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REVIEW ARTICLE

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How the EU Soil Observatory is providing solid science for healthy soils

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Abstract

Healthy soils are essential for sustainable food production, achieving climate neutrality and halting the loss of biodiversity. The European Commission turned the spotlights on these vital aspects of soils with the launch of the EU Soil Observatory (EUSO) in 2021 to support the European Green Deal. Also, the EU Soil Strategy for 2030 and the proposed Soil Monitoring Law marked a major milestone for soil protection. This article provides an overview of the functioning of the EUSO within this policy context. Through its activities, the EUSO supports an EU-wide soil monitoring system and provides policy support to a wide range of policy areas. Moreover, the EUSO monitors the state of soil health in the EU through the EUSO Soil Health Dashboard. This comprehensive and easy understandable tool shows, for the first time, where current scientific evidence converges to indicate areas in the EU likely to be affected by soil degradation. Furthermore, the EUSO supports soil research and innovation, enhances the capacity and functionality of the European Soil Data Centre and supports citizen engagements regarding soil matters. Overall, since 2021, the EUSO has successfully taken up its role to be the principal knowledge hub for soil information and data to underpin EU policy development and implementation. Also in the next years, EUSO will continue to provide data and knowledge to monitor, safeguard and restore soils in the EU.

KEYWORDS

EU Soil Observatory, land degradation, policy support, soil health, soil mission, soil monitoring

1 | BACKGROUND

Healthy soils produce food, increase our resilience to climate change, extreme weather events, drought and floods and support our well-being. As the world's population increases and may reach 9 billion by 2050, issues of food security become more pressing, as this trend needs to sustain soil fertility and minimise its degradation (Oliver & Gregory, 2015). As soils are the largest terrestrial pool of carbon on the Earth, their role is important in carbon sequestration and climate change mitigation (Neher et al., 2022).

Land degradation is a serious threat that has no borders and can reduce the soil's capacity to provide ecosystem services (Smiraglia et al., 2016). In addition, this threat has become more prominent as the Russian war against Ukraine has had a serious impact on global food systems. As a result of this conflict, consequences such as halted exports, population displacement, limited access to fertilisers, uncertainty about harvests and loss of fertile soils have emerged (Ben Hassen & El Bilali, 2022; Pereira et al., 2022). In this context, fertile soils are of geostrategic importance to secure our access to sufficient nutritious and affordable food for the global population. In parallel, large expanses of soils, and their associated ecosystem services, have been lost to urban expansion and infrastructure development (Tobias et al., 2018). Soil sealing exacerbates urban heat island effects but also exposes people to greater hydrogeological risks (Nwakaire et al., 2020).

Soil erosion, soil contamination, soil compaction, soil sealing, nutrient depletion and the loss of soil organic matter and biodiversity continue to be major threats to soil health in Europe (Figure 1). Monitoring soil health in a comprehensive manner, understanding the interplay between soils and the essential functions they deliver are pivotal to design solutions and policy intervention to ensure sustainable management of soils. In the European Union (EU), a pivotal role in this respect is played by a dedicated platform, the EU Soil Observatory (EUSO).

The objective of this review is to give an overview of the main activities of EUSO within its policy context. In addition, we show the role of EUSO in converging monitoring evidences, providing indicators, summarising latest scientific findings towards the best possible support to soil-related policies as well as to all the domains where healthy soils are of strategic importance (climate policies,

Highlights

- EU Soil Observatory (EUSO) monitors the state of soil health in the EU through Soil Health Dashboard.
- 62% of soils in the EU are unhealthy based on the 19 soil degradation indicators of the Dashboard.
- 24% of EU soils are subject to one degradation process, 16% to two, 10% to three and 5% to four processes.
- EUSO contributes to the proposal of the Soil Monitoring Law and the implementation of the Soil Mission.

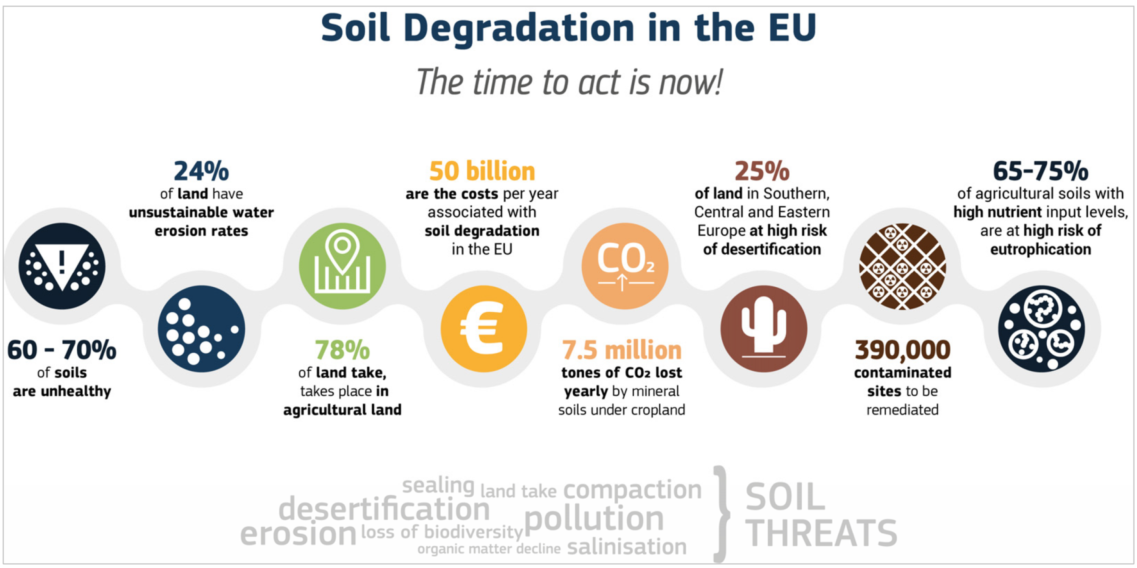

FIGURE 1 Major threats for soil health in the EU and related impacts. Source of the data: Soil Monitoring Law (European Commission, 2023a, 2023b) and scientific publications (De Rosa et al., 2024; Dupas et al., 2015; European Environmental Agency, 2024; Panagos et al., 2020; Pérez & Eugenio, 2018; Prăvălie et al., 2017; Veerman, 2023).

food policies, biodiversity policies, etc.). EUSO activities include implementing an EU-wide soil monitoring system, supporting soil research and innovation, enhancing the capacity and functionality of the European Soil Data Centre (ESDAC), monitoring soil health and policies in the EU and supporting citizen engagements regarding soil matters. The article also provides evidence about the EUSO contribution to soil science and an outlook for the future developments of the EUSO.

2 | POLICY CONTEXT AND THE EUSO

The EU has put in place many policies for agro-environmental protection since 2000, including soil protection. Since 2020, the European Green Deal has set an ambitious roadmap to make the EU the first carbon-neutral continent with a modern, competitive and resource-efficient economy. As part of Green Deal, the European Commission (EC) has put soil protection in a high position on the EU policy agenda as healthy soils are important to achieve climate neutrality, zero pollution, sustainable food provision and a resilient environment (Montanarella & Panagos, 2021). The EC adopted the EU Soil Biodiversity Strategy 2030, the Zero Pollution Action Plan, the Farm to Fork Strategy, the EU Climate Adaptation Strategy, the Carbon Removal Certification framework and published in July 2023 the proposal for the Soil Monitoring Law.

A Soil Monitoring Law will put the EU on a pathway to healthy soils by 2050, by gathering data on the health of soils and making it available to farmers and other soil managers. The law also makes sustainable soil management the norm and addresses situations of unacceptable health and environment risks due to soil contamination (European Commission, 2023b).

Moreover, since September 2021, the EC adopted five Research and Innovation Missions to bring solutions to major societal challenges in the EU and deliver concrete results by 2030. The Mission 'A Soil Deal for Europe' will support the EU's ambition to manage land in more sustainable ways, put in place 100 Living Labs and develop a harmonised framework for soil monitoring in Europe (Panagos, Montanarella, et al., 2022; Veerman, 2023). The ambitious objectives of the Soil Mission and the legislative proposal for a Soil Monitoring Law requested scientific evidence about the state of soil health in the EU.

To support the Green Deal, the EUSO was launched by the EC in December 2019. With the publication of the EU Soil Strategy for 2030, the proposed Soil Monitoring Law and the Soil Mission, the importance of the EUSO was highlighted again as these policy developments marked a major milestone for soil protection in the EU. The EUSO is developed by the Joint Research Centre (JRC) of the EC and published in a dedicated platform that is publicly accessible.

Given this policy context, the main objective of the EUSO is to provide the EC and the broader soil user community with the knowledge and data needed to monitor, safeguard and restore soils at EU level. The EUSO aims to be the principal provider of reference data and knowledge at EU level for all matters related to soils. Furthermore, the EUSO aims to support EU Research and Innovation on soils and raise societal awareness of the value and importance of soils to the lives of citizens, including connecting soils with overall production and consumption patterns. Besides their natural value, soils are essential to support basically all economic sectors that underpin production and consumption in the EU and globally. However, production and consumption patterns that depend upon soils are also the major driver of soil degradation (intensive agriculture, mining and raw materials extraction, housing and infrastructure, etc.). Moreover, due to the global nature of supply chains, many soil-related impacts are displaced (Wiedmann & Lenzen, 2018). Namely, EU production and consumption patterns not only affect EU soils but imply impacts in third countries, for example, from where raw materials or commodities are imported.

Overall, the EUSO supports the EU policies by ensuring that the EC is able to fully capitalise on the information made available through integrated data flows by transitioning from simply monitoring to understanding. In this manner, the EUSO supports the implementation of all soil-related objectives of the European Green Deal.

Active for 3 years, the EUSO plays a key role in supporting soil policy development, monitoring the state of soil health, supporting and interacting with research activities and raisings citizens' awareness of the need for soil protection.

To achieve the main objective of the EUSO to act as the key knowledge centre for EU soil policies, five sub-objectives have been defined (Figure 2):

1. Support the development of an operational EU-wide Soil Monitoring System.
2. Further consolidate and enhance the capacity and functionality of the ESDAC.
3. Monitor the state of soil health and the policies in place to enhance soil protection, through Soil Health and Policy Dashboards.
4. Support research and innovation through the implementation of Horizon Europe's Mission 'A Soil Deal for Europe'.

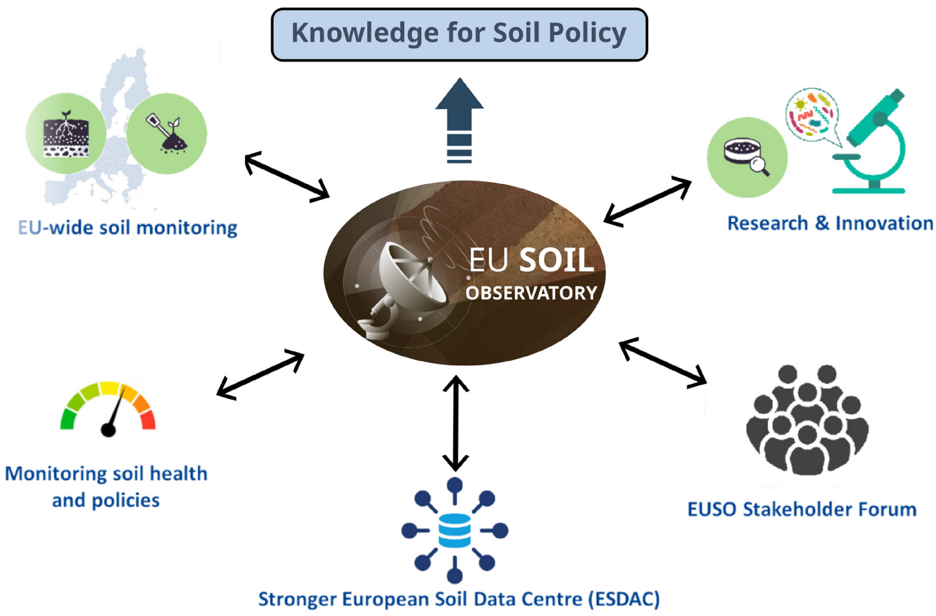

FIGURE 2 The five objectives of the EU Soil Observatory.

5. Provide an open and inclusive European Soil Stakeholders Forum that supports citizen engagements and the drive towards a societal change in the perception of soil.

3 | EU-WIDE SOIL MONITORING SYSTEM

The EUSO continues to provide an essential and unique soil monitoring service at the EU level through the Land Use/Cover Area Frame Survey soil module (LUCAS Soil). In its first campaigns (2009/2012 and 2015), LUCAS Soil collected around 20,000 samples per sampling round and targeted physico-chemical properties (e.g., pH, texture, organic carbon content, nutrients and heavy metals). In 2018, additional properties, namely bulk density, soil biodiversity (DNA-based), measurements for organic-rich soil and soil erosion, were considered (Orgiazzi et al., 2018). The data generated by LUCAS Soil have been used to establish baselines for several soil indicators across the EU (Figure 3). Such an effort has led to the LUCAS Soil module becoming a reference system for soil monitoring in the EU.

Currently, the LUCAS Soil module is the only EU-wide harmonised and regular soil survey. It covers the entire territory of the EU, targeting simultaneously major land cover types (i.e., cropland, grassland and woodland), in a short sampling period (Figure 3).

In 2022, around 38,000 samples were collected, doubling the effort of the previous campaign (19,000 samples taken in 2018). Around 22,000 new points supplemented a fixed pool of 16,000 sampling points (made up of locations that had been revisited at least twice in the 2009/2012–2015–2018 surveys). For the selection of new sampling locations, a novel approach was applied based on the prediction of soil organic carbon (SOC) concentrations. Thanks to the support of the Alpine Convention Working Group for Soil Protection (Markus, 2017), sampling locations also included areas above an elevation of 1500 m mainly distributed in the Alpine region, which was underrepresented in previous LUCAS campaigns. Those numbers will allow, among others, to provide a more statistically robust assessment of SOC stocks in croplands (regional level: NUTS 2) and woodlands and grasslands (country level: NUTS 0) and, thus, better reporting on this matter in relation to environmental, climate and agricultural policy implementation.

In close coordination with the European Joint Programme (EJP) Soil (Keesstra et al., 2024), the EUSO has supported a study on the inter-comparison of the LUCAS Soil module and existing national soil monitoring systems in the EU. Data harmonisation is paramount for a future EU soil monitoring scheme, guaranteeing a systematic soil health assessment among Member States (MS), but also allowing to produce knowledge for informed land management and policy decision-making. Currently, MS use a variety of methodologies to determine soil chemical and physical properties, but also specific sampling schemes, which often differ from the LUCAS topsoil (0–20 cm) procedure. To facilitate the harmonisation of data originating from different sampling and laboratorial schemes, a double sampling was performed under the LUCAS 2022 survey towards the comparison of the LUCAS (single-lab) approach with 13 other MS laboratorial procedures. The double

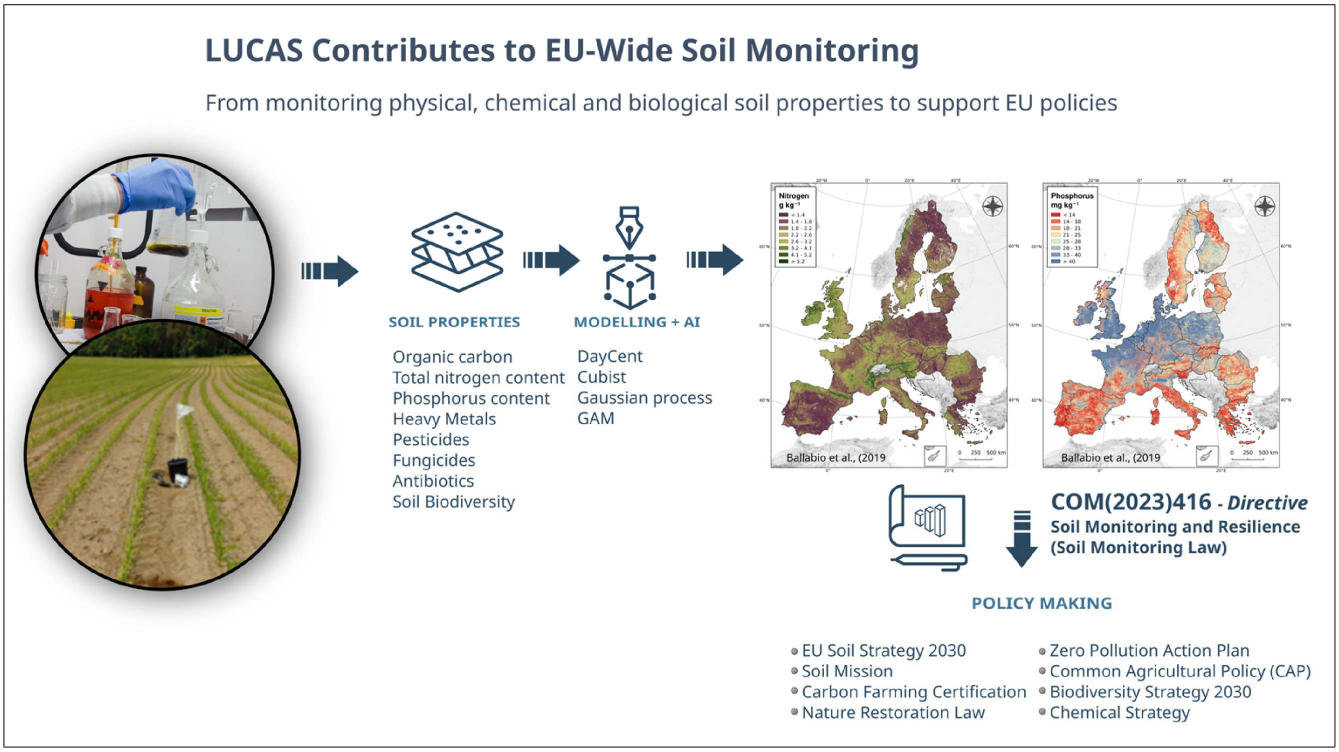

FIGURE 3 LUCAS Soil Survey—from field sampling, lab testing, dataset development, modelling (including AI) and mapping to policy making. The maps are examples of chemical properties (Ballabio et al., 2019). The figure from the laboratory is from Soils Lab of Michigan (CC BY 2.0).

sampling also addresses in situ variations as such as sampling at different soil depths (0–20 cm vs. 0–30 cm). The final objective of this intercomparison is to develop a set of pedotransfer functions (Hollis et al., 2012; Steinfurth et al., 2021; Visconti et al., 2010) for data harmonisation, but also to allow a direct comparison and valorisation of soil legacy data.

The recently presented proposal for a Soil Monitoring and Resilience Directive (European Commission, 2023b) sees monitoring as a core action for ensuring soil protection. An effective strategy for tracking soil characteristics and their temporal variations at the EU level would be required. Such a monitoring programme should be able to assess soil parameters under different land use/land cover scenarios and in response to climate change, with a focus on spatial and temporal aspects. Moreover, the sampling strategy must gather comprehensive data, not just on physico-chemical properties but also the biological component. To reach this goal, the EUSO proposed a stratified sampling method that possibly meets these requirements, while minimising the cost of sampling. The minimum sampling size is calculated by implementing the Bethel algorithm (Bethel, 1989) with subgroups divided following the methodology of Ballin and Barcaroli (2013). The efficiency of stratification is measured by the extent to which it minimises the cost of sampling while maintaining sufficient accuracy in estimating the target variables. In this context, it is important to select the independent variables that are most strongly correlated with the target variables, such as soil carbon content, pH and nitrogen content (Ballin et al., 2018; Ballin & Barcaroli, 2013). The EUSO's approach will be discussed with MS to verify its applicability and integration with national monitoring schemes.

In light of the proposal for the EU Soil Monitoring Law, the EUSO will deepen its interaction with MS to facilitate the exchange of harmonised information about the state of soils and their assimilation at EU level. The final goal of the EUSO is the creation of a European harmonised data infrastructure (digital EU Soil Health Portal) to integrate pan-European national/regional soil monitoring data as well as legislative reporting obligations.

4 | STRONGER ESDAC

The ESDAC, hosted by the JRC, has become the leading web platform for gathering and disseminating soil scientific data and knowledge in the EU. As such, the ESDAC is at the core of the EUSO by providing the scientific and data management foundation on which other activities can build (Panagos, Van Liedekerke, et al., 2022).

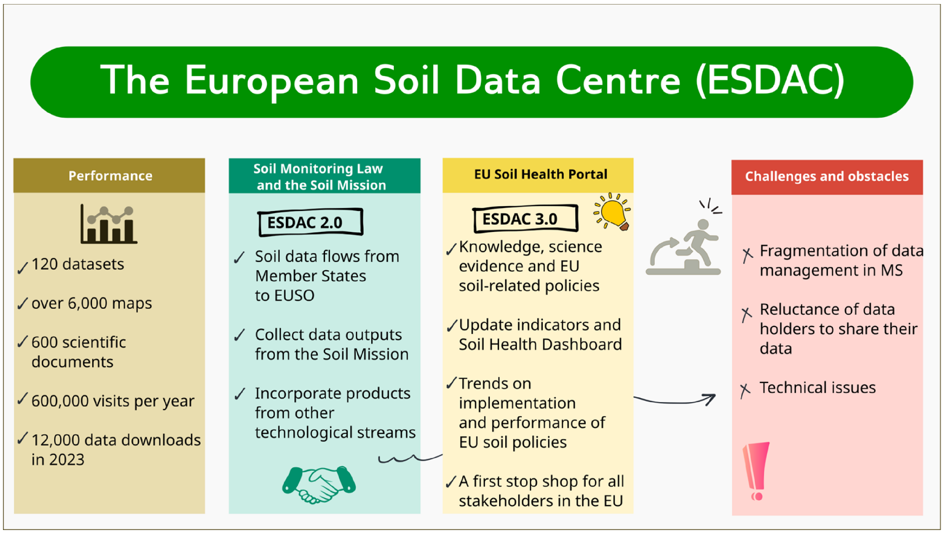

FIGURE 4 The European Soil Data Centre and evolution to the EU Soil Health Portal.

The ESDAC currently hosts 120 blocks of datasets, over 6000 maps, 600 scientific documents (including 400 scientific publications), 7 atlases and a wide range of soil-related material (Figure 4). In 2023, the ESDAC grew substantially as 17 new datasets were added, all accompanied by scientific publications.

In terms of data usage and visits, the ESDAC distributed 11,675 datasets during 2023, which is 18% higher than in 2022 and 150% higher than 2018. A total of 62% of these distributed datasets were downloaded in an EU country and 38% in a non-EU country. The ESDAC is one of the most visited sites within the JRC domain with 200,000 visitors annually, 600,000 page views and 140,000 document downloads in 2023 (Figure 4).

The integrated soil monitoring system envisaged in the Soil Monitoring Law and the Soil Mission should be supported by a modern data management platform of soil information across the EU. This EU Soil Health Portal is foreseen as the evolution of ESDAC 2.0 and would (a) include soil data flows from MS to the EUSO; (b) co-ordinate and collect data outputs from the Soil Mission projects and other HORIZON projects; and (c) incorporate products from technologically innovative streams such as COPERNICUS, drones, citizen science and sensors for precision agriculture (Figure 4).

As such, the EU Soil Health Portal (ESDAC 3.0) would then serve as an advanced soil digital platform, to (a) provide knowledge and science evidence to underpin EU soil-related policies; (b) update indicators on soil health in the EU and update the EUSO Soil Health Dashboard; (c) keep track of EU soil-related policies by providing trends on implementation and performance; and (d) become the single-stop shop for soil-related data and knowledge for all stakeholders in the EU (e.g., land managers, farmers, agri-businesses, industrial sector, teachers, policymakers, NGOs, etc.). Consequently, the EU Soil Health Portal (ESDAC 3.0) would contribute to better soil governance in the EU, propose a new data governance model (digital transformation), integrate with national data platforms and safeguard soil health in the EU.

However, this digital transformation of soil data governance faces huge challenges and obstacles. First, soil-related data and data management in the MS are currently fragmented, with various institutions, agencies and research organisations involved. Second, data holders, researchers, farmers and other actors are currently reluctant to share their data. Third, technical issues related to format, scale, protocols, intellectual properties, quality assurance and lack of documentation also form an important obstacle to data integration (Figure 4). These challenges and obstacles will be addressed in the evolution towards ESDAC 3.0.

5 | MONITORING SOIL HEALTH AND SUPPORTING POLICIES

The Soil Monitoring Law aims to provide a legal framework to help achieve healthy soils by 2050, putting in place a solid and coherent monitoring framework for all soils. Therefore, MS can take measures to regenerate degraded soils (European Commission, 2023b). This ambitious goal will be achieved by making sustainable soil management the norm in the EU. The Law targets soil health for all soils and provides the means for the systematic monitoring and identification of areas under higher degradation state, which are no longer able to provide the full range of soil ecosystems services.

The EUSO contributed intensively to the design and drafting of the proposed Soil Monitoring and Resilience Directive, which was adopted by the Commission in July 2023. In particular, the EUSO was central to defining the need for action on soil by demonstrating the extent of soil degradation (60%–70% of EU soils are affected by issues such as erosion, loss of soil organic matter, salinisation, contamination, compaction, sealing, as well as loss of soil biodiversity). The EUSO contributed to the impact assessment (European Commission, 2023a), with the revision of various versions and also through the provision of a series of soil health statistics and maps at different scales (regional, MS and EU). The monitoring component of the Law is inspired by the LUCAS Soil module, where a revised version is proposed as a contribution by the EC to reduce the burden on MS by collecting approximately 20% of samples targeted by the Law. In addition, the EUSO supports the discussion of the proposal for a Soil Monitoring Law in the European Parliament's Committees and in the European Council (led by the Spanish and Belgian presidency).

The EUSO Soil Health Dashboard supported the importance for a Soil Monitoring Law, by demonstrating the need for soil protection and restoration actions at the EU level. As such, the dashboard forms a key component of the EUSO and has a major contribution for soil literacy. The EUSO Soil Health Dashboard provides a spatial assessment of where unhealthy soils may be located in the EU and which degradation processes affect them. The dashboard uses a convergence of evidence methodology, which spatially combines datasets to highlight the intensity and location of 19 soil degradation processes (Figure 5). The resulting map shows, for the first time, where current scientific evidence converges to indicate areas that are likely to be affected by soil degradation. Although the dashboard is subject to a degree of uncertainties and underlying assumptions, it provides for the first time a comprehensive and easy understandable overview of soil health in the EU, which can be used to demonstrate progress towards the vision of the EU Soil Strategy.

The EUSO Soil Health Dashboard consists of five key features (Figure 5):

- The convergence of evidence map shows in which areas scientific evidence converges to indicate areas that are likely to be affected by soil degradation processes.
- The speedometer indicates the proportion of land likely to be affected by one or more soil degradation processes or by soil sealing in the EU. It is based on the convergence of evidence map.
- The dependency wheel shows the extent of the overlapping area between pairs of soil degradation processes of the convergence of evidence map.
- The intensity of concurrent soil degradation processes and analysis per land cover (agriculture, forest, grassland, etc.).

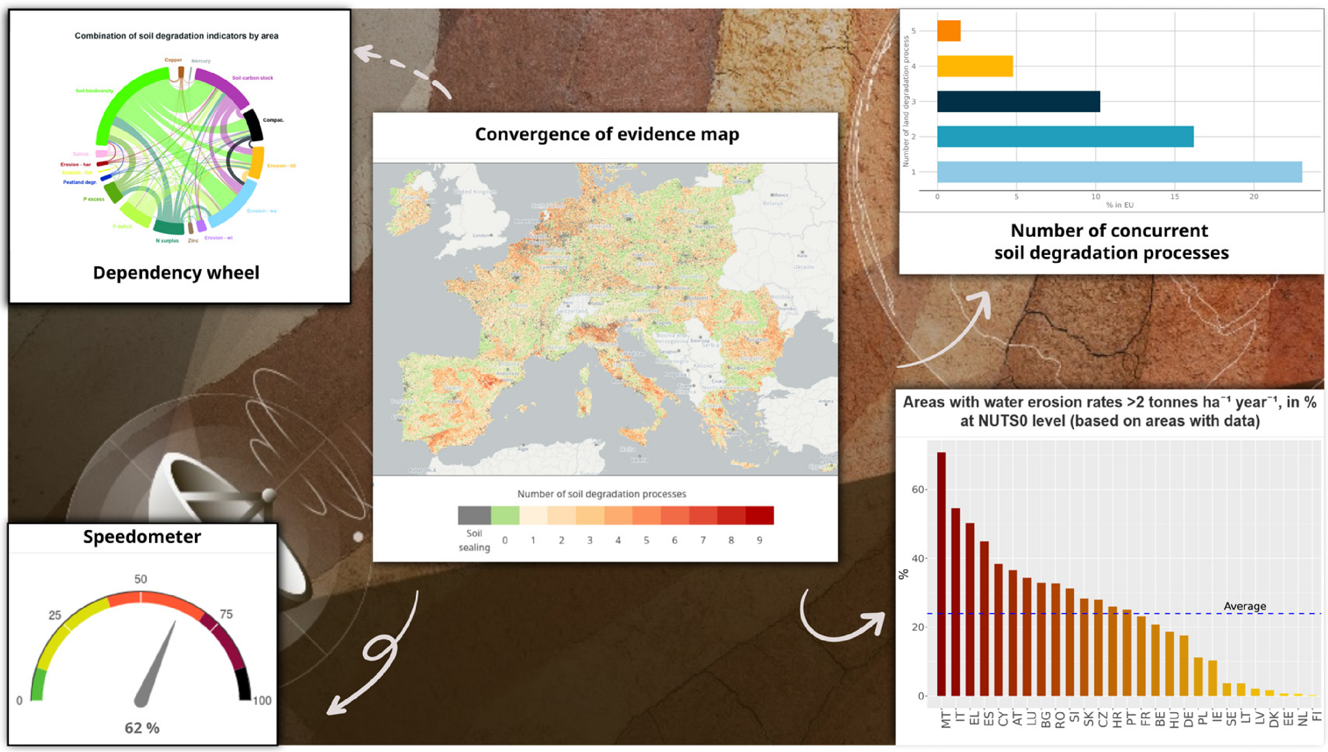

FIGURE 5 The EUSO Soil Health Dashboard key functionalities.

- The soil degradation indicators statistics as each individual soil degradation process is presented through an interactive display where users can select the process and the scale. Statistics and maps are available at national (NUTS 0) and regional level (NUTS 2).

In addition to the Soil Monitoring Law, the EUSO also contributes to a number of EU policies within the Green Deal. In the Zero Pollution Action Plan, the EC aims to address pollution and adverse impact on human health and the environment. As a relevant objective in this Action Plan, the EC intends to improve soil quality by reducing nutrient losses and chemical pesticides' use by 50%. The EUSO has contributed with spatial explicit assessments in the first Soil Pollution Monitoring and Outlook Communication (European Commission, JRC, 2022) and has run various scenarios for nutrient losses (Grizzetti et al., 2022).

The EU's objective to become the first climate-neutral continent by 2050 is targeted through the Climate Law. Soils are an important part of this objective as there are plans to reduce CO_2 emissions from agriculture, preserve wetlands and restore drained peatlands. The EC adopted a proposal for the first EU-wide voluntary framework to reliably certify high-quality carbon removals. In the Carbon Removal Certification framework, the EUSO proposed practices to enhance SOC stocks (e.g., through crop rotation or reduced tillage; Lugato et al., 2014) and attempted to establish baselines of carbon stocks in EU agricultural topsoils (De Rosa et al., 2024).

The Nature Restoration Law aims to restore degraded peatlands and levels of SOC content in areas of cropland mineral soils. The EUSO contributed with baselines on SOC and areas where SOC losses have been evident in agricultural soils (De Rosa et al., 2024). In addition, the EUSO provided evidence of the impacts of multiple farming practices that can contribute to nature restoration and improvement of soil quality (Liquete et al., 2022).

The Biodiversity Strategy 2030 is a comprehensive, ambitious and long-term plan to protect nature and reverse the degradation of ecosystems including soils. Particular focus is given in increasing EU-protected areas at a minimum of 30%, reinforcing the application of landscape features (grass margins, buffer strips, terraces) in agricultural areas and reducing soil erosion and land take. As soil is a critical habitat, data and knowledge on soil biodiversity support this strategy.

The Common Agricultural Policy (CAP) 2023–2027 is giving emphasis to environmental performance and climate resilience. The CAP objectives include, among others, the sustainable management of natural resources and climate action, with a focus on greenhouse gas emissions, biodiversity, soil and water. The performance monitoring and evaluation framework (PMEF) of the CAP uses a set of performance indicators shifting the policy focus from compliance to results. The EUSO contributed by providing evidence and performance indicators on soil erosion and SOC for the CAP PMEF.

Recently, the EUSO has provided scientific evidence in relation to the heavy metal content of sewage sludge application rates per country (Sewage Sludge Directive). In total, 36% of LUCAS samples (2009 survey) in agricultural soils exceeded the strictest limit values of heavy metal content (Yunta et al., 2024). In the same context, the EUSO has assessed the cadmium content in EU topsoils (Ballabio et al., 2024) that contributes to evaluation of the impact of recent EU regulations regarding the cadmium content in phosphate fertilisers (Fertilizer Regulation).

To further enhance the awareness of the interplay between soils and production and consumption patterns, the EUSO will host information and indicators on how current and future patterns affect soils. This will build from a set of life cycle assessment-based indicators that the EC is already using in a number of official monitoring systems to link the use of natural resources throughout the economy and the related environmental impacts. The consumption footprint platform (European Commission, 2024) currently assesses the use of soils and land in five areas of consumption (food, housing, mobility, household goods and appliances) and estimates the environmental impacts of those areas of consumption in terms of changes in SOC, buffering capacity of the soils towards acidification and eutrophication, ecotoxicity, and so forth. This set of indicators considers both domestic (those happening in EU soils) and the embodied impacts (those happening in third countries as a consequence of production and consumption in Europe).

6 | SUPPORTING SOIL RESEARCH AND INNOVATION

The EUSO contributes directly to the advancement of scientific knowledge on soils in the EU through its in-house research activities. In 2023, the scientists working in the EUSO published 46 papers in Scopus-indexed journals and numerous technical reports. Most of the publications are in high-impact journals and are relevant to indicators and datasets hosted in the EUSO. This research activity contributes to the 400 publications produced by the soil group of the JRC during the last 12 years. Moreover, the EUSO hosted and mentored six PhD candidates in 2020–2023 in the context of the Collaborative Doctoral Partnership (CDP). The CDP is an initiative of the JRC to establish strategic collaborations with higher education institutions (universities) that grant doctoral degrees (Panagos &

Orgiazzi, 2023). The CDP is characterised by research excellence and high international reputation.

Furthermore, the EUSO is responsible for the soil monitoring elements of the Horizon Europe Mission 'A Soil Deal for Europe' (Soil Mission, 2021). The Soil Mission is providing funding of nearly 1 billion Euro over the period 2022–2030 to soil-relevant HORIZON Europe projects and 100 Living Labs (Panagos, Borrelli, et al., 2024). The Soil Mission has already funded 29 projects for €162 million in 2021–2022, 2 projects of €30 million with other missions, 19 projects for €139 million in 2023 and allocated €135 million for 2024 HORIZON Europe calls. The EUSO contributes to the Mission's annual work programme by identifying gaps and proposing innovative subjects for research. The EUSO is also a beneficiary of the outcomes of the research activities (data, knowledge) of the Soil Mission projects. In this respect, the EUSO works in close collaboration with several of the Mission Soil projects to ensure that their deliverables can directly support the policy process. The EUSO is also proposing new methodologies for better monitoring of soils such as spectroscopy and artificial intelligence algorithms. In 2023, several collaborations and interactions between the EUSO and projects of the Soil Mission were started.

The EUSO is also the interface between the Soil Mission projects and the various Directorate Generals (DGs) of the EC who address policy needs, questions and knowledge gaps to the soil research community. The Soil Mission has set up eight objectives (full list in the Annex S1; Figure 6). These objectives are associated with eight groups of indicators that have the broad agreement and application throughout the soils community (Figure 6; Bünemann et al., 2018).

In addition, the Soil Monitoring Law has defined 12 descriptors, which include indicators addressing the soil degradation processes (Annex S2). Those 12 descriptors are in line with the eight indicators in the Soil Mission implementation plan (Figure 6). The EUSO steers and coordinates the development of indicators at EU scale, which will serve both the Soil Mission Objectives and the Soil Monitoring Law.

7 | STAKEHOLDER ENGAGEMENT AND EUSO FORUM

The EUSO Stakeholder Forum, organised annually by the EUSO, is an open and inclusive event providing an opportunity to engage with the European and global soil community. The Stakeholder Forum brings together soil scientists, policymakers, regional and national bodies and interested citizens. It aims to support citizen engagement and drive towards a societal change in the perception of soil. The third edition of the EUSO Stakeholders Forum took place in two parts, with the Working Group

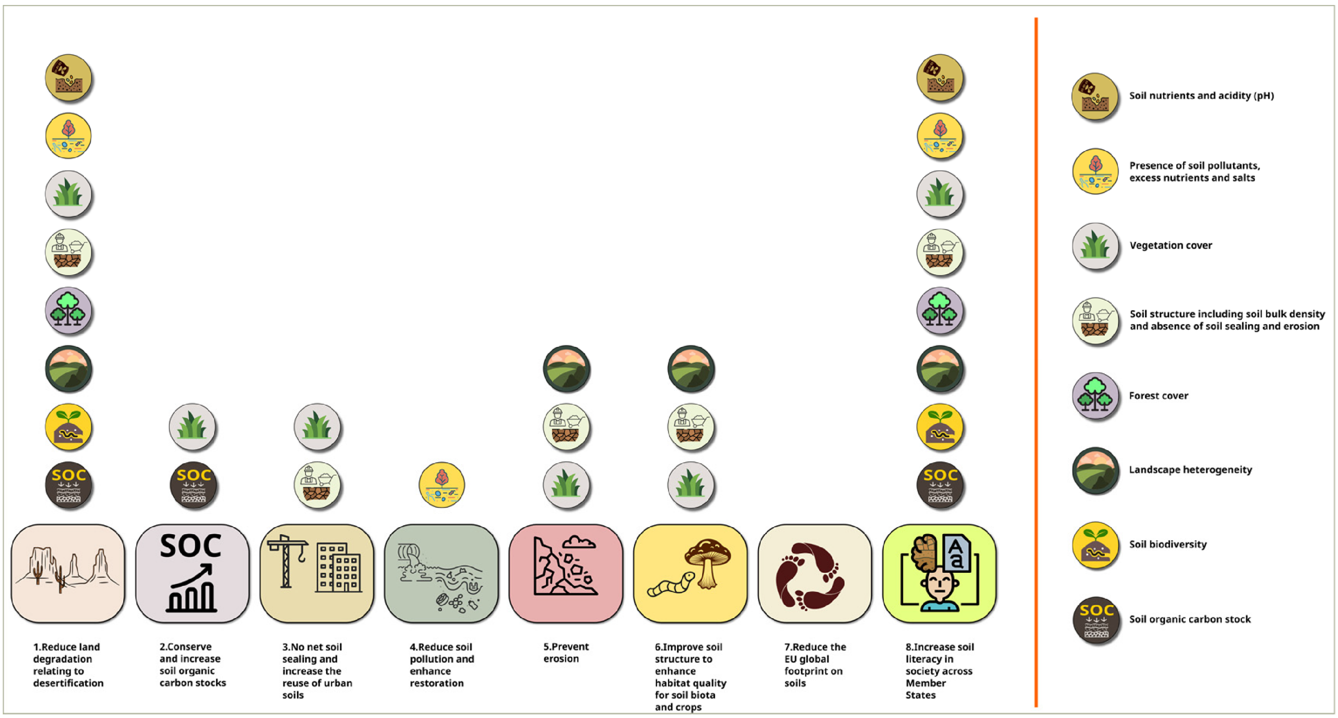

FIGURE 6 The objectives (bottom) and indicators (right) of the Soil Mission.

FIGURE 7 Examples of the EUSO activities to raise soil awareness and citizen engagement.

(WG) meetings on 15–17 November 2023 (online) and the European Mission Soil Week on 21–23 November 2023 (in-person) in Madrid, Spain.

Each edition of the Stakeholder Forum has raised the interest of 900–1000 attendees each. The Stakeholder Forum is organised around WGs, which are a key element of the EUSO involving stakeholders. The WGs are composed of relevant topical experts from academia, businesses or policy and are co-chaired by EUSO staff and external partners. Each WG develops its own work agenda, aiming to provide relevant advances to current scientific and policy questions. In 2023, six WGs were active: (1) data sharing and integration, (2) soil erosion, (3) soil biodiversity, (4) SOC monitoring reporting and verification, (5) soil monitoring and (6) soil pollution.

The EUSO also drives many activities to raise soil awareness and citizen engagement (Figure 7). One successful example of awareness raising is the publication of the soil atlases (covering Europe, Asia, Africa, Latin America and Caribbean, Biodiversity and Circumpolar). These atlases have a high impact as they are written in an easily understandable language and come with many illustrations. In addition, the ESDAC monthly newsletter (with 160 releases in 14 years) is distributed monthly to 13,000 followers and includes the top five EUSO news. Furthermore, the co-development of a citizen science database, the participation in awareness-raising events (e.g., EU Green week, ECOMONDO, EGU, REMTECH) and the organisation of summer schools and courses are also among the most impactful activities for public dissemination. The EUSO has also organised the first edition of the Young Soil Researchers Forum with 100 abstracts and 58 presentations in 2021 (Panagos & Orgiazzi, 2023). As a final example, the EUSO has also contributed to a broad acceptance of the Mission Soil Manifesto by different stakeholders.

The above-mentioned activities of the EUSO are important to raise awareness and citizen engagement related to soils. Until the establishment of EUSO, the involvement of stakeholders to soil-related policy development was limited. However, successful policy development should include all actors (stakeholders, farmers, private sector, landowners, agri-business, etc.). The mobilisation of citizens towards a soil health approach should raise awareness about the importance of soils in food security (95% of food comes from soils) (Lal, 2009), climate change (soils can contribute to climate mitigation; Minasny et al., 2017), fight against pollution (role of waste management, overconsumption and intensive agriculture; Zwolak et al., 2019) and well-being (changing of diets, organic, improvement of agri-food; Brevik & Sauer, 2015). Such a mobilisation process needs a paradigm shift from the current consumption model to a more sustainable one with important behaviour changes. The EUSO, with various actions of stakeholder engagement and awareness raising, aims to mobilise these different actors (Figure 7). In particular, the EUSO engages the young researchers who can find more space in various working groups (Panagos & Orgiazzi, 2023).

The 100 Living Labs as foreseen in the Soil Mission would be among the mechanisms to involve actively those stakeholders, improve soil health and have an important societal and economic impact in local societies (Ceseracciu et al., 2023). The EUSO will be involved in this transition and longevity of Living Labs. In addition, it would be important to evolve the current business model financed by the Soil Mission to a more active participation of the private sector. Interest in this process has been identified by philanthropic organisations in relation to investments and funding in the longevity of Living Labs, carbon farming, soils in Africa and nutrient management.

8 | EUSO ASSESSMENTS ON HEALTHY SOILS

Soil degradation processes lead to the physical, chemical and biological decline in soil quality. Recent EU policy documents (i.e., Soil Mission implementation plan and Soil Monitoring Law) identified a set of major soil degradation processes including, among others, soil erosion, loss of SOC, nutrient losses, soil biodiversity decline, salinisation, soil compaction, soil contamination and soil sealing.

Within its interdisciplinary research activities, the EUSO has developed the Soil Health Dashboard that provides the first comprehensive pan-EU assessment of soil degradation based on the latest state-of-the-art indicators of soil degradation (Table 1). Those indicators have broad agreement and application throughout the soil community (Bünemann et al., 2018) and have been proposed by research framework projects (Stolte et al., 2015). Even if pioneering, and still lacking an optimal level of data

TABLE 1 Soil degradation processes, indicators, threshold and data sources are currently used in the development of the EUSO Health Dashboard.

Soil degradation	Indicator	Threshold used	Data used (reference)
Soil erosion	Water erosion	Erosion rate >2 tonnes ha^{-1} year^{-1}	Panagos et al. (2020)
	Wind erosion	Erosion rate >2 tonnes ha^{-1} year^{-1}	Borrelli et al. (2017)
	Tillage erosion	Erosion rate >2 tonnes ha^{-1} year^{-1}	Borrelli et al. (2023)
	Harvest erosion	Erosion rate >2 tonnes ha^{-1} year^{-1}	Panagos et al. (2019)
	Post-fire recovery	Recovery rate <1	Vieira et al. (2023)
Soil pollution	Copper excess	Cu concentration >100 mg kg^{-1}	Ballabio et al. (2018)
	Mercury excess	Hg concentration >0.5 mg kg^{-1}	Ballabio et al. (2021)
	Zinc excess	Zn concentration >100 mg kg^{-1}	Van Eynde et al. (2023)
	Cadmium excess	Cd concentration >1 mg kg^{-1}	Ballabio et al. (2024)
	Arsenic excess	Probability of high As (>45 mg kg^{-1}) >5%	Fendrich et al. (2024)
Soil nutrients	Nitrogen surplus	Agricultural areas where N surplus >50 kg ha^{-1}	Grizzetti et al. (2022); Lugato et al. (2018)
	Phosphorus deficiency	P deficiency <20 mg kg^{-1}	Ballabio et al. (2019)
	Phosphorus excess	P excess >50 mg kg^{-1}	Ballabio et al. (2019)
Loss of soil organic carbon	Distance to maximum SOC level	Distance from 'maximum' SOC >60%	De Rosa et al. (2024)
Loss of soil biodiversity	Potential threat to biological functions	≥Moderately high level of risk	Orgiazzi et al. (2016)
Soil compaction	Soil packing density	High packing density (>1.75 g cm^{-3})	Panagos, De Rosa, et al. (2024)
Salinisation	Secondary salinisation	Areas in Mediterranean biogeographical region where >30% is equipped for irrigation	Siebert et al. (2010)
Loss of organic soils	Peatland degradation	Peatlands under hotspots of cropland	UNEP (2022)
Soil sealing	Built-up areas	No threshold applied (all built-up areas)	Copernicus (2018)

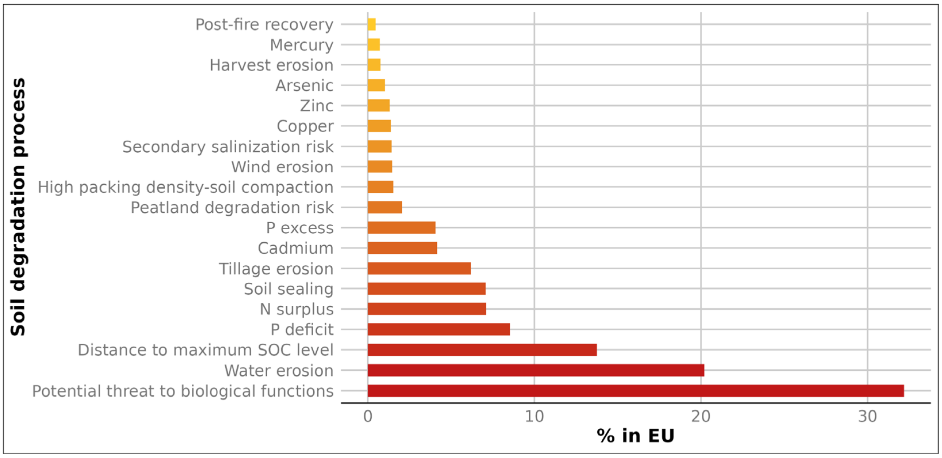

FIGURE 8 Percentage (%) of unhealthy soils in the EU, by soil degradation process (*Source*: EU Soil Health Dashboard).

harmonisation, the preliminary information on soil degradation provided by the EUSO Soil Health Dashboard represents a key first step towards comprehensive mapping of soil degradation in the EU based on a large number of indicators ($n = 19$; Figure 8). Below, an overview of those assessments is illustrated (as also in Annex S3).

Soil erosion by water is found to be one of the most prominent soil degradation processes in the EU, with an estimated 24% of EU land exhibiting unsustainable rates (>2 t ha^{-1} year^{-1}) exceeding soil formation rates (Panagos et al., 2020). Soil formation rates found in the literature vary quite significantly as early studies report rates of 0.05–0.5 mm per year (1 t ha^{-1} year^{-1}) or 1.4 t ha^{-1} year^{-1} (Verheijen et al., 2009). Based on existing soil formation data and measured soil erosion rates of 10,000 plot years from 255 sites, it is estimated that 16% of conventionally managed soils exhibit lifespans of <100 years (Evans et al., 2020).

Wind erosion primarily occurs in dry conditions when the soil is exposed to wind and the finest particles, particularly organic matter, clay and loam, are removed and potentially transported over long distances before being redeposited (Webb et al., 2006). To gain a better understanding of the wind erosion situation in Europe, a working group at the JRC carried out one of the first continental-scale quantitative estimates of wind erosion. The results of our modelling exercise suggested that wind erosion in croplands may have a mean rate of 0.53 t ha^{-1} year^{-1}, with the first and third quantiles at 0.3 and 1.9 t ha^{-1} year^{-1}, respectively (Borrelli et al., 2017).

Tillage erosion occurs in cultivated fields due to tillage operations that result in a downhill displacement of soil. Soil erosion due to tillage has been modelled at pan-EU scale as a function of the erosivity of tillage operations and the erodibility of the cultivated landscape. The resulting estimates indicate that 17% of EU arable land may suffer from high soil displacement due to tillage activities (Borrelli et al., 2023).

During the harvest of root and tuber crops, the soil often sticks to the crop and ends up being moved away from the field (or it is displaced from the plot) together with stable soil clods and rock fragments (Ruysschaert et al., 2004). This phenomenon is generally named as soil loss by crop harvesting (SLCH). Several factors affect the magnitude of SLCH, such as the soil moisture, soil texture, soil organic matter and soil structure, the crop type, the agronomic practices (e.g., plant density, crop yield) and the harvest techniques (technology, effectiveness and velocity of harvester) (Ruysschaert et al., 2004). During the period 2000–2016, SLCH associated with sugar beets and potatoes in the EU is estimated to be around 0.13 t ha^{-1} year^{-1}, equal to a total of 14.7 million of tons of soil lost per year (Panagos et al., 2019).

Considering non-agricultural lands, it is estimated that a rather low average annual soil loss occurs in undisturbed forests, equal to 0.086 t ha^{-1} year^{-1} (Borrelli et al., 2016). More than 1.4 million hectares of land are impacted by wildfires every year in the EU and UK (EFFIS, 2022), and such events greatly impact topsoil physical and chemical characteristics. Burned soils are considered sensitive areas because of their increased on-site risk for runoff and erosion, but also off-site risks for flooding, debris flows and landslides. The recent study of Vieira et al. (2023) suggests that in the first post-fire year, the average erosion rate may rise by as much as 33.5 ± 10.3 t ha^{-1} year^{-1}, showing a remarkable increase. The prediction of post-fire soil erosion rates obtained by Vieira et al. (2023) led to the development of a post-fire soil recovery indicator (RCOVER), which is based on the ground cover recovery rate. This indicator identifies a soil surface area in which vegetation cover is still below (i.e., not recovered) the pre-fire conditions from the latest wildfire, for all EU burned areas since 2017.

The depletion of SOC in agricultural lands poses a significant threat, manifesting as reduced fertility, disrupted water and nutrient cycles and diminished biodiversity in soils. Alarmingly, an analysis covering the EU and UK from 2009 to 2018 revealed a net SOC reduction of 0.75% relative to the 2009 SOC content in cropland and grassland (De Rosa et al., 2024), highlighting the urgency of this issue. The accurate measurement of existing SOC levels and the identification of factors affecting its variability are pivotal for crafting policies that enhance the resilience of EU farming systems. In response, the EU has amplified the importance of land management and forestry within its climate strategy, targeting enhanced carbon sequestration in soils, particularly through agricultural practices, as delineated in the EU Soil Strategy 2030 (McGrath et al., 2023). Boosting SOC not only aids in climate change mitigation but also elevates soil health, reduces erosion and bolsters crop yield and adaptability, offering notable advantages during droughts (Oldfield et al., 2019; Paustian et al., 2019). Topsoil SOC content is influenced by a myriad of environmental elements, resulting in unique variances tied to the specific makeup of land coverage and intrinsic factors like the type of soil and climatic conditions, which often fall outside the scope of direct management. Therefore, proposing an unbiased SOC metric that works for all soils in the EU and different climate conditions is a challenge (Drexler et al., 2022; Feeney et al., 2023; Poeplau & Don, 2023). The EUSO dashboard proposed a layer which shows the distance between the current level of SOC and a 'maximum' level of SOC content achievable in the medium–long term in EU croplands and grasslands, employing a data driven modelling approach. For each pixel, the 'maximum' SOC value is determined by the potential gain in SOC if the area remained as permanent grassland for 40 years, without being tilled. In this analysis, soils are labelled as unhealthy when their SOC content is more than 60% below this ideal maximum. Conversely, soils are considered healthy when their SOC levels are within 60% of this peak value. This pivotal 60% threshold was derived from analysing the gap between the highest (75th percentile) and lowest (25th percentile) SOC measurements from the LUCAS Soil survey, which were clustered beforehand based on environmental and soil edaphic factors. This analysis is subject to a certain level of uncertainty, stemming from the training dataset and the variables employed to upscale the model. Consequently, the results should be considered as a rough estimate of the current status of SOC stocks across the EU and UK. With the incorporation of additional data and the enhancement of spatial layer information, it is anticipated that this uncertainty could be mitigated.

Biodiversity supports the multi-functionality of soils, underpinning the delivery of several ecosystem services (e.g., food provision and climate regulation). Many anthropogenic factors affect soil organisms and their functions (Rillig et al., 2019). In this context, soil biodiversity is estimated to be at risk in 56% of the EU soils (Orgiazzi et al., 2016). Such an assessment took into account 13 potential threats to soil organisms (e.g., intensive exploitation and soil pollution) that were assessed and ranked by expert knowledge. Subsequently, a spatial proxy was assigned to each of the pressures in order to map the distribution of risk across EU countries. Finally, the analysis was used to generate a first indicator of healthy soils in relation to biological elements (i.e., soils with low risk to soil life are classified as healthy). Over the last few years, thanks to the LUCAS Soil Biodiversity component (2018), the first assessment of drivers of soil organism distribution in EU was carried out (Köninger et al., 2023; Labouyrie et al., 2023). Through the analysis of the largest European soil DNA dataset (i.e., 881 sample locations), edaphic, climatic and land cover factors were explored for their capability to shape richness, diversity and structure of soil-living assemblages. Currently, maps of the richness and diversity of soil microorganisms and associated functional groups (e.g., bacterial pathogens and fungal saprotrophs) are under development. Once ready, those indicators may be used for refining soil health evaluation in relation to biodiversity, for instance, by considering the distribution of organisms known to be beneficial to plant growth (e.g., N-fixing bacteria and symbiotic fungi).

In relation to soil contamination, the EUSO has advanced with the spatial assessments of copper, mercury, zinc, cadmium and arsenic. High copper concentrations have been noted in vineyards and olive groves (Ballabio et al., 2018). About 1.1% of soil samples were found to have higher copper concentrations than the indicated threshold of 100 mg kg^{-1} (Figure 8). High mercury concentrations have been found close to gold mining, coal power plants, chlor-alkali plants and small-scale industries employing mercury (Ballabio et al., 2021). Less than 1% of the samples have been found to have higher mercury concentrations than the indicated threshold of 0.5 mg mg kg^{-1}. Elevated zinc (Zn) concentrations have been found close to deposits and mining activities. Samples within 10 km from these sites had the highest Zn concentrations above 167 mg kg^{-1}, representing only 1% of all LUCAS Soil samples (Van Eynde et al., 2023). The relatively higher Zn concentrations found in grasslands may suggest manure as an important Zn source in these soils. Topsoil Zn concentrations were also lower in coarse-textured soils and in soils with low (below 4.5) and high (above 8) pH. Significant sources of natural cadmium are rock weathering, volcanic emissions and wildfire ash. Cadmium content in EU agricultural soils is of concern due to intense fertilisation and high cadmium content of certain fertilisers (Ballabio et al., 2024). Around 5% of the LUCAS samples have Cd concentrations higher than the threshold of 1 mg kg^{-1} (Figure 8). Recently, a high resolution assessment of arsenic in topsoils (Fendrich et al., 2024) was included in the dashboard. Higher As concentrations are associated with warmer, higher areas with clayey and phosphorus-rich soils. Other sources of diffuse contamination caused by pesticides (Silva et al., 2019), microplastics (Hurley & Nizzetto, 2018), veterinary and pharmaceutical products (Gros et al., 2019) and other heavy metals can be included when spatial explicit assessments will become available.

Phosphorus (P) is an essential nutrient for plant growth as it plays a key role in energy transfer and many other biological processes (Marschner, 2011). Phosphorus excess takes place when phosphorus inputs to soils (e.g., from inorganic fertilisers or manure) exceed crop demands, thereby building up P concentrations in soils with a risk of losses to the environment (Sattari et al., 2012). Phosphorus deficiency takes place when phosphorus availability in soils may be too low to sustain crop requirements and needs to be replenished by P inputs (Steinfurth et al., 2022). Various soil tests exist across the EU to define P deficiency and excess, also with large variation in threshold values (Jordan-Meille et al., 2012; Steinfurth et al., 2022). Based on LUCAS topsoil data and a regression model, the EUSO made available the distribution of phosphorus concentrations in agricultural land in the EU measured in an Olsen soil extraction (Ballabio et al., 2019). The layer presented in the EU Soil Health Dashboard shows agricultural land areas with a risk of P deficiency (<20 mg kg^{-1}) and P excess (>50 mg kg^{-1}), and the thresholds were chosen as the average thresholds reported for EU MS using Olsen extraction by Jordan-Meille et al. (2012).

Nitrogen (N) is the element after carbon that is required in the largest amounts by plants. It is an integral constituent of proteins and other metabolites (Marschner, 2012). Given its critical role for plant production, N inputs such as nitrogen-containing fertilisers and organic inputs are extensively used in agriculture worldwide. However, excessive and inefficient nitrogen application is a major source of soil pollution, with consequences also for air, water quality and public health, while it contributes to greenhouse gas emissions. Nitrogen surplus occurs where nitrogen inputs (e.g., fertiliser and manure application, bacterial N fixation and atmospheric deposition) exceed outputs (e.g., uptake by plants and harvest). Using agricultural data and a European biogeochemical model framework, this layer shows areas of agricultural land in EU subject to nitrogen surplus (N input – N output). The layer presented in the EU Soil Health Dashboard shows agricultural areas where nitrogen surplus exceeds 50 kg ha^{-1} year^{-1} (Grizzetti et al., 2022) above which it can be considered that N losses to the environment are unacceptably high (Grizzetti et al., 2022; Quemada et al., 2020).

Soils are sealed by their covering with an impermeable material, buildings, constructions, roads, and so forth. It is one of the main causes of soil degradation in the EU as it is an irreversible process causing a loss of soil functions. According to the Impervious Built-up data layer of the EEA (Copernicus, 2018), 7% of the EU lands are sealed.

Peatlands degradation, soil compaction and soil salinisation have been included in the dashboard but better refinement of the data is needed. Peatlands degradation is accelerated through climate change, peat extraction, drainage, burning and land-use modification (Swindles et al., 2019). In the EU, more than 4 million hectares of drained peatlands are managed as cropland or grassland (Tanneberger et al., 2021). The peatlands degradation layer presented in the EUSO dashboard presents peatland areas under hotspots of cropland (i.e., density of cropland occurring within a fixed radius around peatland areas); therefore, they are considered to be at risk of being degraded. Salinisation is an issue of increasing concern in irrigated lands and in coastal southern Europe where the problem is intensified by the increase of groundwater abstractions that facilitate seawater intrusions of aquifers (Daliakopoulos et al., 2016). Regarding soil compaction, an estimated 23% of EU agricultural subsoils are affected by high densities (Schjønning et al., 2015). The new assessment of bulk density and packing density have been included as proxies for soil compaction estimation (Panagos, De Rosa, et al., 2024) replacing the past expert assessments (Houšková & Montanarella, 2008).

In relation to the 4.2 million km^2 of the EU, pressures on soil biodiversity are the degradation process with the largest spatial extent, followed by soil erosion by water, and SOC losses (Figure 8). The overlay of all soil degradation processes (including the 7% soil sealing) has resulted in the estimation that 62% of soils in the EU are unhealthy. In relation to the intensity of soil degradation, 24% of EU soils are subject to one degradation process, 16% to two degradation processes, 10% to three degradation processes, 5% to four or more degraded processes and 7% are sealed (Figure 5).

9 | PLANNED DEVELOPMENTS FOR THE EUSO

The EUSO Health Dashboard will be updated to complete the assessment of the state of soil health in the

EU. The planned updates will include adding new pan-European datasets for missing soil degradation processes (e.g., pollution due to pesticides, other heavy metals concentrations, acidification, gully erosion, maps of the richness and diversity of soil microorganisms and associated functional groups, etc.), adding information on temporal changes in soil degradation processes, and adding new functionalities to provide better user experience. The EUSO policy tracker dashboard will be a new development monitoring the impact of soil-related policies in improving the soil health in the EU. Therefore, trends in soil degradation indicators will allow to better monitor the implementation of soil-relevant policies.

The EUSO aims to enhance the EU Soil Health Dashboard by incorporating the extent/level of soil degradation, interactions of multiple soil degradation processes, refinement of thresholds and the uncertainties resulting from the variability in climate and soils across the EU. The convergence of evidence approach highlights the scale of soil degradation based on crucial thresholds, which require further fine-tuning through emerging research. Moreover, the use of thresholds should more accurately account for the pedo-climatic conditions in the EU and incorporate a range of uncertainties. Finally, the combination of indicators should result in a well-defined and tested Soil Health Index.

The EUSO has a well-defined plan, which among others include the quantification and improvement of soil health in Africa and the development of Africa-wide Soil Health Dashboard, building on the experience of the EUSO Soil Health Dashboard. Secondly, the EUSO plans the development of a comprehensive and accurate assessment of land degradation in the EU (Prăvălie et al., 2024). The EU has flagged an intention to be declared as affected by desertification under the UNCCD. This will involve utilising the current baselines of soil degradation from the EUSO Soil Health Dashboard and other biophysical indexes such as aridity, groundwater decline and vegetation degradation. These actions are in response to the recommendations of the European Court of Auditors' recommendations, highlighting the ineffective efforts of both the EC and MS in addressing the risk of desertification in the EU. In addition, the EUSO will contribute to the development of criteria for assessing the greenness of new constructions under the EU Taxonomy Regulation. Important advancements are also expected in relation to soil biodiversity with new research in drivers of antimicrobial resistance and antibiotic synthesis genes across Europe. Additionally, soil biological indicators will be proposed. In particular, the distribution of beneficial (e.g., symbiotic fungi) and detrimental (e.g., plant pathogens) soil-living organisms will be included in future upgrades of the EUSO Soil Health Dashboard. Finally, integrating soil contamination assessments (e.g., pesticides, diffuse pollution) with impacts on soil biodiversity and food security is among the future research priorities of the EUSO.

Regarding soil monitoring, the EUSO will support MS in establishing and operating national or regional monitoring systems and support them in ensuring an exchange of harmonised information about the state of soils, for their integration at the EU level. Ideally, the future EU Soil Health Portal will include data from national monitoring systems integrated with LUCAS topsoil surveys.

In relation to the evolution of ESDAC 2.0, an increased number of data flows from Soil Mission projects is foreseen within the next 6 years and operational data flows from MS within the application of Soil Monitoring Law. Finally, it is expected that new technical developments in remote sensing (e.g., Copernicus Sentinel expansion programme from the European Space Agency), spectroscopy and citizen science will contribute to new pan-European datasets on soil properties.

AUTHOR CONTRIBUTIONS

Nils Broothaerts: Conceptualization (equal); methodology (equal); visualization (equal); writing – original draft (equal); writing – review and editing (equal). **Cristiano Ballabio:** Conceptualization (equal); data curation (equal); formal analysis (equal); investigation (equal); supervision (equal); visualization (equal); writing – original draft (equal). **Alberto Orgiazzi:** Methodology (equal); resources (equal); validation (equal); visualization (equal); writing – original draft (equal); writing – review and editing (equal). **Daniele De Rosa:** Data curation (equal); investigation (equal); methodology (equal); writing – original draft (equal). **Pasquale Borrelli:** Data curation (equal); formal analysis (equal); methodology (equal); writing – original draft (equal). **Leonidas Liakos:** Data curation (equal); formal analysis (equal); resources (equal); software (equal); visualization (equal). **Diana Vieira:** Methodology (equal); visualization (equal); writing – original draft (equal). **Elise Van Eynde:** Methodology (equal); validation (equal); writing – original draft (equal). **Cristina Arias Navarro:** Visualization (equal); writing – original draft (equal). **Timo Breure:** Visualization (equal); writing – original draft (equal). **Arthur Fendrich:** Investigation (equal); methodology (equal); writing – original draft (equal). **Julia Köninger:** Methodology (equal); writing – original draft (equal). **Francis Matthews:** Data curation (equal); writing – review and editing (equal). **Anna Muntwyler:** Data curation (equal); writing – original draft (equal). **Maeva Labouyrie:** Methodology (equal); writing – original draft (equal). **Juan Martin Jimenez:** Data curation (equal). **Piotr Wojda:** Resources (equal). **Felipe Yunta:** Data curation (equal); writing – review and editing (equal). **Anne Marechal:** Conceptualization (equal); methodology (equal). **Serenella Sala:** Conceptualization (equal); project administration (equal); resources (equal); writing – review and editing (equal). **Arwyn Jones:** Methodology (equal); project administration (equal); resources (equal); writing – original draft (equal); writing – review and editing (equal).

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CONFLICT OF INTEREST STATEMENT

The authors confirm that there is no conflict of interest with the networks, organisations and data centres referred to in this paper.

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REFERENCES

Ballabio, C., Jiskra, M., Osterwalder, S., Borrelli, P., Montanarella, L., & Panagos, P. (2021). A spatial assessment of mercury content in the European Union topsoil. *Science of the Total Environment*, *769*, 144755.

Ballabio, C., Jones, A., & Panagos, P. (2024). Cadmium in topsoils of the European Union–an analysis based on LUCAS topsoil database. *Science of the Total Environment*, *912*, 168710.

Ballabio, C., Lugato, E., Fernández-Ugalde, O., Orgiazzi, A., Jones, A., Borrelli, P., Montanarella, L., & Panagos, P. (2019). Mapping LUCAS topsoil chemical properties at European scale using gaussian process regression. *Geoderma*, *355*, 113912.

Ballabio, C., Panagos, P., Lugato, E., Huang, J.-H., Orgiazzi, A., Jones, A., Fernández-Ugalde, O., Borrelli, P., & Montanarella, L. (2018). Copper distribution in European topsoils: An assessment based on LUCAS soil survey. *Science of the Total Environment*, *636*, 282–298.

Ballin, M., & Barcaroli, G. (2013). Joint determination of optimal stratification and sample allocation using genetic algorithm. *Survey Methodology*, *39*, 369–393.

Ballin, M., Barcaroli, G., Masselli, M., & Scarnó, M. (2018). Redesign sample for land use/cover area frame survey (LUCAS) 2018. Eurostat: Statistical Working Papers. https://doi.org/10.1002/uog.13236

Ben Hassen, T., & El Bilali, H. (2022). Impacts of the Russia-Ukraine war on global food security: Towards more sustainable and resilient food systems? *Food*, *11*, 2301.

Bethel, J. (1989). Sample allocation in multivariate surveys. *Survey Methodology*, *15*, 47–57.

Borrelli, P., Lugato, E., Montanarella, L., & Panagos, P. (2017). 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.

Borrelli, P., Panagos, P., Alewell, C., Ballabio, C., de Oliveira Fagundes, H., Haregeweyn, N., Lugato, E., Maerker, M., Poesen, J., & Vanmaercke, M. (2023). Policy implications of multiple concurrent soil erosion processes in European farmland. *Nature Sustainability*, *6*, 103–112.

Borrelli, P., Panagos, P., Langhammer, J., Apostol, B., & Schütt, B. (2016). Assessment of the cover changes and the soil loss potential in European forestland: First approach to derive indicators to capture the ecological impacts on soil-related forest ecosystems. *Ecological Indicators*, *60*, 1208–1220.

Brevik, E. C., & Sauer, T. J. (2015). The past, present, and future of soils and human health studies. *The Soil*, *1*, 35–46.

Bünemann, E. K., Bongiorno, G., Bai, Z., Creamer, R. E., De Deyn, G., De Goede, R., Fleskens, L., Geissen, V., Kuyper, T. W., & Mäder, P. (2018). Soil quality–a critical review. *Soil Biology and Biochemistry*, *120*, 105–125.

Ceseracciu, C., Branca, G., Deriu, R., & Roggero, P. P. (2023). Using the right words or using the words right? Re-conceptualising living labs for systemic innovation in socio-ecological systems. *Journal of Rural Studies*, *104*, 103154.

Copernicus. (2018). Impervious Built-up (IBU) areas [WWW Document]. https://land.copernicus.eu/pan-european/high-resolution-layers/imperviousness/status-maps/impervious-built-up-2018

Daliakopoulos, I. N., Tsanis, I. K., Koutroulis, A., Kourgialas, N. N., Varouchakis, A. E., Karatzas, G. P., & Ritsema, C. J. (2016). The threat of soil salinity: A European scale review. *Science of the Total Environment*, *573*, 727–739.

De Rosa, D., Ballabio, C., Lugato, E., Fasiolo, M., Jones, A., & Panagos, P. (2024). Soil organic carbon stocks in European croplands and grasslands: How much have we lost in the past decade? *Global Change Biology*, *30*, e16992.

Drexler, S., Broll, G., Flessa, H., & Don, A. (2022). Benchmarking soil organic carbon to support agricultural carbon management: A German case study. *Journal of Plant Nutrition and Soil Science*, *185*(3), 427–440. https://doi.org/10.1002/jpln.202200007

Dupas, R., Delmas, M., Dorioz, J.-M., Garnier, J., Moatar, F., & Gascuel-Odoux, C. (2015). Assessing the impact of agricultural pressures on N and P loads and eutrophication risk. *Ecological Indicators*, *48*, 396–407.

EFFIS. (2022). European Forest fire information system.

European Commission. (2023a). Impact assessment for the proposal for a directive on soil monitoring and resilience (COM 2023 416 final).

European Commission. (2023b). Proposal for a directive on soil monitoring and resilience (COM 2023 416 final).

European Commission. (2024). Consumption footprint.

European Commission JRC. (2022). Zero Pollution Outlook 2022.

European Environmental Agency. (2024). Net land take in cities and commuting zones in Europe.

Evans, D. L., Quinton, J. N., Davies, J. A., Zhao, J., & Govers, G. (2020). Soil lifespans and how they can be extended by land use and management change. *Environmental Research Letters*, *15*, 0940b2.

Feeney, C. J., Robinson, D. A., Keith, A. M., Vigier, A., Bentley, L., Smith, R. P., Garbutt, A., Maskell, L. C., Norton, L., Wood, C. M., Cosby, B. J., & Emmett, B. A. (2023). Development of soil health benchmarks for managed and semi-natural landscapes. *Science of the Total Environment*, *886*, 163973. https://doi.org/10.1016/j.scitotenv.2023.163973

Fendrich, A. N., Van Eynde, E., Stasinopoulos, D. M., Rigby, R. A., Mezquita, F. Y., & Panagos, P. (2024). Modeling arsenic in European topsoils with a coupled semiparametric (GAMLSS-RF) model for censored data. *Environment International*, *185*, 108544.

Grizzetti, B., Vigiak, O., Aguilera, E., Aloe, A., Biganzoli, F., Billen, G., Caldeira, C., De, M., Egle, L., & Einarsson, R. (2022). Knowledge for Integrated Nutrient Management Action Plan (INMAP).

Gros, M., Mas-Pla, J., Boy-Roura, M., Geli, I., Domingo, F., & Petrović, M. (2019). Veterinary pharmaceuticals and antibiotics in manure and slurry and their fate in amended agricultural soils: Findings from an experimental field site (Baix Empordà, NE Catalonia). *Science of the Total Environment*, *654*, 1337–1349.

Hollis, J. M., Hannam, J., & Bellamy, P. H. (2012). Empirically-derived pedotransfer functions for predicting bulk density in European soils. *European Journal of Soil Science*, *63*, 96–109.

Houšková, B., Montanarella, L., 2008. The natural susceptibility of European soils to compaction. Threats to Soil Quality in Europe EUR 23438. 23–35.

Hurley, R. R., & Nizzetto, L. (2018). Fate and occurrence of micro (nano) plastics in soils: Knowledge gaps and possible risks. *Current Opinion in Environmental Science & Health*, *1*, 6–11.

Jordan-Meille, L., Rubæk, G. H., Ehlert, P. A. I., Genot, V., Hofman, G., Goulding, K., Recknagel, J., Provolo, G., & Barraclough, P. (2012). An overview of fertilizer-P recommendations in Europe: Soil testing, calibration and fertilizer recommendations. *Soil Use and Management*, *28*, 419–435.

Keesstra, S. D., Chenu, C., Munkholm, L. J., Cornu, S., Kuikman, P. J., Thorsøe, M. H., Besse-Lototskaya, A., & Visser, S. M. (2024). European agricultural soil management: Towards climate-smart and sustainability, knowledge needs and research approaches. *European Journal of Soil Science*, *75*, e13437.

Köninger, J., Ballabio, C., Panagos, P., Jones, A., Schmid, M. W., Orgiazzi, A., & Briones, M. J. I. (2023). Ecosystem type drives soil eukaryotic diversity and composition in Europe. *Global Change Biology*, *29*(19), 5706–5719. https://doi.org/10.1111/gcb.16871

Labouyrie, M., Ballabio, C., Romero, F., Panagos, P., Jones, A., Schmid, M. W., Mikryukov, V., Dulya, O., Tedersoo, L., Bahram, M., Lugato, E., van der Heijden, M. G. A., & Orgiazzi, A. (2023). Patterns in soil microbial diversity across Europe. *Nature Communications*, *14*(1). https://doi.org/10.1038/s41467-023-37937-4

Lal, R. (2009). Soil degradation as a reason for inadequate human nutrition. *Food Security*, *1*, 45–57.

Liquete, C., Prakash, S., & Adamo, A. (2022). Scientific evidence showing the impacts of nature restoration actions on food productivity.

Lugato, E., Bampa, F., Panagos, P., Montanarella, L., & Jones, A. (2014). Potential carbon sequestration of European arable soils estimated by modelling a comprehensive set of management practices. *Global Change Biology*, *20*(11), 3557–3567. https://doi.org/10.1111/gcb.12551

Lugato, E., Leip, A., & Jones, A. (2018). Mitigation potential of soil carbon management overestimated by neglecting N_2O emissions. *Nature Climate Change*, *8*, 219–223.

Markus, T. (2017). The alpine Convention's soil conservation protocol: A model regime? *International Yearbook of Soil Law and Policy*, *2016*, 149–164.

Marschner, H. (2011). *Marschner's mineral nutrition of higher plants*. Academic Press.

Marschner, P. (2012). *Marschner's mineral nutrition of higher plants*. Academic Press. https://doi.org/10.1016/c2009-0-63043-9

McGrath, M. J., Petrescu, A. M. R., Peylin, P., Andrew, R. M., Matthews, B., Dentener, F., Balkovič, J., Bastrikov, V., Becker, M., & Broquet, G. (2023). The consolidated European synthesis of CO2 emissions and removals for the European Union and United Kingdom: 1990-2020. *Earth System Science Data*, *15*, 4295–4370.

Minasny, B., Malone, B. P., McBratney, A. B., Angers, D. A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z.-S., Cheng, K., & Das, B. S. (2017). Soil carbon 4 per mille. *Geoderma*, *292*, 59–86.

Montanarella, L., & Panagos, P. (2021). The relevance of sustainable soil management within the European green Deal. *Land Use Policy*, *100*, 104950.

Neher, D. A., Harris, J. M., Horner, C. E., Scarborough, M. J., Badireddy, A. R., Faulkner, J. W., White, A. C., Darby, H. M., Farley, J. C., & Bishop-von Wettberg, E. J. (2022). Resilient soils for resilient farms: An integrative approach to assess, promote, and value soil health for small-and medium-size farms. *Phytobiomes Journal*, *6*, 201–206.

Nwakaire, C. M., Onn, C. C., Yap, S. P., Yuen, C. W., & Onodagu, P. D. (2020). Urban Heat Island studies with emphasis on urban pavements: A review. *Sustainable Cities and Society*, *63*, 102476.

Oldfield, E. E., Bradford, M. A., & Wood, S. A. (2019). Global meta-analysis of the relationship between soil organic matter and crop yields. *The Soil*, *5*, 15–32.

Oliver, M. A., & Gregory, P. J. (2015). Soil, food security and human health: A review. *European Journal of Soil Science*, *66*, 257–276.

Orgiazzi, A., Ballabio, C., Panagos, P., Jones, A., & Fernández-Ugalde, O. (2018). LUCAS soil, the largest expandable soil dataset for Europe: A review. *European Journal of Soil Science*, *69*, 140–153.

Orgiazzi, A., Panagos, P., Yigini, Y., Dunbar, M. B., Gardi, C., Montanarella, L., & Ballabio, C. (2016). A knowledge-based approach to estimating the magnitude and spatial patterns of potential threats to soil biodiversity. *Science of the Total Environment*, *545*, 11–20.

Panagos, P., Ballabio, C., Poesen, J., Lugato, E., Scarpa, S., Montanarella, L., & Borrelli, P. (2020). A soil erosion indicator for supporting agricultural, environmental and climate policies in the European Union. *Remote Sensing*, *12*, 1365.

Panagos, P., Borrelli, P., Jones, A., & Robinson, D. A. (2024). A 1 billion euro mission: A soil Deal for Europe. *European Journal of Soil Science*, *75*, e13466.

Panagos, P., Borrelli, P., & Poesen, J. (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.

Panagos, P., De Rosa, D., Liakos, L., Labouyrie, M., Borrelli, P., & Ballabio, C. (2024). Soil bulk density assessment in Europe. *Agriculture, Ecosystems & Environment*, *364*, 108907.

Panagos, P., Montanarella, L., Barbero, M., Schneegans, A., Aguglia, L., & Jones, A. (2022). Soil priorities in the European Union. *Geoderma Regional*, *29*, e00510.

Panagos, P., & Orgiazzi, A. (2023). Let's give a voice to young soil researchers. *European Journal of Soil Science*, *74*(6), e13441.

Panagos, P., Van Liedekerke, M., Borrelli, P., Köninger, J., Ballabio, C., Orgiazzi, A., Lugato, E., Liakos, L., Hervas, J., & Jones, A. (2022). European soil data Centre 2.0: Soil data and knowledge in support of the EU policies. *European Journal of Soil Science*, *73*, e13315.

Paustian, K., Collier, S., Baldock, J., Burgess, R., Creque, J., DeLonge, M., Dungait, J., Ellert, B., Frank, S., & Goddard, T. (2019). Quantifying carbon for agricultural soil management: From the current status toward a global soil information system. *Carbon Management*, *10*, 567–587.

Pereira, P., Bašić, F., Bogunovic, I., & Barcelo, D. (2022). Russian-Ukrainian war impacts the total environment. *Science of the Total Environment*, *837*, 155865.

Pérez, A. P., & Eugenio, N. R. (2018). *Status of local soil contamination in Europe*. Publications Office of the European Union.

Poeplau, C., & Don, A. (2023). A simple soil organic carbon level metric beyond the organic carbon-to-clay ratio. *Soil Use and Management*, *39*(3), 1057–1067. https://doi.org/10.1111/sum.12921

Prăvălie, R., Borrelli, P., Panagos, P., Ballabio, C., Lugato, E., Chappell, A., Miguez-Macho, G., Maggi, F., Peng, J., Niculiță, M., Roşca, B., Patriche, C., Dumitraşcu, M., Bandoc, G., Nita, I.-A., & Birsan, M.-V. (2024). A unifying modelling of multiple land degradation pathways in Europe. *Nature Communications*, *15*(1). https://doi.org/10.1038/s41467-024-48252-x

Prăvălie, R., Patriche, C., & Bandoc, G. (2017). Quantification of land degradation sensitivity areas in southern and central southeastern Europe. New results based on improving DISMED methodology with new climate data. *Catena*, *158*, 309–320.

Quemada, M., Lassaletta, L., Jensen, L. S., Godinot, O., Brentrup, F., Buckley, C., Foray, S., Hvid, S. K., Oenema, J., & Richards, K. G. (2020). Exploring nitrogen indicators of farm performance among farm types across several European case studies. *Agricultural Systems*, *177*, 102689.

Rillig, M. C., Ryo, M., Lehmann, A., Aguilar-Trigueros, C. A., Buchert, S., Wulf, A., Iwasaki, A., Roy, J., & Yang, G. (2019). The role of multiple global change factors in driving soil functions and microbial biodiversity. *Science*, *366*, 886–890.

Ruysschaert, G., Poesen, J., Verstraeten, G., & Govers, G. (2004). Soil loss due to crop harvesting: Significance and determining factors. *Progress in Physical Geography*, *28*, 467–501.

Sattari, S. Z., Bouwman, A. F., Giller, K. E., & van Ittersum, M. K. (2012). Residual soil phosphorus as the missing piece in the global phosphorus crisis puzzle. *Proceedings of the National Academy of Sciences*, *109*, 6348–6353.

Schjønning, P., van den Akker, J. J., Keller, T., Greve, M. H., Lamandé, M., Simojoki, A., Stettler, M., Arvidsson, J., & Breuning-Madsen, H. (2015). Driver-pressure-state-impact-response (DPSIR) analysis and risk assessment for soil compaction—A European perspective. *Advances in Agronomy*, *133*, 183–237.

Siebert, S., Burke, J., Faures, J.-M., Frenken, K., Hoogeveen, J., Döll, P., & Portmann, F. T. (2010). Groundwater use for irrigation–a global inventory. *Hydrology and Earth System Sciences*, *14*, 1863–1880.

Silva, V., Mol, H. G., Zomer, P., Tienstra, M., Ritsema, C. J., & Geissen, V. (2019). Pesticide residues in European agricultural soils–a hidden reality unfolded. *Science of the Total Environment*, *653*, 1532–1545.

Smiraglia, D., Ceccarelli, T., Bajocco, S., Salvati, L., & Perini, L. (2016). Linking trajectories of land change, land degradation processes and ecosystem services. *Environmental Research*, *147*, 590–600.

Soil Mission. (2021). EU mission: A soil Deal for Europe - Soil mission.

Steinfurth, K., Börjesson, G., Denoroy, P., Eichler-Löbermann, B., Gans, W., Heyn, J., Hirte, J., Huyghebaert, B., Jouany, C., & Koch, D. (2022). Thresholds of target phosphorus fertility classes in European fertilizer recommendations in relation to critical soil test phosphorus values derived from the analysis of 55 European long-term field experiments. *Agriculture, Ecosystems & Environment*, *332*, 107926.

Steinfurth, K., Hirte, J., Morel, C., & Buczko, U. (2021). Conversion equations between Olsen-P and other methods used to assess plant available soil phosphorus in Europe–a review. *Geoderma*, *401*, 115339.

Stolte, J., Tesfai, M., Øygarden, L., Kværnø, S., Keizer, J., Verheijen, F., Panagos, P., Ballabio, C., & Hessel, R. (2015). *Soil threats in Europe*. Publications Office Luxembourg.

Swindles, G. T., Morris, P. J., Mullan, D. J., Payne, R. J., Roland, T. P., Amesbury, M. J., Lamentowicz, M., Turner, T. E., Gallego-Sala, A., & Sim, T. (2019). Widespread drying of European peatlands in recent centuries. *Nature Geoscience*, *12*, 922–928.

Tanneberger, F., Appulo, L., Ewert, S., Lakner, S., Ó Brolcháin, N., Peters, J., & Wichtmann, W. (2021). The power of nature-based solutions: How peatlands can help us to achieve key EU sustainability objectives. *Advanced Sustainable Systems*, *5*, 2000146.

Tobias, S., Conen, F., Duss, A., Wenzel, L. M., Buser, C., & Alewell, C. (2018). Soil sealing and unsealing: State of the art and examples. *Land Degradation & Development*, *29*, 2015–2024.

UNEP GP. (2022). Global peatlands assessment: The state of the World's peatlands.

Van Eynde, E., Fendrich, A. N., Ballabio, C., & Panagos, P. (2023). Spatial assessment of topsoil zinc concentrations in Europe. *Science of the Total Environment*, *892*, 164512.

Veerman, C. P. (2023). Activity update of the Mission Board of European Union on soil health and food. *Soil & Environmental Health* Elsevier, *1*(2), 100018.

Verheijen, F. G., Jones, R. J., Rickson, R. J., & Smith, C. J. (2009). Tolerable versus actual soil erosion rates in Europe. *Earth-Science Reviews*, *94*, 23–38.

Vieira, D. C. S., Borrelli, P., Jahanianfard, D., Benali, A., Scarpa, S., & Panagos, P. (2023). Wildfires in Europe: Burned soils require attention. *Environmental Research*, *217*, 114936.

Visconti, F., de Paz, J. M., & Rubio, J. L. (2010). What information does the electrical conductivity of soil water extracts of 1 to 5 ratio (w/v) provide for soil salinity assessment of agricultural irrigated lands? *Geoderma*, *154*, 387–397.

Webb, N. P., McGowan, H. A., Phinn, S. R., & McTainsh, G. H. (2006). AUSLEM (AUStralian land erodibility model): A tool for identifying wind erosion hazard in Australia. *Geomorphology*, *78*, 179–200.

Wiedmann, T., & Lenzen, M. (2018). Environmental and social footprints of international trade. *Nature Geoscience*, *11*, 314–321.

Yunta, F., Schillaci, C., Panagos, P., Van Eynde, E., Wojda, P., & Jones, A. (2024). Quantitative analysis of the compliance of EU sewage sludge directive by using the heavy metal concentrations from LUCAS topsoil database. *Environmental Science and Pollution Research*. https://doi.org/10.1007/s11356-024-31835-y

Zwolak, A., Sarzyńska, M., Szpyrka, E., & Stawarczyk, K. (2019). Sources of soil pollution by heavy metals and their accumulation in vegetables: A review. *Water, Air, & Soil Pollution*, *230*, 1–9.

SUPPORTING INFORMATION

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

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