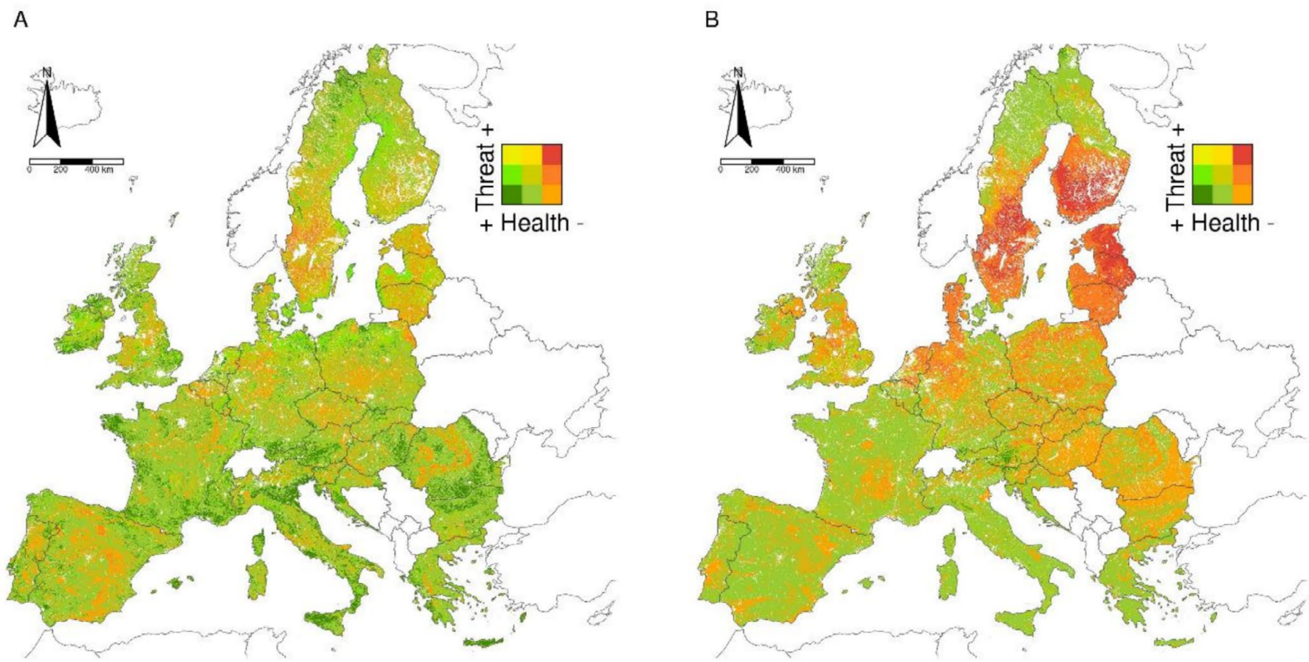

FIGURE 5 | Bivariate maps of soil threats and health for SOC stocks (A) and compaction (B) by 2050.

that not only rehabilitate degraded soils but also prevent further deterioration. Some attempts at identifying multiple soil threats in Europe were recently made (Panagos et al. 2024; Prăvălie et al. 2024). However, while Coblinski et al. (2023) only consider four of the soil threats, Prăvălie et al. (2024) mixed soil threat indicators (defined as a process) with soil health indicators (soil state called threats in that work). We demonstrated here that the two are not equivalent and consider that they should not be mixed when addressing either soil health or soil threat bundles. However, we also showed that there is added value in analyzing them together (e.g., SOC loss and SOC stock or compaction and bulk density in this study).

4.2 | Consequences for the Soil Monitoring and Resilience Directive

The main goal of the EU Soil Strategy for 2030 is to have all European soils in a healthy condition by 2050 through specific actions aimed at climate change mitigation, circular economy, soil restoration, monitoring and others (Panagos et al. 2022, 2024). EC (European Parliament 2025) therefore acknowledges the necessity of setting "measures for monitoring and assessing soil health, managing soils sustainably and tackling contaminated sites to achieve healthy soils by 2050." This necessitates the use of a monitoring system descriptors of soil health that should be assessed at a given time and that should be compared to reference values or thresholds. While the soil monitoring and resilience directive states that these reference values/thresholds should be adapted to local conditions, including soil type, climate and land use, it provides, for some soil health criteria, a unique reference value/threshold (e.g., for soil salinity, see Annex 1 of European Parliament 2025). In addition, there is a certain level of confusion in the directive between targeting soil health or soil threats. As an example, the directive proposes as indicator of SOC loss the SOC content. As SOC loss is a threat, it should be measured as a change in SOC stock over time, as discussed above but not as a soil condition which is associated to a reference level and is thus a soil health descriptor. On the opposite, in the case for soil erosion the chosen indicator (expressed as loss of soil in ton ha^{-1} $year^{-1}$) does indeed represent a soil threats. As a result, while soil health is its main interest, the soil monitoring law actually mixes the soil health and soil threat concepts. As discussed before, while monitoring soil health provides valuable information about soil conditions, it is equally important to clearly separate soil health from soil threats and integrate monitoring indicators that specifically target soil threats. By incorporating monitoring of soil threats to existing frameworks, policymakers and land managers can indeed gain a more comprehensive understanding of soil degradation processes and implement targeted interventions to mitigate risks for soils that may still be under healthy condition but are following a trend of degradation (Niemeijer and de Groot 2008). This would allow tackling incipient degradation processes and therefore probably reduce the costs of action and promote soil resilience.

4.3 | Limits of the Proposed Approach and Actions Needed in Research, Soil Monitoring and Society to Overcome Them

The approach presented concerning soil threats and soil health is based on very important choices such as (1) the level from which a change in soil properties (expressing a soil process) is considered to be a threat to soils depending on the intensity of that change and (2) the choice of thresholds above or below which a soil is considered healthy or not. This last choice has a large impact on the definition of a healthy soil and depends on the soil type, the climate under which it develops and potentially the land use, as not considering the land use may for certain soil descriptors (e.g., SOC status) results in most of the agricultural soil being classified as unhealthy. While research can provide the statistical distribution for each soil under each specific climate and land use, the choice of the type of threshold and reference value to be chosen are a matter of societal discussion and political decision depending on how conservative we want to be (Matson et al. 2024). Indeed, the definition of thresholds and targets are mainly arbitrary and subjective process (Matson et al. 2024; Sparling et al. 2003). Do we want all the soils to have the same characteristics as less managed ones? Do we want only the most damaged soils to be restored? For example, if soils have medium health, do we consider them healthy or not? In addition, the "distribution" approach strongly depends on the data availability (Drexler et al. 2022). As a result, the reporting results in a specific study can be optimistic or pessimistic as demonstrated by Chen et al. (2019) for SOC storage in French croplands using four percentiles as thresholds (80%, 85%, 90%, and 95%). In the same way, in our analysis, we made the choice to count them as healthy soils, but the opposite choice would be in line with the precautionary principle.

The same discussion applies for soil threats. While science can indicate the frequency of monitoring that would allow changes to be detectable, depending on the threats considered, existing knowledge and measurement method sensitivity, society should decide which level of threats requires action and what is the budget to be dedicated to it. But let's remember that, as already demonstrated in the context of ecosystem services related to soil, the inaction cost remains high (Krasilnikov et al. 2017).

Consequently, the thresholds used here were mainly selected for the purposes of illustrating the contrast between soil health and soil threats and should not be considered as granted. At last, the projecting approach proposed here is a statistical approach that does not allow considering important dynamics that could be approached by process-based modeling. This DSM approach however allows having a consistent framework for the different soil threats and soil health indicators, which is difficult to achieve by with process-based modeling due to the absence of a process-based model capable of simulating threats and soil health.

5 | Conclusion

The intricate interplay between soil threats and soil health is influenced by the escalating challenges of growing human pressure on soils and the pervasive impacts of climate change, further emphasizing the need for comprehensive and sustainable soil management strategies. In this study, we demonstrated that mapping these two concepts indicates different levels of caution for the same area but provides complementary results, underlining the necessity for diverse approaches to land resource management and preservation. We conclude that, depending on the objectives and actions required, it is essential to clearly distinguish between the concept of soil threat and soil health. It may sometimes be interesting to choose the appropriate one, but we argue that in most cases it is more relevant to articulate them to target interventions capable of addressing the multiple challenges facing soils. However, in existing regulations, the difference between soil threats and health is sometimes unclear. While the primary goal of the EU Soil Strategy for 2030 is to bring all European soils to a healthy state, the issue of preventing threats to soils may be overlooked due to the chosen indicators. In addition, bringing all European soils to a healthy state will necessitate to define the level of health one wants to achieve for our soils in the future and therefore the definition of thresholds for soil health that should depend on soil, climate and probably land use, have to be defined on a sound scientific basis and society discussion. In the end, soil threats and soil health indicators should be treated jointly.

Author Contributions

Azamat Suleymanov: conceptualization, data curation, investigation, formal analysis, validation, visualization, writing – original draft, writing – review and editing. **Sophie Cornu:** conceptualization, data curation, formal analysis, methodology, investigation, writing – original draft, writing – review and editing, supervision, validation. **João Augusto Coblinski:** data curation, formal analysis, methodology, validation,

writing – review and editing. **David Montagne:** conceptualization, writing – review and editing. **Rudi Hessel:** conceptualization, writing – review and editing. **Isabelle Cousin:** conceptualization, writing – review and editing, supervision, funding acquisition. **Antonio Bispo:** writing – review and editing, conceptualization, supervision, funding acquisition. **Nicolas P. A. Saby:** conceptualization, data curation, formal analysis, investigation, methodology, validation, supervision, writing – review and editing, writing – original draft.

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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.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** European map of soil (a), climate zones (b), and land use as proposed by LUISA base map 2012 (c). **Figure S2:** Map of the 730 soil units defined using the soil map, climate regions, and land use.