Journal of Plant Nutrition and Soil Science

WILEY-VCH

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RESEARCH ARTICLE OPEN ACCESS

A First Quantitative Assessment of Soil Health at European Scale Considering Soil Genesis

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Received: 16 May 2025 | **Revised:** 9 October 2025 | **Accepted:** 10 October 2025

Academic Editor: Hermann Jungkunst

Keywords: risk assessment | soil degradation | soil disturbance | soil quality

ABSTRACT

Background: Soil health degradation is a major threat to European food security, biodiversity, and climate stability. While scientists have debated how to define soil health during recent decades, a quantifiable framework for monitoring, management, and policy remains lacking.

Aim: We introduce SHERPA (Soil Health Evaluation, Rating Protocol, and Assessment) as a framework for discussion and present a first quantitative soil health assessment across Europe.

Methods: All major soil degradation processes (with the exception of organic contamination) were scored, averaged, and subtracted from the intrinsic soil health resulting in quantitative final scores.

Results: As reported before, cropland soils throughout Europe are highly degraded. Surprisingly, soil health of grasslands is also very negatively impacted. Soil erosion, nutrient surplus, and pesticide risk are largely driving poor soil health aligning with reported high biodiversity loss in agricultural land. Forest soils are also surprisingly low in health, mainly because of nitrogen surplus, reflecting documented widespread forest decline from nutrient imbalances. Interactive maps highlight specific threats to soil health across Europe, offering valuable insights for targeted action.

Conclusions: SHERPA is able to quantify soil health across Europe. However, at the current state of data availability, soil health is likely to be overestimated. Monitoring data of soil structure, compaction, pesticide spread and, in forest ecosystems, disturbance of humus layer are urgently needed for final assessment of soil health.

Christine Alewell and Surya Gupta share first authorship.

1 | Need for a Clear Quantitative Definition of Soil Health

Reduced soil health is increasingly recognized as one of the most critical threats to European food security, aquatic and terrestrial biodiversity, and climate change mitigation (Li et al. 2024). Due to soil's broad environmental and societal functions, soil scientists request that soil health should be legally recognized as a common good (Lehmann et al. 2020). In response, the European Union (EU) has identified soil health as one of five Mission themes (Arias-Navarro et al. 2024), representing a new approach to addressing some of Earth's greatest challenges. The EU Soil Strategy for 2030 (European Commission 2021) was launched to combat declining soil health in Europe and beyond. The ambition is for the entirety of Europe to have healthy soils by 2050 (Arias-Navarro et al. 2024; Panagos et al. 2025) with a European Soil Monitoring & Resilience Law (SML 2023) recognizing the ecosystem services provided by healthy soils. Although an awareness is growing that healthy soils are the basis of a healthy society, anchoring this view into policy is still a challenge (van der Putten et al. 2023), with one of the most difficult tasks to define and quantify soil health. To make the European Union's Soil Monitoring Law operational, soil health needs to be measurable (van der Putten et al. 2023) and requires a legal framework to address the multitude of processes that are involved in land degradation.

The comparison of soil health to human health was established as early as the 1990s (Doran and Parkin 1994), where a physician assesses various bodily functions, including temperature, blood pressure, pulse rate, and specific blood or urine analyses. In addition to these measurements, the physician must also observe visible indicators of health, which can be regarded as intrinsic health characteristics. In contrast, soils represent intricate systems characterized by potentially high biodiversity, influenced by both physical and chemical parameters in situ and ex situ. Consequently, the evaluation of soil health is considerably more complex than that of human health, particularly since there is no individual present to provide information regarding its well-being. Numerous reviews, assessments and concepts of soil health have been published in recent years (e.g., Bünemann et al. 2018; Doran and Parkin 1994; Guo 2021; Harris et al. 2022; Lehmann et al. 2020). The recognition of the extensive and critical issue of soil degradation in Europe is often approached through oversimplified methods that rely on a "convergence of evidence" perspective, indicating that 60%–70% of soils are in a non-healthy state (Panagos et al. 2024; Prăvălie et al. 2024). However, there remains a significant gap in the establishment of a clear and quantifiable framework for the monitoring, protection, and management of soil health, which is essential for enabling a quantitative assessment of soil condition. Such definitions are crucial for effective monitoring, management, policy decisions, and implementation. Finding efficient, easy-to-measure indicators for soil health is challenging because there is no one-size-fits-all indicator for the multifunctionality of soil (Bünemann et al. 2018; Doran and Parkin 1994).

Many reviews do not differentiate clearly between soil quality and soil health or even consider the terms equivalent (Bünemann et al. 2018; Doran and Parkin 1994). We propose following a concept that in contrast to soil quality, which is largely chemical in focus and mostly used to characterize the status of soil to sustain crop productivity, is more holistic (Lehmann et al. 2020). It is based on the recognition of the soil's natural capital and the ecosystem services that soils provide. Soil quality refers to the capacity of soil to function for a specific use. With that said, we would like to point out that an in-depth discussion of soil quality, soil health, and related definitions can be found in Bünemann et al. (2018) and is beyond the scope of our focus here (for further discussion, see Supporting Information 1, section "Justification of a quantitative soil health definition used and separating soil health from soil quality").

The EU Soil Monitoring & Resilience Law defines soil health as "the physical, chemical and biological condition of the soil determining its capacity to function as a vital living system and to provide ecosystem services" (SML 2023). Our working definition of soil health for the Soil Health Evaluation, Rating Protocol, and Assessment (SHERPA) is that a soil is healthy if its natural functions in relation to its land use type are not subject to degradation in any significant way.

2 | The SHERPA Framework and Structure

We propose SHERPA (Soil Health Evaluation, Rating Protocol, and Assessment) as a framework, where in a first part the intrinsic soil health status is assessed with key indicators of emergence associated with healthy soil profile development. The indicator uses, for example, soil genetic factors such as climate and environment (pedo-climatic regions), surface cover, soil management, and soil structure to assess soil health in a decision tree logic (Figure 1; Supporting Information 1 for the full key). It is essential to consider the concept of soil health in relation to the processes of soil formation, or pedogenesis, which includes both the progressive development of soils and the particular evolutionary stage reached by a specific soil type. This perspective is deeply rooted in the European tradition of soil science. While our methodology for soil assessment of Part 1 considers practical and operational aspects, it remains fundamentally anchored in post-Darwinian natural sciences, which explicitly recognize the evolutionary context of the subject. The second part follows a ruling out of the most important soil threats parallel to, but refining and expanding, the ideas of soil health assessment of the European Union Soil Dashboard as in Panagos et al. (2024) and Prăvălie et al. (2024).

Regarding the intrinsic health of a soil, it has been argued that it will be challenging to find natural soils that can act as a reference, especially for healthy agricultural soils and that the challenge for soil laws will be how to develop gold standards for healthy soils (van der Putten et al. 2023). We argue that soil scientists know the basic soil properties that indicate healthy soils under specific land use conditions and environmental settings, and we followed these criteria to define intrinsic soil health in Part 1.

As such, SHERPA represents a framework that embodies these concepts and generates a score that can be interpreted as the health of the soil in an objective and quantifiable way. It is the first soil health assessment that assigns numerical scores across

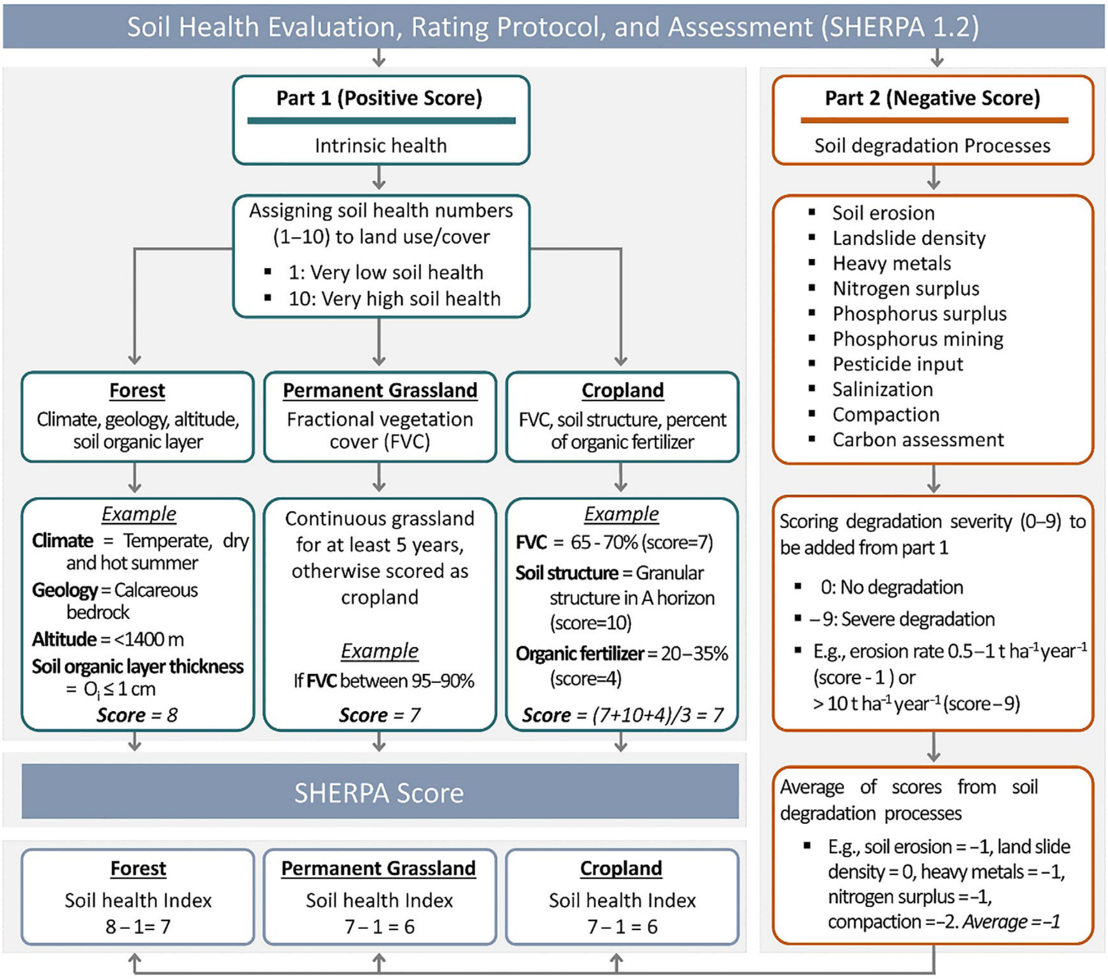

FIGURE 1 | Concept of SHERPA including one hypothetical example to calculate soil health. See all considered degradation processes of Part 2 in Table S2.1.

different land uses. The negative scores of the threats assessed in Part 2 are set against (e.g., negative scores added to) positive scores indicative of intrinsic soil health (Part 1) (Figure 1). A novel contribution of this work is recognizing that the soil state is the balance between health and the processes that lead to degradation and generating a scoring framework that captures this:

SHERPA

= Intrinsic soil health (positive scores Part 1) + degradation processes (negative scores Part 2).

This score can be used to monitor trends over time and across regions, assess the severity of different soil threats, inform policy measures, aid goal setting for management, and may eventually help evaluate the economic costs of soil degradation and restoration.

The aim is to keep the SHERPA key as parsimonious as possible, suitable for large scale monitoring. Increasing the number of indicators will not only increase collinearity as well as the complexity of the relationships between indicators and management options, but will also result in increased costs of monitoring (Bünemann et al. 2018). We propose a simple key, with the chosen parameters being reduced to the feasible minimum programmed in the open-source R Software platform. We plan to keep the structure open (e.g., in a sense of non-final, like the philosophy of R itself) for later additions, corrections, extensions in areas or knowledge of area specifics, improvements, and sharing with other collaborators. The logic of the key follows in Part 1 a general intrinsic soil health from which the assessment of potential degradation factors following a ruling out principle will lead to negative soil health scores in Part 2 to be added to Part 1 (Figure 1). We consider the average of negative Part 2 scores to be added to Part 1 to (1) value the intrinsic soil health assessment of Part 1 highly and (2) to mitigate the bias due to potentially missing data of degradation processes in Part 2.

2.1 | Part 1: Intrinsic Soil Health Assessment

Part 1 evaluates the inherent health of soil not through generic thresholds based on a combination of parameters, but by examining fundamental soil characteristics that signify healthy soils within specific land use contexts and environmental conditions. This assessment follows a decision tree framework that is informed by the understanding of soil formation, which is influenced by factors such as geology, mineralogy, climate, altitude, surface cover, and land management practices. The intrinsic health of a soil is assessed with a positive scoring between 1 (low soil health) and 10 (healthy soil). SHERPA will classify forest soils according to their Köppen-Geiger climate class (Beck et al. 2018; Peel et al. 2007), geology considering mineralogical nutrient and buffer capacity, altitude, humus layer structure, and signs and spatial extent of humus layer disturbance (see Supporting Information 1). Grasslands are separated into permanent and non-permanent grasslands, where the latter will be assessed together with cropland soils, orchards, and vineyards. Permanent grasslands are classified by their fractional vegetation cover, assuming that a closed vegetation cover will indicate soil health in grasslands considering the soil degradation factors assessed and considered in Part 2. Cropland soils, orchards, vineyards, and non-permanent grasslands are classified according to their extent of vegetation cover throughout the year (e.g., cover crops, mulching, plant residue cover, intermittent crops), soil structure, and the type of fertilizer used (as the use of organic over mineral fertilizer use has been shown to significantly enhance soil health, see Section 1.3 in Supporting Information 1 for discussion). For wetlands, drainage and vegetation cover would be the main indicators (note that even though we are currently developing a framework for wetland assessment and mapping, assessing wetlands were beyond the scope of this current study and will follow in a later step).

2.2 | Part 2: Soil Degradation Process Assessment

Part 2 (Soil degradation processes) considers the main soil degradation processes dependent on relevance and data availability for the three land-use types: croplands, grasslands, and forests (Supporting Information 2, Table S2.1; for all scientific background as well as justification of score assignment, see Supporting Information 1; for data sources and their spatial resolution, see Supporting Information 2, Table S2.2). We consider the following main soil degradation processes (Table S2.1): soil erosion as the sum of wind, water, harvest, and tillage for cropland soils (Borrelli et al. 2023) and water erosion only for grasslands and forests, land sliding, heavy metal contamination, and nitrogen surplus. Phosphorus surplus, salinization, compaction, and soil organic carbon loss were considered in cropland soils and grasslands, while pesticide input and phosphorus mining were only considered in cropland soils (for all scientific background as well as justification of score assignment, see Supporting Information 1). Each of the degradation factors will be assigned a negative score from 0 (no degradation) to −9 (worst degradation influence). The final score of Part 2 will be an average of all degradation processes considered. For data sources and spatial resolution, see Supporting Information 2, Table S2.2.

2.3 | Example Calculation of SHERPA

An example calculation of SHERPA would be a beech forest with humus form mull and granular soil structure but high atmospheric nitrogen deposition. An intrinsic soil health index of 8–10 in Part 1 will be assigned; however, the humus form might have been influenced by surplus nitrogen deposition, thus simulating a better humus form than what would naturally be there. Therefore, negative scores will be assigned to be added to the basic soil health scores assigned in Part 1 to reflect the human disturbance of this system due to nitrogen deposition. Note that following the concept of adding negative Part 2 scores to Part 1, a soil health index of 10 would be the healthiest soil possible with no degradation at all and full intrinsic soil health, while an index of −8 would be the most degraded soil possible (with an intrinsic soil health of 1 and an average Part 2 score of −9). Thus, if multiple degradation processes are co-existing (e.g., soil erosion rate of 12 t ha^{-1} $year^{-1}$ [Part 2 score −8] and a copper concentration of 80 mg kg^{-1} [Part 2 score −6]), a mean Part 2 score of −7 would be added potentially to a low Part 1 score resulting in an overall negative assigned soil health index.

As we cannot always differentiate if a soil is degraded by natural hazards or human impact, the cause of disturbance might sometimes be natural hazards. For instance, a landslide in alpine grasslands might be triggered by an avalanche. Whether or not this avalanche is originally triggered by natural hazards, or human induced due to prior vegetation damage or by climate change will not be assessed with this key.

3 | Assessing the Intrinsic Soil Health of Forests, Grassland, and Cropland Soils

In defining the intrinsic soil health of forest soils, we rely strongly on humus layer occurrence, thickness, and disturbance. The humus layer has long been acknowledged as a fundamental component of numerous biological and physico-chemical processes that are vital for soil development and the functioning of terrestrial ecosystems within forest environments (Ponge et al. 2010). Consequently, it serves as a critical indicator of forest soil health. However, it is only recently that the concept emerged of humus forms as a digest of major processes, which shape and stabilize ecosystems, pointing to the need for a better and worldwide assessment of diagnostic characters of humus forms (Ponge 2003; Zanella et al. 2011). Even though the general concept and classification of three different humus layer types are generally agreed upon worldwide (Mull, Moder, Mor/Raw humus), many region- and country-specific differences and specialties exist in the exact classification (Zanella et al. 2011). Thus, we use occurrence and thickness of humus layer rather than humus forms as well as the general occurrence of a closed humus layer cover above the mineral soil as identifiers for soil health (for the exact classification of soil health scores, see Supporting Information 1, Section 1.1). Plantation forests will be assessed with the same key as natural or semi-natural forests, as we can expect the same processes and ecosystem functions in all these forested systems. If plantation forests are in a transition phase from cropland or grassland to forest systems or are intensively managed, this indicates a lower ecosystem stability which will be considered by SHERPA as we do not expect a fully developed humus layer coverage and/or signs of compaction (tracks of heavy machinery). If pesticides are used or degradation due to compaction is noted, this will be considered by the ruling out criteria of Part 2 of SHERPA.

The rationale for assessing the soil health of permanent grasslands follows the concept that usually vegetation cover is a safe indicator for soil health of grassland soils (considering that any form of contamination including pesticide treatment is assessed in Part 2). Wherever we have degradation by livestock (trails as well as sheet erosion due to overgrazing), construction, land sliding, erosion, snow ablation, or avalanche activity, this will result in a reduced vegetation cover. However, there are some exceptions (see Supplementary Information 2, Figure S2.3) like livestock resting places as well as places around farms, settlements with heavy manure, or waste water input which might have high vegetation cover but not necessarily a diverse community typical for permanent grasslands. Instead, we will find monocultures or low-diverse cultures from, for example, Rumex spec., Epilobium spec. This is mostly very local. Here, spectral indices could be developed reflecting the heterogeneity of grasslands. For example, if we have dense Rumex communities (or, another example, Calamagrostis mats) with one to two species only, we should have a very homogenous spectral reflectance. However, as this is very local, often close to settlements or alpine huts, these areas will not be considered at the moment but will be left for future projects to be covered. In any case, they will be scored negatively in Part 2 of SHERPA, as they are subject to high nitrogen and phosphorus surplus and prone to compaction. Regarding species diversity, we expect that with permanent grassland development for more than 5 years, species composition will adapt to (1) ecological zone parameters and (2) land use. However, grasslands are managed ecosystems, like cropland soils. If we would subtract scores, just because the grassland is not natural anymore, this would also mean that agricultural use would by definition never be assessed with good soil health scores. Eventually, separate tables for natural grasslands could be developed; however, we do not really have many natural grasslands in Europe except the higher alps. The latter zones would be classified with high soil health score, except they have high rates of erosion. In summary, the key for the grasslands soils follows the order of (1) asking for permanence of grassland over winter and spring in the Mediterranean and full year-round in all other climate zones for more than 5 years, and (2) mapping fractional vegetation cover.

The intrinsic health of cropland soils is assessed with three main parameters: surface cover as fractional vegetation cover throughout the year, mineral versus organic fertilizer addition, and soil structure. We realize that the first two attributes are driving factors of soil health, while the third, soil structure, is an intrinsic soil property directly indicating the status of soil health.

Vegetation cover throughout the year is an important factor of soil health as it reduces erosion, conserves moisture, reduces temperature, intercepts rainfall, and suppresses weed growth (Larkin 2015). Furthermore, it provides habitat for soil organisms as living plants provide the most readily available food source for soil microbes in the rhizosphere, an area of concentrated microbial activity, which is the most active part of the soil ecosystem with readily available food and peak nutrient and water cycling (Larkin 2015). Thus, growing plants throughout the year (long-season crops or multiple short-season crops, rotations, cover crops) helps the soil–food web and cycle the nutrients that plants need to grow (Larkin 2015).

It is generally considered that soil management with organic fertilizer will intensify soil health, due to the positive relationship between organic fertilizer input; increase in soil organic matter and carbon sequestration, cation exchange capacity, pH, and acid buffering capacity; decrease in bulk density, improvement of soil structure, water retention, and infiltration; and increase in permeability, fungal and bacterial diversity as well as microbial activity, plant nutrient supply, fruit quality, and even suppression of plant pathogens and diseases (Hatano et al. 2024; Khasawneh and Othman 2020; Larkin 2015; Lehmann et al. 2020; Rayne and Aula 2020). While green manure has been considered to be superior in its effects on soil health compared to animal products (Khasawneh and Othman 2020), animal manure applications have also been concluded to be beneficial for all of the above discussed improvements (Larkin 2015; Rayne and Aula 2020). Conserving and/or maintaining existing soil organic matter levels need regular additions of organic matter to replenish soil resources and improve soil health, and it represents the energy source that enables the soil ecosystem to grow and thrive. Organic matter can be added through crop residues, rotations, and cover crops, as well as via off-field sources of organic amendments such as compost, manures, and mulches (Larkin 2015). There has been some evidence that the exclusive use of swine manure, even though having many beneficial effects, might have some negative effects like decreasing bulk density (Yost et al. 2022). However, we consider the overwhelming evidence of studies on positive effects of organic fertilizer crucial. An overapplication of organic fertilizer will, of course, have detrimental effects not only on the environment (e.g., nitrogen, phosphorus leaching) but are also an unappealing management form from a labor and cost perspective. However, the latter is not needed to be considered for soil health. In addition, as we consider nitrogen and phosphorus surplus in Part 2 of SHERPA, here the percent of organic fertilizer of the total fertilizer input will be considered a generally beneficial factor.

Management practices such as tillage versus conservational tillage (no till or stripping) are not considered in SHERPA, due to the contradictory effects on soil health. While tillage might increase soil erosion (which is considered in Part 2), conservational tillage might be beneficial in increasing soil's penetration resistance, organic carbon content, and biota biomass but has also been shown to lead to higher compaction and sealing (also increasing erosion) and a greater number of root feeding nematodes (Khasawneh and Othman 2020).

It might also seem surprising that soil texture is not considered in the below tables, especially as compaction and soil structure is, of course, strongly dependent on soil texture. However, as we strive for healthy soils, we need land use and management that is adapted to soil-specific characteristics. As such, a soil that is prone to compaction due to texture and/or angular structure (e.g., clay rich) needs adjusted management practices that prevent compaction and promote biological turnover supporting zoogenic soil structure (e.g., granular); otherwise, it cannot be considered healthy. Note that soil erosion, soil compaction (with consideration of soil texture), overfertilization, and erosion as well as contamination with, or application of, pesticides are considered in Part 2 as ruling out principles.

4 | Soil Health in Europe per Land Use Type as Indicated by SHERPA

We applied SHERPA using datasets from the Europe-wide LUCAS (Land Use/Cover Area frame statistical Survey Soil) soil sampling for cropland and grassland soils (Land Use/Cover

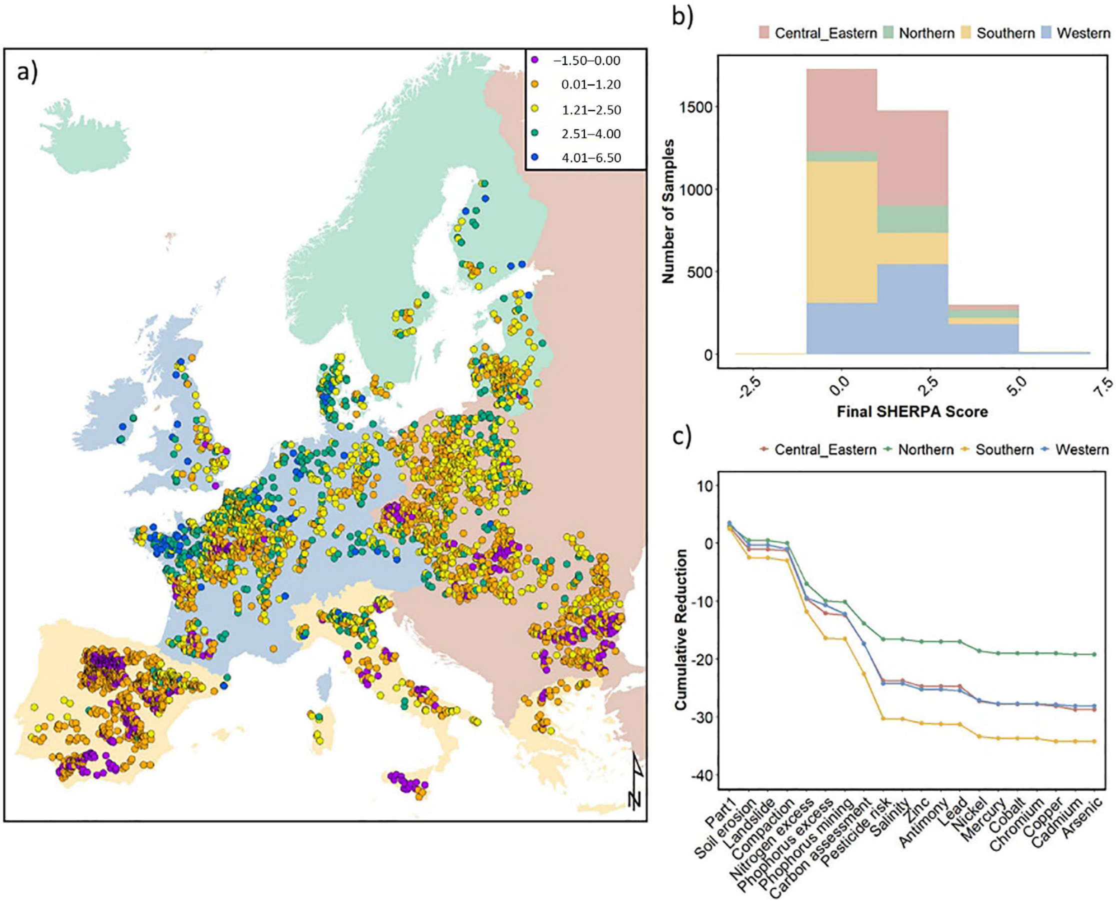

FIGURE 2 | Soil health assessment in European cropland soils (colors demarcate central eastern, northern, southern, and western Europe with n = 1113, 270, 1094, and 1057, respectively. Total n = 3534. Note that n depends on and varies with data availability of all parameters). (a) Distribution and scores of assessed points. For interactive maps to assess contribution of single processes to the final score, see link: https://www.google.com/maps/d/u/0/edit?mid=1LdyqCR4hiMQz2J8JLLroSd4LxWPTlok&usp=sharing. (b) Frequency distribution of SHERPA's soil health scores and (c) cumulative plot of SHERPA scores for the single soil degradation processes subtracted from Part 1.

Area frame statistical Survey Soil; Orgiazzi et al. 2018), as well as the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forest (ICP-Forest; https://icp-forests.net/ Ferretti and Fischer 2013; Haußmann and Fischer 2004; Puletti et al. 2019). We combined these with available studies on degradation processes (see Table S2.2) to conduct a statistically robust initial assessment across Europe. It is important to emphasize that we assessed point data only as any kind of extrapolation and scaling into maps would not adequately address the highly heterogeneous nature of soil health. However, due to the lack of data required, we relied for some parameters on data extracted from published maps (see Table S2.2).

SHERPA results allow for the first time (1) a quantitative assessment of the severity of the different soil risk factors and (2) a yardstick by which different soils in different regions may be compared.

Not surprisingly, and as reported previously (Panagos et al. 2024; Prăvălie et al. 2024), cropland soils are highly degraded. While 99.3% of these soils have an overall soil health score between 5 and −1 (Figure 2b; with 10 being the absolute possible maximum of a healthy soil), the majority of all cropland soils (85.2%) even score below 2.5. Data distribution (Figure 2b) and cumulative numbers (Figure 2c) clearly point to southern European soils having the lowest scores followed by western and central eastern with northern soils scoring the highest on average.

The majority of cropland soils in Europe are affected substantially by several soil degradation processes. Each single process (or the average) of Part 2 has a maximum negative score of −9. Cumulative scores (Figure 2c) illustrate highly negative scores pointing to the cumulative effects of several degradation processes. Comparing the different geographical regions of Europe (EUROVOC 2025), southern European cropland soils are the most degraded (cumulative score −34.2, overall average soil health score as Part 1 + Part 2 = 0.6) followed by central (−28.7, 1.2) and western European soils (−28.1, 1.8, respectively) with northern croplands being the least affected (−19.2, 1.9, respectively; Figure 2c). The degradation processes affecting cropland the most are soil erosion (medium severity between −2.5 in northern and −5 in southern regions), nitrogen (severe impact of −7 to −9), and phosphorus excess (medium −1.2 in western to −4.5 in southern regions) as well as pesticide input (medium-to-severe impact of −2.7 in northern to −7.7 in southern regions, Figure 2c). Note that a direct comparison of scores between processes are not meaningful as these scores indicate the severity of a degradation process within the reported occurrence with all processes being equally weighted

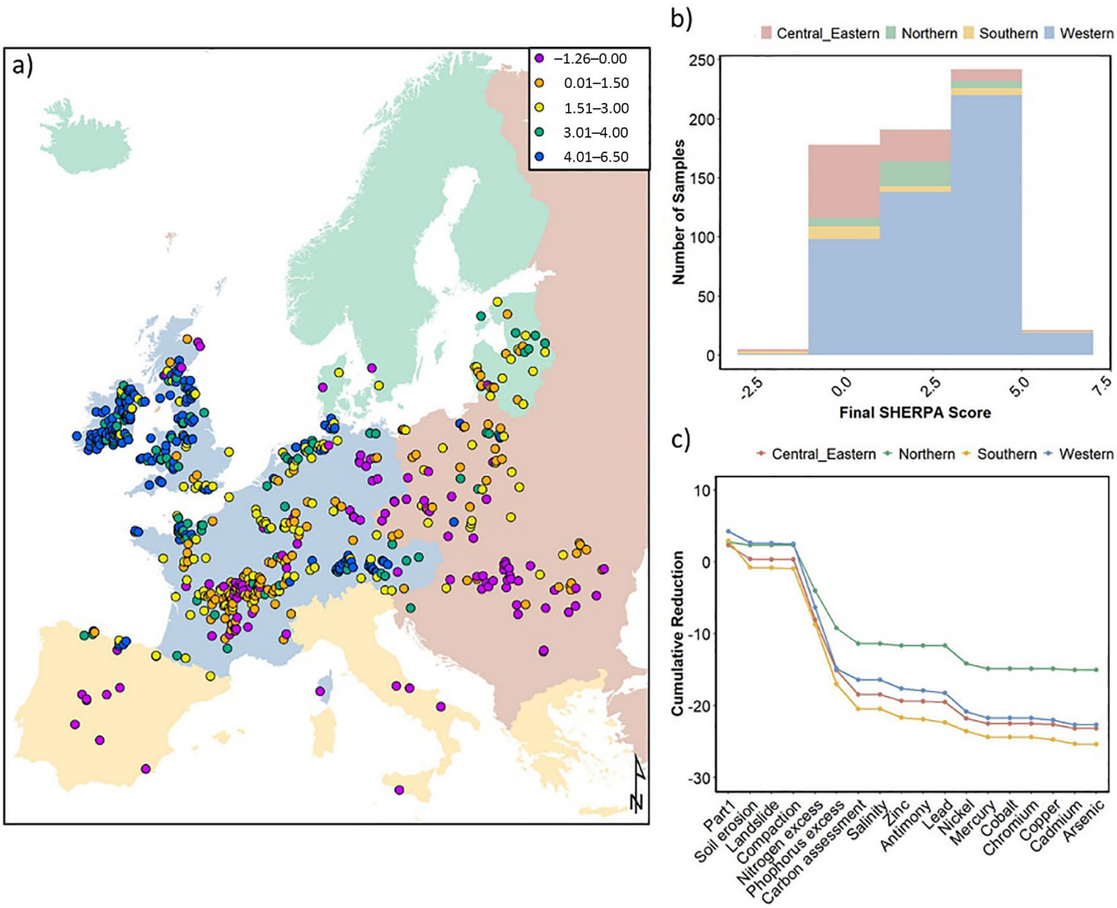

FIGURE 3 | Soil health assessment in European grassland soils (colors demarcate central eastern, northern, southern, and western Europe with n = 102, 34, 25, and 476, respectively. Total n = 637. Note that n depends on and varies with data availability of all parameters). (a) Distribution and scores of assessed points. For interactive maps to assess contribution of single processes to the final score, see link: https://www.google.com/maps/d/u/0/edit?mid=1LdyqCR4hiMQz2J8JLLroSd4LxWPTlok&usp=sharing. (b) Frequency distribution of SHERPA soil health scores and (c) cumulative plot of SHERPA scores for the single soil degradation processes.

(see below for discussion). While the latter results of high soil degradation in European croplands are nothing new, this clear nutrient overload alongside high pesticide risk is consistent with the dramatic ongoing and ever accelerating biodiversity decline in Europe (Pereira et al. 2024) with both soils and adjacent waters being affected.

According to SHERPA scores, soil health in European grasslands is also surprisingly low, with the highest frequency of soil health scores are calculated between 5 and –1 indicating high rates of soil degradation (51.1% of all assessed grassland soils score between 2.5 and –1 and 27.9% of grasslands score between 1 and –1). Again, degradation has progressed severely especially in southern, central-eastern and western Europe with northern regions being clearly less negative in the cumulative plot (Figure 3c), note that at current data availability sample numbers differ significantly with 476, 102, 34, 25 for western, central eastern, northern, and southern grasslands, respectively, Figure 3). While the average of northern grasslands finalizes in the cumulative plot with –15 and an average soil health score of 1.7, averages of southern (–25.3, 1.3), central eastern (–23.2, 0.8), and western European grasslands again (–22.65, 2.68 respectively) score lower (Figure 3c). Thus, SHERPA indicates that soil health in European grasslands is only slightly better than in croplands. This is consistent with most grasslands being affected by at least two or three degradation processes (Figure 3c) with southern and central-eastern Europe having the highest rates of soil erosion and southern, western, and central eastern regions showing to have higher nitrogen and phosphorus surplus compared to northern regions. The soil degradation processes affecting the SHERPA score most in grasslands are nitrogen (–6.3 in northern to –8.8 in western) and phosphorus surplus (–5.2 in northern to –8.5 in western) followed by soil erosion (–0.5 in northern to –3.7 in southern). The latter is consistent with the reports of high and still dramatically proceeding decline in biodiversity loss in European agricultural lands, which is of course partly due to the impact of cropland, but, as demonstrated by SHERPA scores, is also attributed to the nutrient overloading of grasslands (and, of course, from croplands and grasslands to the adjacent waters). Also, there is a high uncertainty assessing the pesticide risk in grasslands. Tang et al. (2021) only consider the pesticide risk based on pesticides loads and thus pesticides were not considered for the calculation of pesticide risk in grasslands. This neglects the widely documented negative effects of diffuse pesticide pollution across landscapes outside target areas (Cederlund 2017; de Jong et al. 2008; Linhart et al.

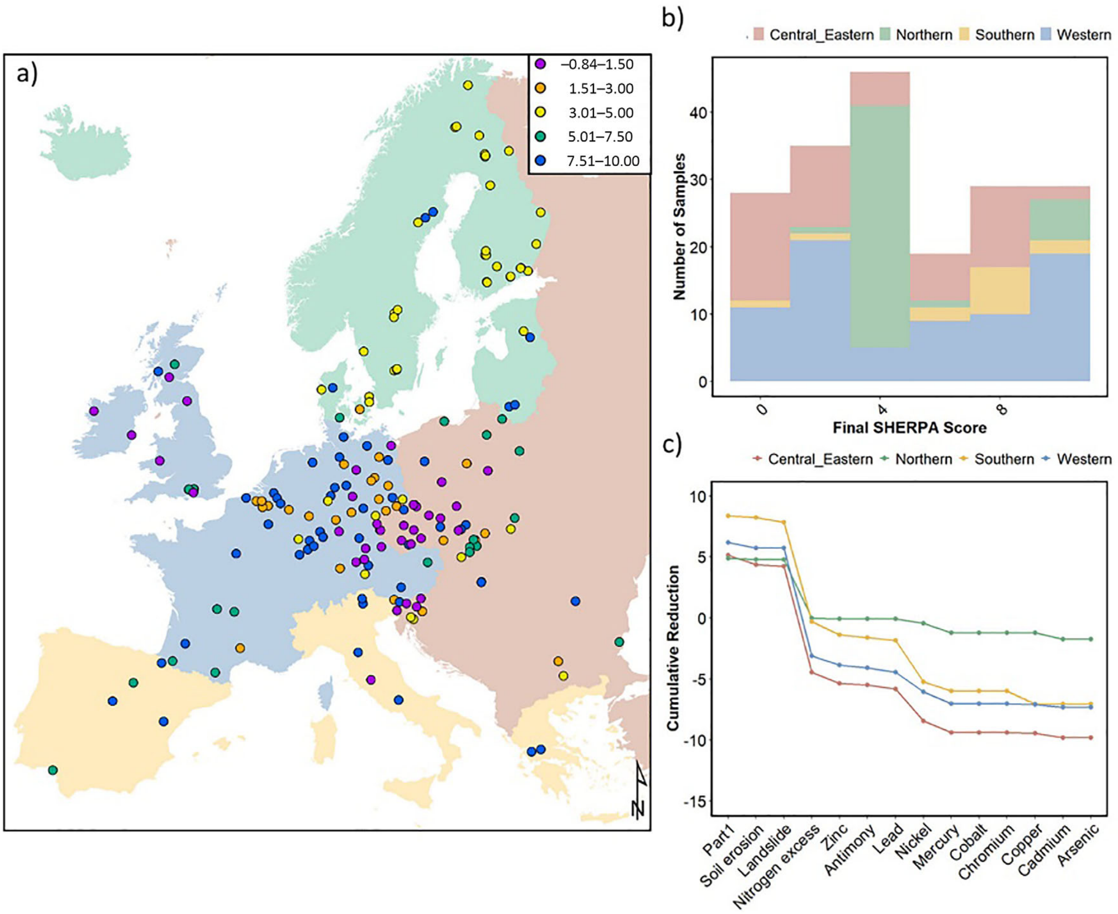

FIGURE 4 | Soil health assessment in European forest soils (colors demarcate central eastern, northern, southern, and western Europe, with n = 54, 44, 13, and 75, respectively. Total n = 186. Note that n depends on and varies with data availability of all parameters). (a) Distribution and scores of assessed points. For interactive maps to assess contribution of single processes to the final score, see link: https://www.google.com/maps/d/u/0/edit?mid=1LdyqCR4hiMQz2J8JLLroSd4LxWPTlok&usp=sharing. (b) Frequency distribution of SHERPA soil health scores, and (c) cumulative plot of SHERPA scores for the single soil degradation processes.

2021). Thus, we have to state that the soil health assessment in grassland at the current state of data availability (no data on diffuse pesticide input) is rather underestimating degradation processes.

Even though soil health scores in European forests are clearly more positive compared to grasslands and croplands with one peak in frequency distribution between 7 and 10 (all regions), a second, higher peak between 5 and 1 (Figure 4b) points to considerably soil degradation. Surprisingly, the highest intrinsic soil health (Part 1 score) is found in the southern regions of Europe, followed by western, central eastern, and northern regions. However, here Part 1 scores should be interpreted with some caution, as intrinsic soil health status of forests is at present mainly based on humus layer stratification and thickness (humus layer disturbance and soil structure data are currently not available). This likely introduces a high uncertainty and possibly some bias in soil health assessment of forest soils until this data gap is filled.

Being strongly three-dimensional structures, forests have a high filtering capacity for air pollutants, and this is reflected in the two main soil health threats to forests: nitrogen surplus and metal contamination (Figure 4c). Nitrogen surplus results in 4.8 (northern) to 8.8 (western and central eastern) negative scores; nickel and mercury contamination yields up to 3.4 and 0.8 negative scores, respectively, in southern regions. Metal contamination is often overlooked as a stressor in forests; however, many forest soils, particularly in heavily populated or industrialized regions, retain significant metal contamination from legacy air pollution dating from the Industrial Revolution to the end of the last century. Ultimately, central eastern forests are the most degraded (cumulative score average −9.7; Figure 4c) followed by western and southern regions (approximately −7) with the healthiest forests in northern Europe (−1.8). The substantial soil degradation rates in forest soils are alarming but are consistent with forest monitoring data of Europe, observing high, and alarmingly increasing rates of forest disturbance in more than one third of the forested area (Maes et al. 2023). While some of this increasing disturbance is partly induced by more frequent and more severe droughts (Potočić et al. 2021), the high nutrient imbalances due to nitrogen overloading is identified as one severe driver of forest decline (Du et al. 2025; Krüger et al. 2020). The results underpin the call for a stronger representation of forest soils in the proposed European Soil Monitoring and Resilience Law (Wellbrock et al. 2024).

5 | Discussion

Our regional patterns align well with recent assessments by Li et al. (2024), Panagos et al. (2024), and Prăvălie et al. (2024) (see comparison Figure S2.1), with the lowest degradation in northern regions, followed by western, central eastern, and southern regions. It could be discussed that within SHERPA all soil degradation processes are simply averaged with being equally weighted. We argue that weighting of parameters will insert a subjective view of severity of disturbance or threat and will as a result limit the usability of a key to specific contexts only. And how can one objectively determine whether the long-term toxicity of heavy metal contamination pose a greater threat than the structural degradation caused by soil compaction? Or, as a further example, if the degradation process due to erosion is more or less harmful than nitrogen surplus? Therefore, we provide interactive maps (see link in subtitles of Figures 2–4), where at each assessed point the intrinsic soil health (Part 1) as well as the negative scoring of each Part 2 soil degradation process is presented. Thus, anyone can use the information needed for specific questions in specific regions. In using these interactive maps, we would like to point out how to handle this point information appropriately: some degradation processes as well as soil parameters were extracted from published maps with coarse resolution (Table S2.2). As long as no detailed monitoring data of all parameters are available, we suggest evaluating the quantitative data of SHERPA not in an absolute way for point or site assessment, but to compare regions, land use types, and dynamics of soil degradation processes only.

Regarding heavy metal pollution, each element is considered separately with each potentially contributing to the overall mean health score of Part 2 with a maximum of −9 scores. The presence of multiple co-contaminants not only exacerbates overall toxicity through potential synergistic and additive effects (Lin et al. 2024; Olaniran et al. 2013; Qu et al. 2024) but also significantly complicates remediation efforts, as each additional pollutant introduces unique chemical interactions and sometimes opposite properties, which challenges remediation, or containment strategies (Li et al. 2025; Lin et al. 2024). Even though heavy metal contamination in Europe is not the main driver of soil degradation, it does influence soil health scores significantly as it contributes to the overall Part 2 mean negative scores of 5.0, 4.7, and 5.4 in cropland, grassland and forest soils, respectively. Following the structure of SHERPA, geogenic high content of heavy metals in soils will be classified as low soil health. For practical purposes, this is useful, as these areas and soils should not be used for drinking water production, partly not usable for livestock grazing or recreational areas, where small children might play and would be exposed to potential uptake of soil material. However, for mapping endeavors, these areas could be marked with striped or gridded pattern, to indicate the geogenic origin of the high heavy metal content, the knowledge of which might be useful for management or planning options both for possible (non-)remediation action but also for, for example, any kind of construction. Construction on, for example, geogenic high Arsenic content soils will result in substantial extra costs for disposing the excavated soil.

Regarding the assessment of heavy metal contamination in Part 2 of SHERPA, we realize that the setting of the upper and lower boundaries of each heavy metal might seem arbitrary for the moment and that values need to be based on further research for each heavy metal separately. Here, we demonstrate the concept and structure envisaging future scientifically based limit values for each element. Also, the list of heavy metals is not complete, but we could only include elements which are considered in available guidelines as well as published monitoring and mapping endeavors. In case of soil contamination with an element missing in Table S2.2 (Supporting Information 1), the local (national) regulation should be considered. In such a case, 9 scores should be subtracted if the concentration of element exceeds the local guideline/intervention value (i.e., the concentration which requires soil remediation). Also, the present assessment of arsenic seems insufficient; however, due to its substantial underrepresentation in both European and national legal systems, a definition of limit values is difficult. The element's high toxicity demands a more comprehensive evaluation and stricter regulatory actions in the future.

Soil biodiversity is not considered explicitly in our indicator set, even though recent discussion on soil health highly recommends or even requests a greater inclusion of biological indicators in soil health assessments (Bünemann et al. 2018; Harris et al. 2022; Lehmann et al. 2020; van der Putten et al. 2023). There is no doubt that soil organisms play a central role in soil functioning, but finding a pan EU indicator is challenging. A recent study showed an increase in microbial diversity and significant differences in microbial community structure from forests to extensively used grasslands to highly managed intensively used crop lands (Labouyrie et al. 2023). These changes are still far from being fully understood. Furthermore, the study only illustrated the changes from one land-use type to another, not the effect of disturbance or degradation within land-use types (Labouyrie et al. 2023), which are necessary for assessing soil health quantitatively. As we want to keep SHERPA an open concept to be continuously improved or adapted generally or regionally, we do not rule out that with the recent rapid developments in soil biology as well as big data evaluations, the consideration of genotypic and phenotypic community diversity parameters with molecular DNA and/or RNA screening within regular monitoring programs might hold potential to specify a future version of SHERPA to certain regions, conditions or even in general. Until this happens, biological health is, in some regards, implicit within the consideration of pedogenic development (soil structure) and emphasis on soil organic matter and humus genetic forms captured in Part 1.

Recent discussions on soil health and quality suggest that extrinsic factors, including parent material, climate, topography, and hydrology, may substantially influence the potential values of soil properties to such a degree that it is impossible to establish universal target values, particularly in absolute terms and that soil health is not a readily quantifiable or measurable entity (Bünemann et al. 2018; Harris et al. 2022). However, as our results show, in following a decision tree concept rather than a fixed indicator combination for the intrinsic soil health, we can differentiate between specific environmental settings and single out degradation and disturbance from healthy soil systems. This then offers an additional lens through which soil assessment can be undertaken to contribute to more informed goal setting and effective decision-making. As such, the results of SHERPA, which might be judged preliminary due to the lack of high-resolution monitoring data for all parameters necessary, can contribute to better access and monitoring of soil health in the European Union as this is one of the main four objectives in the Soil Mission. The tool should not necessarily be seen as an end in itself, but as offering a new structured way of developing an assessment of soil health and required management to retain or restore soils into a healthier status. At the very least, it might be considered a tool that provides a framework for starting and guiding a discussion with soil managers regarding the status of their soils. Also, SHERPA clearly visualizes the need for better monitoring of soil data, mainly soil structure, compaction, high resolution pesticide input, and, in forest soils, the disturbance of surface soils and humus layers. Furthermore, SHERPA scores can be used to monitor soil health trends over time and across regions, assess the severity of different soil threats, inform policy measures, aid goal setting for management, and may eventually help evaluate the economic costs of soil degradation and restoration.

6 | Conclusions

We developed a first quantitative soil health assessment concept SHERPA for evaluation on large scales which we would like to present for discussion and evaluation with this publication. The concept is fundamentally new in aligning an assessment of intrinsic soil health from 1 to 10 against soil degradation factors scoring 0 to −9 to quantify overall soil health scores. In relying on the LUCAS and ICP-Forest data, grasslands score surprisingly low being only slightly more positive compared to cropland soils and clearly more negative than forest soils. Soil erosion, nutrient surplus, and pesticide risk are the main degradation factors in agricultural land, and low soil health aligns with reported high biodiversity loss. Forest soils are mainly affected by nitrogen surplus and heavy metal input due to interception deposition where canopy structures filter pollution from the atmosphere. Especially the effects of high nitrogen surplus in forests are documented widely causing forest decline due to nutrient imbalances.

At the current stage of data availability, we are restrained to point assessment only refraining to extrapolate to full maps due to the highly variable nature of soil health. Missing or scarce data on soil structure, pesticide input but also pesticide spread across landscapes, compaction, and, in forest soils, humus layer information (thickness and degree of disturbance) most likely lead to an overestimation of soil health and an underestimation of the severity of degradation.

With an improved availability of soil monitoring data in the future, an evaluation of soil health across Europe with SHERPA will not only allow assessment of soil health trends over space and time and decrease the uncertainty in soil health assessment (with a likely overestimation of soil health in the current evaluation) but might eventually be suitable for assessing causal relationships to environmental or socioeconomic drivers as well as potential costs of remediation.

Acknowledgments

We thank *Peter Schad* and *Sabine Rumpf* for discussion and input on an early version of the SHERPA concept. This research has received funding from *European Union's Horizon Europe projects* and the *Swiss State Secretariat for Education, Research and Innovation* (SERI) for the projects "*Accelerating collection and use of soil health information using AI technology to support the Soil Deal for Europe and EU Soil Observatory (AI4SoilHealth)*" *grant agreement no. 101086179* and "*Biodiversity and Functionality of Mediterranean Olive Groves (Soil O-live)*", *grant agreement ID: 101091255*.

Open access publishing facilitated by Universitat Basel, as part of the Wiley - Universitat Basel agreement via the Consortium Of Swiss Academic Libraries.

Data Availability Statement

These data were derived from the following resources available in the public domain: Interactive maps, https://www.google.com/maps/d/u/0/viewer?mid=1LdyqCR4hiMQz2J; R code for programming, https://github.com/ETHZ-repositories/SHERPA, LUCAS data: https://esdac.jrc.ec.europa.eu/projects/lucas, ICP Forest data: https://www.icp-forests.net/.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting File 1: jpln70034-sup-0001-SuppMat.pdf.

Supporting File 2: jpln70034-sup-0002-SuppMat.pdf.