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A proposal for soil health indicators at EU-level

Report on indicator framework available through the EU Soil Observatory

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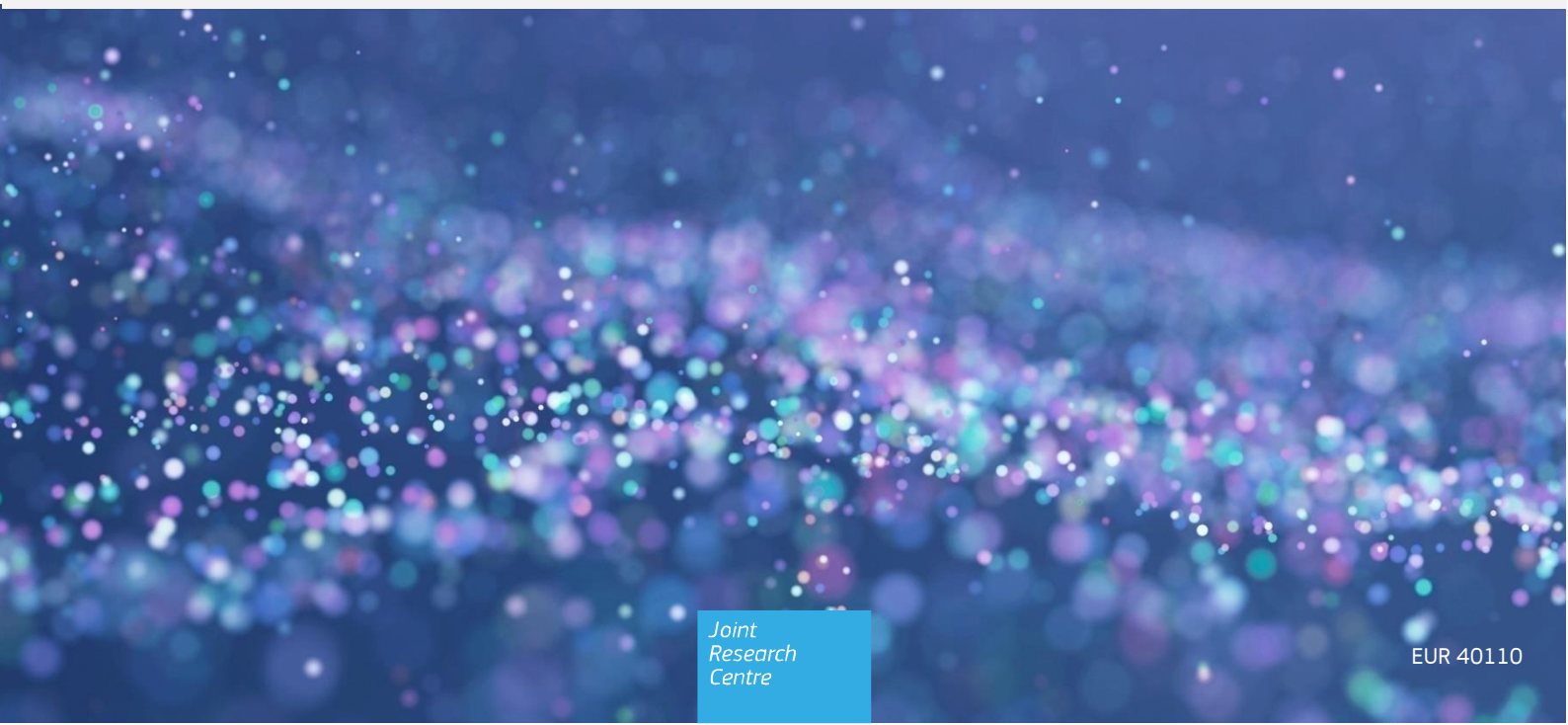

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Contents

Abstract

Healthy soils are essential for our environment and society, as soils deliver crucial ecosystem services. The publication of the EU Soil Strategy for 2030 and the Soil Monitoring Law marked major milestones for soil protection and restoration in the EU. In parallel, the Mission Soil aims to advance knowledge on healthy soils and establish 100 Living Labs and Lighthouses to co-create innovations for soil health. Contributing to a better EU soil health monitoring and a complete set of indicators at the EU-level are crucial components of the Mission Soil's objectives. This report proposes a list of indicators for soil health in the EU, together with targets and thresholds for these indicators. Nineteen indicators are presented, representing the main soil degradation processes and monitoring the state of soil health at EU scale. The EUSO Soil Degradation Dashboard is proposed as the main platform for presenting these indicators, together with key results and statistics. The dashboards shows that, based on the proposed indicators, more than 60% of EU soils are currently unhealthy. Planned updates on the proposed indicator framework include: (i) refining, updating and adding new datasets for indicators, (ii) refining thresholds for the indicators, and (iii) developing a composite Soil Health Index. For these planned activities, close collaboration with the Mission Soil projects will be crucial.

Acknowledgements

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Authors

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1 Introduction

Healthy soils are essential for our environment, economy and society, as soils deliver crucial ecosystem services. For example, soils help to prevent droughts and floods, mitigate climate change and ensure clean freshwater and food security. The European Green Deal has highlighted these vital aspects of healthy soils. Sustainable land management and healthy soils are vital in achieving some of the European Green Deal targets, such as sustainable farming and forestry, biodiversity, zero-pollution and climate resilience. Also the publication of the EU Soil Strategy for 2030 and the Directive on Soil Monitoring and Resilience (Soil Monitoring Law, SML) marked major milestones for soil protection and restoration in the EU. The EU Mission "A Soil Deal for Europe" (Mission Soil) supports the EU ambitions on soil health and sustainable land management. The Mission Soil aims to establish 100 Living Labs and Lighthouses to co-create, test and pioneer innovations for soil health, next to advancing knowledge on healthy soils. In addition, establishing a soil health monitoring framework is a crucial component of the Mission Soil. For this, a systematic and harmonised soil health monitoring framework at the scale of the EU is needed, as well as a complete set of measurable indicators that reflect the state of soil health in the EU. To be able to monitor soil health, to know where and to which extent remediation and restoration actions are needed, and how effective such actions are, it is essential to have a robust set of soil health indicators. Moreover, expected ranges to help to benchmark soil health for such a set of indicators are needed.

Given this context, the EU Soil Observatory (EUSO) has an important role as the principal provider of soil-related data and knowledge at the EU-level. The EUSO is hosted within the Joint Research Centre (JRC) of the European Commission. The EUSO is a dynamic and inclusive platform that supports EU policymaking related to soils. EUSO provides the relevant Commission Services and the broader soil user community with the knowledge and data flows needed to monitor, safeguard and restore soils at the EU-level. This also includes supporting the Mission Soil Secretariat in relation to the monitoring activities set out in the Mission Soil Implementation Plan. Through it Soil Degradation Dashboard, EUSO provides a set of soil health indicators at the EU-level.

This report aims to propose a list of indicators for soil health in the EU. Secondly, this report aims to suggest targets and thresholds for these indicators, and to identify expected ranges for soil health benchmarking.

2 Material and methods

2.1 Soil health, soil health indicators and thresholds

In this report, soil health is defined as "the continued capacity of soils to support ecosystem services", following the definition used in the Mission Soil Implementation Plan[1]. It matches the definition in the proposal for a Directive on Soil Monitoring and Resilience (Soil Monitoring Law)[2], in which soil health is defined 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".

To capture and monitor the state of soil health, measurable and well defined indicators are needed. In this report, indicators for soil health at the EU-level were selected based on the following criteria:

- First, the main soil degradation processes and associated indicators described in literature were selected. This literature review also included reports on soil health indicators by Mission Soil projects.
- Second, for each of the Specific Objectives and Indicators of the Mission Soil Implementation Plan (Fig 1), indicators were selected.
- The third criterion for selecting indicators was data availability. Indicators were only selected if EU-wide geospatial data were available for that indicator.
- Fourth, the goal was to provide a comprehensive assessment of soil health by including as many indicators as possible, capturing both soil conditions and degradation processes acting on them.
- However, and this is the fifth criterion, only one indicator for each soil degradation process was retained, to avoid overlap among the indicators and double counting in the soil health assessment.

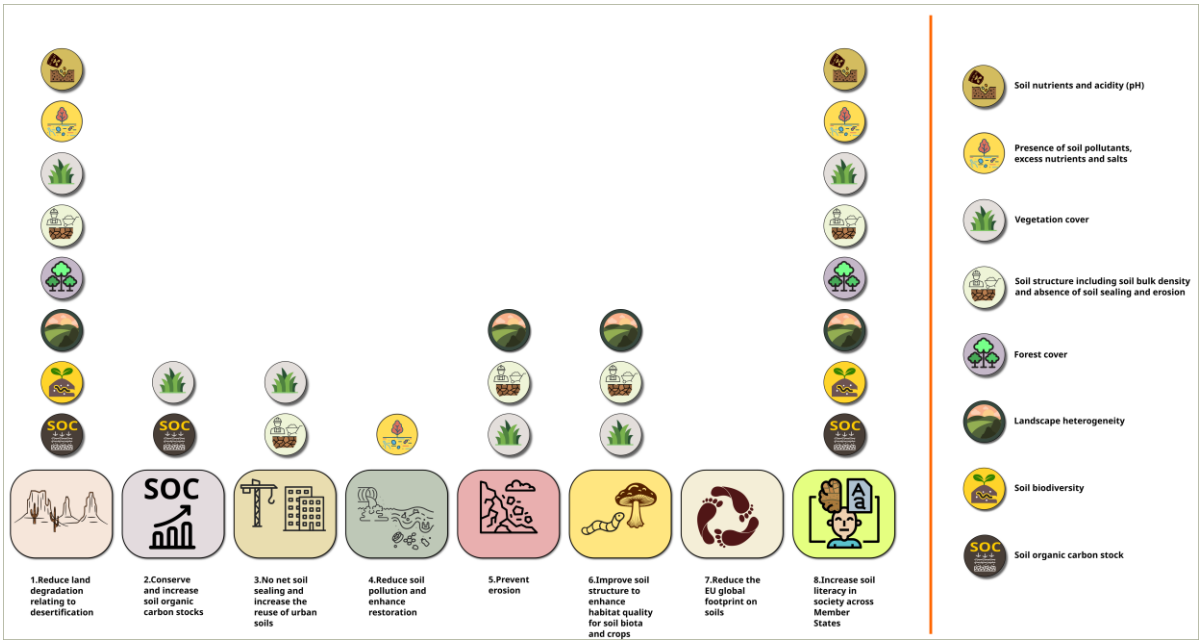
Next, thresholds were defined for each indicator to determine whether soils can be considered healthy or unhealthy. Thresholds were defined based on evidence described in scientific literature. The thresholds are considered as an estimate of the point beyond which soils can be considered as significantly affected by a certain degradation process. In this report, EU-wide thresholds were set for each of the selected indicators, for simplicity and easy interpretation at EU-scale.

If any indicator reaches the threshold, the soil is classified as unhealthy. This principle of 'one out all out', means that if only one indicator is classified as unhealthy, the respective soil site is classified as unhealthy. In other words, a failure to meet any of the criteria, would result in an unhealthy status.

[1] https://research-and-innovation.ec.europa.eu/knowledge-publications-tools-and-data/publications/all-publications/implementation-plans-eu-missions_en

[2] https://environment.ec.europa.eu/publications/proposal-directive-soil-monitoring-and-resilience_en

Figure 1. The Specific Objectives (bottom) and Indicators (right) of the Mission Soil Implementation Plan.



Source: Mission Soil Implementation Plan and Panagos et al. (2024b).

2.2 EUSO Soil Degradation Dashboard

All indicators selected in this report, together with their respective thresholds, are included and presented in the EUSO Soil Degradation Dashboard. This dashboard is the main platform for presenting and updating the indicators, and showing them to the wider soil community, including researchers, policy makers and land managers, as well as the interested public.

The dashboard is a dynamic platform. When new datasets become available that fulfil all criteria, these datasets will be added and the dashboard will be updated. As such, the assessment of the state of soil health in the EU will be updated regularly in the coming years, according to the availability of new data (e.g. from Mission Soil projects) and with the implementation of EU and national soil policies (particularly the proposed Soil Monitoring Law).

The technical creation of the EUSO Dashboard included masking all geo-spatial input layers of the individual indicators. All sealed areas and non-relevant areas (e.g., bare rocks, glaciers and water bodies) were excluded. As soil sealing mask, the Copernicus Impervious Built-up 2018 layer at 100 m resolution was used. As mask to exclude non-relevant areas, the following Corine Land Cover (CLC) 2018 categories were used: CLC 332 Bare rocks, CLC 335 Glaciers and perpetual snow, and CLC 511 512 521 522 523 Water bodies.

2.3 Interaction with Mission Soil projects

EUSO works in collaboration with the Mission Soil projects, including the projects selected under HORIZON-MISS-2021-SOIL-02-02 (i.e. BENCHMARKS and AI4SoilHealth). These collaborations and interactions will result in further development and refining of indicators for soil health. The interactions with these Mission Soil projects include: (i) regular bilateral meetings, (ii) interactions and presentations during the EUSO Stakeholders Forum and EUSO Working Groups, and (iii) coordination of the Mission Soil Cluster on Indicators and Monitoring. The latter will result in completing and refining the work on indicators; identifying new indicators or measurement

methods; identifying knowledge gaps; and elaborating a roadmap for the further development of indicators and soil health monitoring.

3 Results

3.1 Proposed list of soil health indicators and thresholds

19 indicators were selected to represent the main soil degradation processes and to capture and monitor the state of soil health at EU scale (**Table 1**). These indicators match the main soil degradation processes and indicators described in scientific literature (e.g. Bünemann et al., 2018; Stolte et al., 2015). All 19 indicators are included and presented in the EUSO Soil Degradation Dashboard.

For each of these indicators, thresholds were defined to determine whether soils could considered healthy or unhealthy. Thresholds were defined based on scientific evidence described in scientific literature (**Table 1**). EU-wide thresholds were set for each of the selected indicator. Given the wide range of soil types, ecosystems and climate regions, such EU-wide thresholds can result in large uncertainties and incorrect assessments of soil health. However, these EU-wide thresholds were chosen since not for each indicator locally based thresholds are available in literature. Moreover, using EU-wide thresholds are easier to interpret at EU-scale.

The proposed 19 indicators cover very well the indicators included in the Mission Soil Implementation Plan (**Table 2**). Only for Vegetation cover, Landscape heterogeneity and Area of forest, no indicators are currently selected. The first seven Specific Objectives included in the Mission Soil Implementation Plan are covered by the list of proposed indicators (**Table 1** and **Figure 1**).

Similarly, the proposed 19 indicators cover the proposed descriptors of the Soil Monitoring Law (**Table 3**).

With these 19 indicators, this report presents the latest state-of-the-art of indicators on soil health, for which published EU-wide geo-spatial data are available. However, this list does not yet cover every descriptor of the SML (**Table 3**) or indicator of the Mission Soil Implementation Plan (**Table 2**), as not for each indicator such datasets are available. Filling these gaps is planned in the upcoming years (for more details on the planned activities, see section 4).

Table 1. Soil degradation indicators included in this report and in the EUSO Soil Degradation Dashboard, and their respective thresholds, data sources and links to the Mission Soil Implementation plan.

Groups of soil degradation processes	Indicator	Threshold	Reference	Link to Mission Soil Objectives (see Fig 1)	Link to Mission Soil Indicators (see Fig 1)
Soil erosion	Water erosion	Erosion rate > 2 tonnes ha^{-1} yr^{-1}	Panagos et al., 2020	1, 5 and 6	Soil structure and absence of soil sealing and erosion
	Wind erosion	Erosion rate > 2 tonnes ha^{-1} yr^{-1}	Borrelli et al., 2017		
	Tillage erosion	Erosion rate > 2 tonnes ha^{-1} yr^{-1}	Borrelli et al., 2023		
	Harvest erosion	Erosion rate > 2 tonnes ha^{-1} yr^{-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	1 and 4	Presence of soil pollutants, excess nutrients and salts
	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	P(X > 45 mg kg^{-1}) > 5%	Fendrich et al:, 2024		
Soil nutrients	Nitrogen surplus	Agricultural areas where N surplus > 50 kg ha^{-1} yr^{-1}	Grizzetti et al., 2022; Lugato et al., 2018	1	Soil nutrients and acidity; Presence of soil pollutants, excess nutrients and salts
	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 SOC	Distance to max SOC level	Distance to max SOC level > 60%	De Rosa et al., 2024	1 and 2	Soil organic carbon stock
Loss of soil bio-diversity	Potential threat to biological functions	≥ Moderately-High level of risk	Orgiazzi et al., 2016	1 and 6	Soil biodiversity
Soil compaction	Packing density	Packing density ≥ 1.75 g cm^{-3}	Panagos et al., 2024b	1 and 6	Soil structure and absence of soil sealing and erosion
Salinization	Secondary salinization risk	Areas in Mediterranean region where >30% is equipped for irrigation	Siebert et al., 2013	1 and 4	Presence of soil pollutants, excess nutrients and salts
Loss of organic soils	Peatland degradation risk	Peatlands under hotspots of cropland	UNEP, 2022	1 and 2	Soil organic carbon stock
Soil sealing	Built-up areas	No threshold applied (all built-up areas)	Copernicus, 2018	3	Soil structure and absence of soil sealing and erosion

Source: JRC analysis.

Table 2. Mission Soil indicators, as included in the Mission Soil Implementation Plan, and the corresponding indicators presented in this report and in the EUSO Soil Degradation Dashboard.

Mission Soil indicators	**Indicators included in EUSO Dashboard**
Presence of soil pollutants, excess nutrients and salts	Copper excess
	Mercury excess
	Zinc excess
	Cadmium excess
	Arsenic excess
	Nitrogen surplus
	Phosphorus excess
	Secondary salinization risk
Soil organic carbon stock	Distance to max SOC level
	Peatland degradation risk
Soil structure including bulk density and the absence of soil sealing and erosion	Water erosion
	Wind erosion
	Tillage erosion
	Harvest erosion
	Post fire recovery
	Packing density
	Built-up areas
Soil biodiversity	Potential threat to biological functions
Soil nutrients and acidity	Nitrogen surplus
	Phosphorus deficiency
	Phosphorus excess
Vegetation cover	*not yet included in the dashboard*
Landscape heterogeneity	*not yet included in the dashboard*
Area of forests	*not yet included in the dashboard*

Source: JRC analysis.

Table 3. Soil degradation aspects and soil descriptors, as included in the proposed Soil Monitoring Law (SML), and the corresponding indicators presented in this report and in the EUSO Soil Degradation Dashboard.

Soil degradation aspect (SML)	Soil descriptor (SML)	Indicator in EUSO Dashboard
Salinization	Electrical Conductivity	Secondary salinization risk
Soil erosion	Soil erosion rate	Water erosion
		Wind erosion
		Tillage erosion
		Harvest erosion
		Post fire recovery
Loss of soil organic carbon	Soil Organic Carbon concentration	Distance to max SOC level
		Peatland degradation risk
Subsoil compaction	Bulk density in subsoil	*not yet included in the dashboard*
Excess nutrient content in soil	Extractable phosphorus	Phosphorous excess
Soil contamination	Concentration of heavy metals in soil	Copper excess
		Mercury excess
		Zinc excess
		Cadmium excess
		Arsenic excess
	Concentration of a selection of organic contaminants	*not yet included in the dashboard*
Reduction of soil capacity to retain water	Soil water holding capacity of the soil sample	*not yet included in the dashboard*
Excess nutrient content in soil	Nitrogen in soil	Nitrogen surplus
Acidification	Soil acidity (pH)	*not yet included in the dashboard*
Topsoil compaction	Bulk density in topsoil	Packing density
Loss of soil biodiversity	Soil basal respiration	Potential threat to biological functions
Land take and soil sealing	Total artificial land	Built-up areas
	Soil sealing	Built-up areas
	Land take, Reverse land take, Net land take	*not yet included in the dashboard*

Source: JRC analysis.

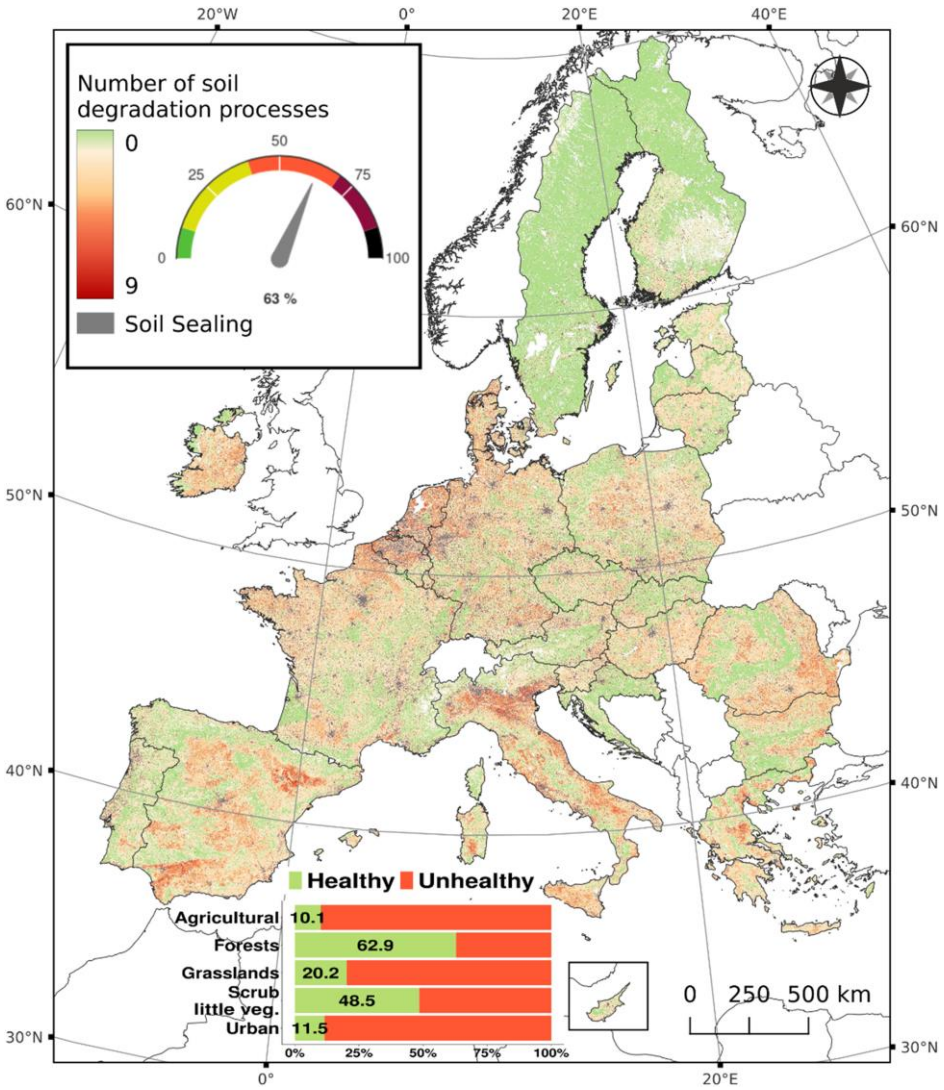
3.2 EUSO Soil Degradation Dashboard

The EUSO Soil Degradation Dashboard aims to be the main platform for gathering and disseminating indicators regarding soil health at EU-level, to provide a spatial visualisation of these data, and to suggest thresholds for unhealthiness. All 19 indicators presented in this report (**Table 1**), are included in the EUSO Soil DegradationDashboard, and are there visualised in a comprehensive way. The dashboard was launched in March 2023, and recently updated in June 2024.

The EUSO Soil Degradation Dashboard consists of four key features:

— **Convergence of evidence map**: the convergence of evidence map shows areas that are likely affected by soil degradation processes, as indicated by scientific evidence (**Figure 2**). A threshold value (**Table 1**) is used for each process, to estimate when soils can be considered unhealthy or healthy (i.e. respectively affected and not affected by the soil degradation process). For each pixel, the map indicates the number of soil degradation processes likely to be present. Although the map is subject to a degree of uncertainty and underlying assumptions, it provides, for the first time, an indication of where unhealthy soils may be located in the EU. The convergence of evidence map can be downloaded through the ESDAC-platform, as a multi-band layer with 20 bands (1 per soil degradation indicator plus the sum-up of all indicators).

Figure 2. EUSO Soil Degradation Dashboard and its convergence of evidence map (indicating the number of soil degradation processes likely to be present) and speedometer (indicating the proportion of land likely to be affected by one or more soil degradation processes or by soil sealing in the EU) (Panagos et al., 2024a).



Source: Panagos et al. (2024a).

— **Speedometer**: 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. Results show that, based on the current available datasets, more than 60% of EU soils are likely to be affected by one or more soil degradation processes or by soil sealing and are thus considered unhealthy (**Figure 2**).

— **Dependency wheel**: the dependency wheel shows the extent of the overlapping area between groups of soil degradation processes of the convergence of evidence map. This diagram provides insights in the type and magnitude of soil degradation combinations occurring in the EU.

— **Soil degradation indicators**: for each individual soil degradation process, statistics and maps are presented through an interactive display where users can select the process and scale. Statistics and maps are available at national (NUTS 0) and regional level (NUTS 2).

3.3 Results from the Dashboard and the proposed indicators

Results from the EUSO Soil Degradation Dashboard show that more than 60 % of the EU soils are unhealthy (**Figure 2**). The dashboard also clearly shows that most unhealthy soils are subject to more than one type of soil degradation. The most prevalent types of soil degradation (**Table 4**) are the loss of soil biodiversity (33% of the EU, **Figure 7**), soil erosion by water (19% of the EU; **Figure 4**), and the loss of soil organic carbon (14% of the EU; **Figure 6**). For some of the indicators, available datasets only cover a small fraction of the EU (e.g. post-fire recovery and peatland degradation risk), or only cover arable areas (e.g. tillage and harvest erosion) (**Table 4**). When looking only at the area for which data are available, the highest proportion of unhealthy soils are post-fire recovery (75% of the area with data), loss of soil organic carbon (53% of the area with data), and the loss of soil biodiversity (37% of the area with data) (**Table 4**).

Table 4. Data coverage and percentage (%) of healthy and unhealthy soils for each indicator. (1) Percentage of (un)healthy soils for area with data. (2) Percentage of the EU land and land cover classes covered by the data (percentages may differ due to different definitions of the land cover classes in the original studies). (3) Percentage of (un)healthy soils in the entire EU.

Indicator	**% of (un)healthy soils for area with data**		**Area covered by the data**		**% of (un)healthy soils in the entire EU**		
	healthy	unhealthy	% of the EU covered	Land cover classes covered by the data	healthy	unhealthy	no data
Water erosion	77	23	84	EU land excl sealed and non-relevant areas	65	19	16
Wind erosion	94	6	23	EU arable land	22	1	77
Tillage erosion	74	26	23	EU arable land	17	6	77
Harvest erosion	97	3	23	EU arable land	22	1	77
Post fire recovery	25	75	0.6	EU burned areas in 2017	0.2	0.5	99.4
Copper excess	98	2	87	EU land excl sealed and non-relevant areas	85	2	13
Mercury excess	99	1	87	EU land excl sealed and non-relevant areas	86	1	13
Zinc excess	99	1	87	EU land excl sealed and non-relevant areas	86	1	13
Cadmium excess	95	5	87	EU land excl sealed and non-relevant areas	83	4	13
Arsenic excess	99	1	87	EU land excl sealed and non-relevant areas	86	1	13
Nitrogen surplus	78	22	32	EU agricultural land	25	7	68
Phosphorus deficiency	79	21	40	EU agricultural land	32	8	60
Phosphorus excess	90	10	40	EU agricultural land	36	4	60
Distance to max SOC level	47	53	26	EU arable land and permanent crops	12	14	74
Loss of soil biodiversity	63	37	88	EU land excl sealed and non-relevant areas	55	33	12
Packing density	98	2	87	EU land excl sealed and non-relevant areas	85	2	13
Secondary salinization risk	93	7	20	Mediterranean biogeographical region	19	1	80
Peatland degradation risk	70	30	7	EU peatland areas	5	2	93
Soil sealing	93	7	100	EU land	93	7	0

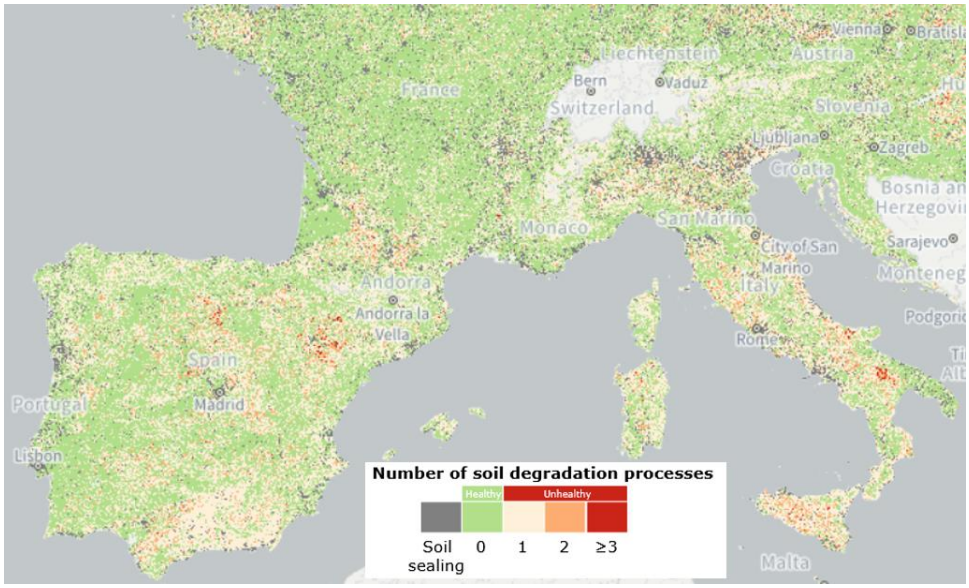
Source: JRC analysis.

3.3.1 Soil erosion

Soil erosion indicators included in the EUSO Soil Degradation Dashboard cover water, wind, tillage and harvest erosion and post-fire erosion. Soil erosion rates higher than 2 ton ha^{-1} yr^{-1} are considered unsustainable and thus unhealthy, as it exceeds average soil formation rates in Europe (0.3 – 1.4 ton ha^{-1} yr^{-1} (Verheijen et al., 2009)). In the dashboard, a convergence of evidence map showing all the erosion indicators can be selected (5 indicators and soil sealing) (**Figure 3**).

In addition, for the individual soil erosion indicators, users can select different thresholds and can change the map and statistics accordingly. As such, the users can select thresholds that are applicable for their specific situation. The thresholds that can be selected are: 1 ton ha^{-1} yr^{-1} (precautionary principle), 2 ton ha^{-1} yr^{-1} (default threshold, used in the convergence of evidence map), 5 ton ha^{-1} yr^{-1} (high erosion rates), and 10 ton ha^{-1} yr^{-1} (severe erosion).

Figure 3. Cut-out of the convergence of evidence map showing the number of unhealthy soil erosion indicators.

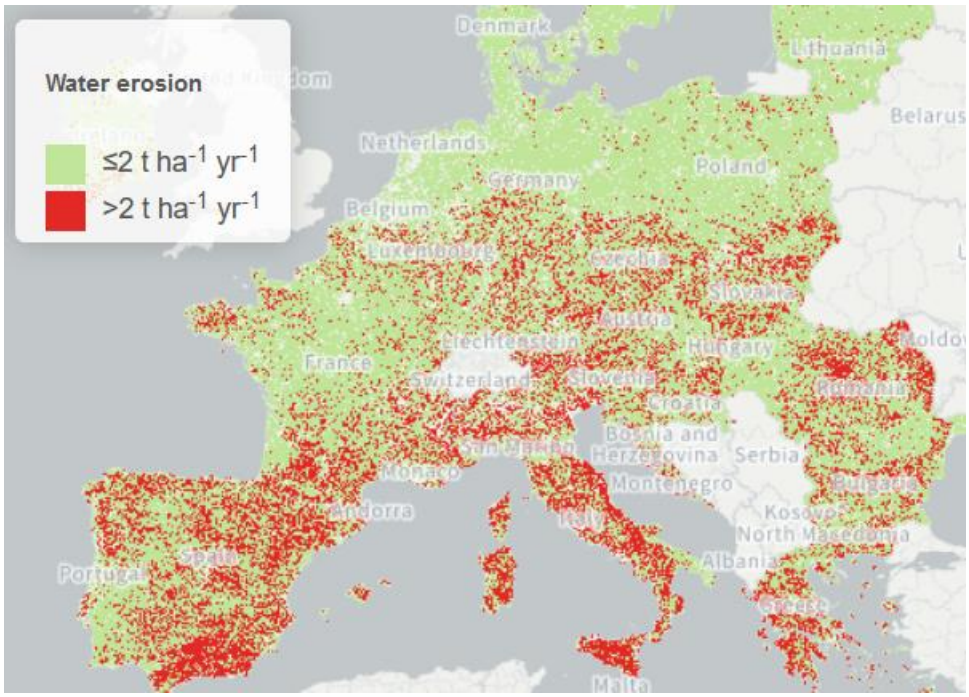


Source: JRC analysis.

Soil erosion by water

The EUSO dashboard uses a soil erosion model of Panagos et al. (2020), estimating the soil loss by water erosion for the year 2016 on all erodible lands in the EU. Erodible land includes agricultural, forests, grasslands, and shrubland. The model takes into account all factors controlling water erosion, such as soil erodibility, rainfall characteristics, topography, soil coverage by vegetation and soil management. The model results presented in the dashboard show that ca 23 % of the relevant EU land has erosion rates higher than the threshold (2 ton ha^{-1} yr^{-1}), and are consequently considered unhealthy (**Figure 4**).

Figure 4. Map of the water erosion indicator, on which the threshold of 2 ton ha^{-1} yr^{-1} is applied.



Source: JRC analysis.

Soil erosion by wind

Wind erosion depends on a range of factors including climate (e.g. speed of wind, soil dryness), the resistance of soil to wind erosion, soil roughness and vegetation cover. The EUSO dashboard uses a spatially distributed model of Borrelli et al. (2017) combining these factors. The model estimates the average annual soil loss rate due to wind erosion on arable land of the EU. 6 % of the EU arable land is considered unhealthy, i.e. having an erosion rate higher than 2 ton ha^{-1} yr^{-1}.

Tillage erosion

Tillage erosion is a soil erosion process occurring in cultivated fields due to downhill movement of soil during tillage operations. The indicator used in the EUSO Dashboard consists of modelling results of Borrelli et al. (2023). This model takes into account the erosivity of tillage operations (how much soil displacement is caused by tillage) and the erodibility of the cultivated landscape (its susceptibility to be eroded, mainly depending on topography). Results show the average annual soil loss due to tillage erosion on EU arable land. 26 % of the EU arable land suffers from unsustainable tillage erosion (higher than 2 ton ha^{-1} yr^{-1}) and are consequently considered as unhealthy.

Harvest erosion

Harvest erosion, or soil loss due to crop harvesting, is the loss of soil adherent to crops and of soil and rock fragments that are removed from the field during harvest. This degradation process is particularly marked for root and tuber crops, such as sugar beets and potatoes. The indicator used in the EUSO dashboard is based on an estimation of harvest erosion by Panagos et al. (2019), taking into account the occurrence of sugar beet and potato crops in the EU, the soil texture in which they are grown, and harvest erosion rates for these crops. Results show that ca. 3% of the EU arable land suffer from unsustainable erosion rates due to crop harvesting (higher than 2 ton ha^{-1}

yr^{-1}) and are considered unhealthy. During the period 2000-2016, harvest erosion is estimated to account for a soil loss of 14.7 million tons yr^{-1} on EU arable land (Panagos et al., 2019).

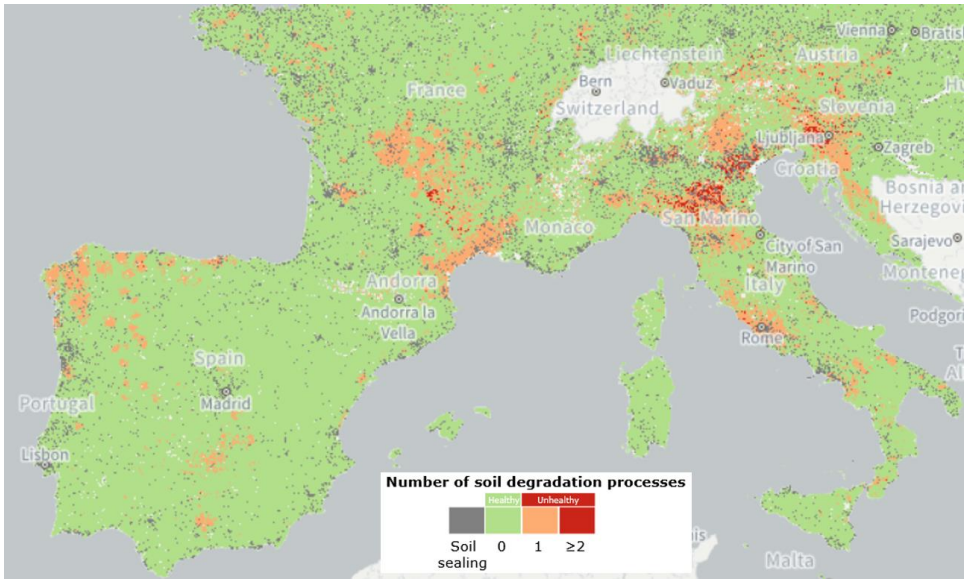
Post-fire soil erosion

Wildfires greatly impact topsoil physic-chemical characteristics. Moreover, burned soils have an increased risk for runoff and soil erosion. The indicator included in the EUSO dashboard that accounts for this post-fire erosion risk is based on the post-fire soil recovery indicator of Vieira et al. (2023). This indicator identifies a soil surface area in which vegetation cover is still bellow (i.e. not recovered) the pre-fire conditions from the latest wildfire, for all EU burned areas in 2017. Soils in this condition, having a post-fire recovery index below 1, are considered unhealthy. Currently, 75 % of all EU burned areas in 2017 are in an unhealthy state.

3.3.2 Soil pollution

Soil pollution indicators included in the EUSO Soil Degradation Dashboard includes excess of copper, mercury, zinc, cadmium and arsenic. In the dashboard, a convergence of evidence map showing all the soil pollution indicators can be selected (5 indicators and soil sealing) (**Figure 5**).

Figure 5. Cut-out of the convergence of evidence map showing the number of unhealthy soil pollution indicators.



Source: JRC analysis.

Copper excess

Copper (Cu) is a micronutrient essential for plant growth, but in high concentrations it can create a potential risk to human health and soil functions. The copper concentration in soils depends on the complex interaction between climate, parent material, soil properties and external inputs from agriculture (e.g. fungicides) or industrial processes. The indicator included in the EUSO dashboard is based on a regression model of Ballabio et al. (2023) based on LUCAS topsoil survey data. The presented indicator shows Copper concentrations for all land cover types in the EU. The threshold to identify unhealthy soils was set at 100 mg kg^{-1}. This threshold is used in Finnish and Swedish legislations (Ministry of the environment - Finland, 2007), and proposed by scientific studies

(Adriano, 2001; Baize, 1997). There is however no common agreement on copper threshold values for the definition of risk in the EU. In the dashboard itself, a lower threshold was used (50 mg kg^{-1}) to replicate the proportion of LUCAS soil samples found to have high metal content. The spatial interpolation of maps tends to smooth outliers. The threshold of 50 mg kg^{-1} is also the lowest limit value for copper concentration in soil set in the EU Sewage Sludge Directive[3]. Currently, 2% of the EU soils have a concentration higher than the threshold, and thus are considered unhealthy. High copper concentrations have been measured mainly in vineyards and olive groves (Ballabio et al., 2018).

Mercury excess

Mercury (Hg) is a toxic metal that can pose a significant risk to human health. Sources of mercury in soils can be natural (such as weathering of rocks) and anthropogenic (mining, coal combustion and metal industry activities). The indicator included in the EUSO dashboard is based on Deep Neural Network learning models using LUCAS topsoil samples (Ballabio et al., 2021). The presented indicator shows mercury concentrations for all land cover types in the EU. The threshold used in the dashboard was set at 200 µg kg^{-1}. This threshold was chosen to replicate the proportion of LUCAS soil samples (1%) found to have high mercury content (defined in that case as 500 µg kg^{-1}, a commonly used threshold and defined by Finnish and Swedish legislations (Ministry of the environment - Finland, 2007). Given that the interpolation model used in this layer tends to smooth the upper outliers, the threshold was lowered in order to show an area of an extent similar to the LUCAS observations. Currently, 0.8% of the EU soils have a concentration higher than the threshold, and thus are considered unhealthy. 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).

Zinc excess

Zinc (Zn) is an essential element to sustain crop production and human health, but can be toxic when present in excess. The indicator included in the EUSO dashboard is based on LUCAS topsoil survey data and Random Forest model based on environmental drivers and land use (Van Eynde et al., 2023). The presented indicator shows Zn concentrations for all land cover types in the EU. The threshold used in the dashboard was set at 65 mg kg^{-1}. This threshold was chosen to replicate the proportion of LUCAS soil samples found to have high Zn concentrations (i.e. 100 mg kg^{-1} (Mininni et al., 2015)). Currently, 1.5 % of the EU soils have a concentration higher than the threshold, and thus are considered unhealthy. The presence of Zn deposits and mining activities mainly explained the occurrence of relatively high Zn concentrations. The overall distribution of soil Zn in Europe is mainly explained by clay content, with lower Zn concentrations in coarser soils. Next to texture, low Zn concentrations were found in soils with low pH (e.g. Podzols), as well as in soils with pH above 8 (i.e., Calcisols) (Van Eynde et al., 2023).

Cadmium excess

Cadmium (Cd) is a naturally occurring toxic metal whose abundance, toxicity, bioaccumulation potential and its relative mobility can pose a significant risk to human health. The indicator included in the EUSO dashboard is based on LUCAS topsoil survey data and machine learning algorithms

[3] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31986L0278

(Ballabio et al., 2024). The indicator shows cadmium concentrations for all land cover types in the EU. The threshold used in the dashboard was set at 0.7 mg kg^{-1}. Soils that were estimated to have a cadmium concentration higher than this threshold were considered unhealthy. This threshold was chosen to replicate the proportion of LUCAS soil samples (5.5%) found to have high cadmium content (i.e. above 1 mg kg^{-1}, the threshold defined by the Finnish Ministries of Environment (2007), Gawlick and Bidoglio (2006), and the EU Sewage Sludge Directive[4]). Given that the spatial interpolation model used in this layer tends to smooth the upper outliers, the threshold was lowered in order to show an area of an extent similar to the LUCAS observations (5.5%). Currently, ca 5% of the EU soils have a concentration higher than 0.7 mg kg^{-1}, and thus are considered unhealthy. Natural factors influencing Cd levels include soil properties (pH, clay), topography, soil erosion, and leaching. Most important anthropogenic factors is phosphorus inputs to agricultural lands (Ballabio et al., 2024).

Arsenic excess

Arsenic (As) is a naturally occurring toxic heavy metal that is extensively used in industrial applications. In an agricultural context, the repeated application of arsenical products leads to elevated soil concentrations. The indicator included in the EUSO dashboard is based on a model approach using LUCAS topsoil survey data (Fendrich et al., 2024). The indicator shows the probability of exceeding 45 mg kg^{-1} arsenic concentration in the soil, and this for all land cover types in the EU. Soils that were estimated to have an exceedance probability higher than 5% were considered unhealthy. This threshold of 45 mg kg^{-1} was defined following the Belgium's 1995 Soil Remediation Act.

3.3.3 Soil nutrients

Nitrogen surplus

Nitrogen (N) is an essential nutrient for plant growth, and nitrogen-containing fertilisers and organic inputs are extensively used in agriculture. However, excessive nitrogen in soil is a major source of soil pollution, and has consequences for air, water quality and public health and contributes to greenhouse gas emissions. Nitrogen excess occurs when nitrogen inputs (e.g. fertilizer and manure application, bacterial N fixation and atmospheric deposition) exceed outputs (e.g. uptake by plants and harvest). The indicator included in the EUSO dashboard is based on agricultural data and a European biogeochemical model framework (Grizzetti et al., 2023). The indicator shows areas of agricultural land in the EU subject to nitrogen surplus (N input – N output). The threshold used in the dashboard was set at a nitrogen surplus of 50 kg ha^{-1} yr^{-1}. Above this threshold, environmental impacts of nitrogen are considered to be significant (Grizzetti et al., 2023). Currently, ca 22 % of the EU-agricultural land have a nitrogen surplus higher than 50 kg ha^{-1} yr^{-1}, and thus considered unhealthy.

Phosphorus deficiency

Phosphorus (P) is an essential nutrient for plant growth. Phosphorus deficiency, when phosphorus availability in soils are lower than needed for crops, is corrected by the application of phosphorus fertilizers or organic inputs. The indicator included in the EUSO dashboard shows the distribution of

[4] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31986L0278

phosphorus concentrations in agricultural land in the EU measured in an Olsen soil extraction. This indicator is based on LUCAS topsoil survey data and a regression model (Ballabio et al., 2019). The threshold used in the dashboard was set at available phosphorus of 20 mg kg^{-1}. Below this threshold, soils are considered to be at risk of phosphorus deficiency for crop production (Jordan-Meille et al., 2012). Currently, ca 21 % of EU-agricultural soils have an available phosphorous below 20 mg kg^{-1} and are thus considered unhealthy.

Phosphorus excess

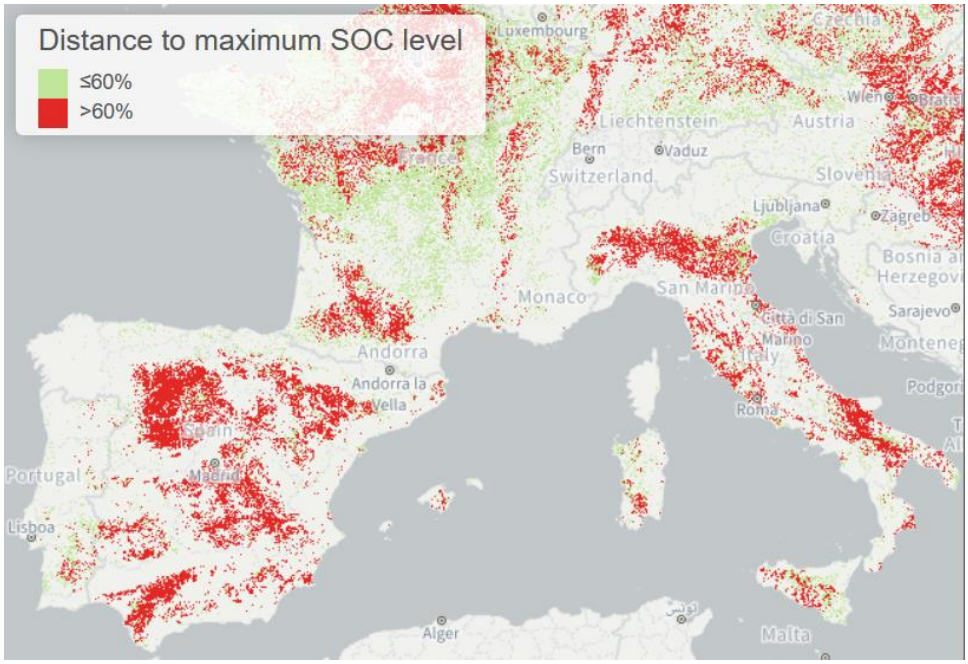
When phosphorus inputs to soils (e.g. from inorganic fertilizers or manure) exceed crop demands, phosphorus concentrations increase in soils. P accumulation in soils causes environmental pollution through eutrophication, resulting in the degradation of water quality, biodiversity decline and high public health risks. The indicator used in the EUSO dashboard shows distribution of phosphorus concentrations in agricultural land in the EU measured in an Olsen soil extraction. This indicator is based on LUCAS topsoil survey data and a regression model (Ballabio et al., 2019), and this is the same indicator as used for the Phosphorous deficiency. The threshold used in the dashboard was set at available phosphorus above 50 mg kg^{-1}. Above this threshold, soils are considered to have an excess in phosphorous with possible environmental risks, and thus are considered unhealthy. The threshold is based on the average of excessive phosphorus concentrations used by a number of European countries (Jordan-Meille et al., 2012). Currently, ca 10 % of EU-agricultural soils have an available phosphorous above 50 mg kg^{-1} and are thus considered unhealthy.

3.3.4 Other soil degradation indicators

Distance to maximum soil organic carbon level

Soil organic carbon (SOC) is important for soil to provide many ecosystem services such as crop production, water and nutrient cycle and biodiversity. SOC levels vary greatly based on soil type, climate and many other factors. A SOC indicator that is useful for all soils and climate regions in the EU is therefore challenging to define. The indicator included in the EUSO dashboard shows the distance between the current level of SOC and a maximum level of SOC achievable in the medium-long term on agricultural land. This maximum level of SOC is calculated as the SOC level that would be achievable if the land was kept under continuous grassland for 40 years without ploughing (De Rosa et al., 2024). The threshold used in the dashboard was set at a distance to the maximum SOC level of 60%. Soils are considered unhealthy if the distance that separates them from the maximum SOC level is more than 60% of the current SOC level. This threshold of 60% has been chosen as it provides a reasonable and pragmatic distance gap from the maximum SOC level achievable. Currently, in ca 53% of EU arable land the distance between the current and maximum SOC level is more than 60%, and thus are considered unhealthy (**Figure 6**).

Figure 6. Map of the indicator 'Distance to maximum soil organic carbon (SOC) level', on which the threshold of 60% is applied.

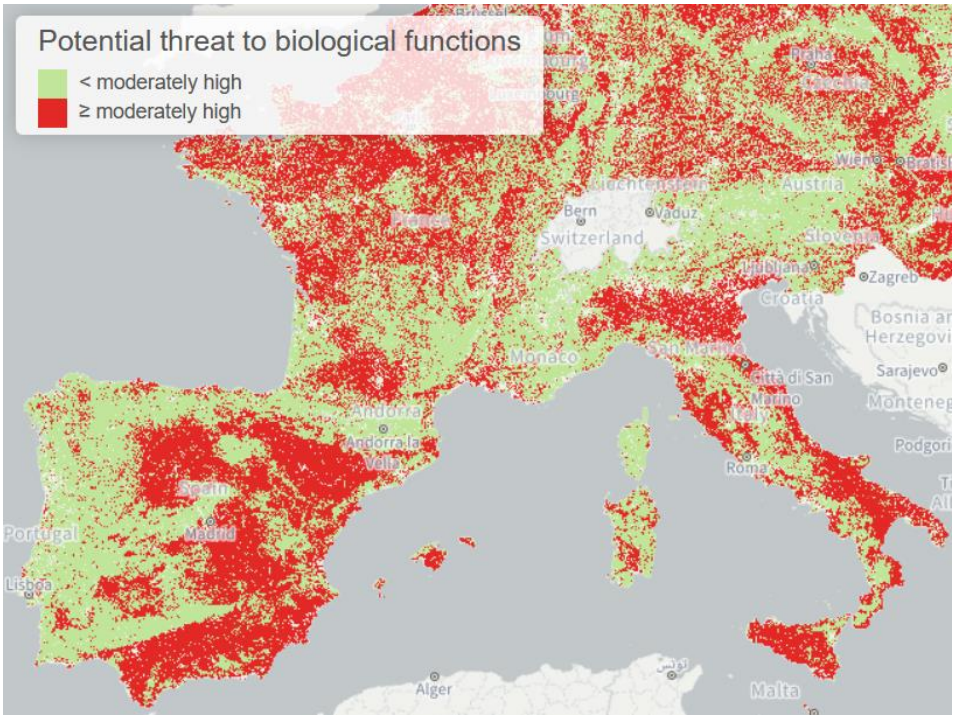


Source: JRC analysis.

Potential threat to biological functions

Organisms living in soils (e.g. worms, fungi and bacteria) are important for soil functions and soil ecosystem services. Many factors such as land management or pollution can negatively affect soil organisms and their functions. The indicator included in the EUSO dashboard combines a set of 13 potential threats preventing soil biodiversity from performing its biological functions. Examples of these threats are habitat fragmentation in natural and rural areas, land use changes or soil pollution. This indicator is based on an assessment of these 13 potential threats to soil organism by expert knowledge (Orgiazzi et al., 2016). A spatial proxy was assigned to each of the pressures in order to map the distribution of risk across the EU (Orgiazzi et al., 2016). Soils are considered unhealthy where the risk is estimated to be moderately high or high. Currently, in ca 37% of EU land the potential threats to biological functions are estimated to be moderately high or high, and thus are considered unhealthy (**Figure 7**). The soil biodiversity indicator is currently being refined, through analysis of the LUCAS Soil Biodiversity component dataset (Köninger et al., 2023; Labouyrie et al., 2023). Once the drivers of soil organism distribution in the EU have been assessed, indicators can be further refined.

Figure 7. Map of the indicator 'Potential threat to biological functions'. Soils are considered unhealthy where the risk is estimated to be moderately high or high.



Source: JRC analysis.

Soil compaction

Soils are porous and as such they can be subject to compaction. Soil compaction occurs typically on agricultural or forest soils through the use of heavy machinery or high stocking densities. Soil compaction reduces agricultural productivity, decrease water infiltration and accelerate run-off and risk of soil erosion. The indicator used in the EUSO dashboard shows the packing density, a proxy for soil compaction. Packing density is calculated based on bulk density and clay content (Panagos et al., 2024c). The threshold used in the dashboard was set at 1.75 g cm^{-3} (Jones et al., 2003; Păltineanu et al., 2015). Soils that have a packing density higher than 1.75 g cm^{-3} are compacted and are considered unhealthy. Currently, 2.2% of all EU land have a packing density above the threshold and are thus considered unhealthy.

Secondary salinization risk

Secondary salinization occurs when the concentration of salts in soils increases as a result of non-optimal or inappropriate irrigation. The use of poor quality irrigation water with excessive salt content or an overuse of irrigation can lead to an increase in soluble salts concentration in soils. This is especially the case in hot climates with low rainfall and where water evaporates more easily, leaving salts behind. The indicator included in the EUSO dashboard shows the presence of irrigation in the Mediterranean biogeographical region, based on Siebert et al. (2013). Areas in these Mediterranean climate zone where more than 30% is equipped for irrigation are considered unhealthy regarding secondary salinization. This threshold of 30% was chosen as from this scale substantial salinization is a significant risk. Currently, ca 7% of the Mediterranean biogeographical region is above this threshold and thus considered to be unhealthy. However, this indicator is only a first attempt to map where in the EU secondary salinization are likely to occur and comes with lots of uncertainties. Better indicators and datasets are needed to be able to better assess this risk.

Peatland degradation risk

Peatlands consist of organic soils that are able to store significant amounts of carbon. A lot of peatlands in the EU are however degraded. One of the main anthropogenic pressures facing peatlands is drainage for agriculture and peat extraction. The indicator included in the dashboard shows peatlands under hotspots of cropland (i.e. density of cropland occurring within a fixed radius around peatland areas), and thus peatlands that are considered to be at risk of being degraded. As such, this indicators highlights where peatlands are likely to be degraded due to agriculture-related pressures. The indicator is based on the UNEP's Global Peatlands Assessment (UNEP, 2022). Currently, ca 30% of the peatlands in the EU are under hotspots of cropland and thus considered at risk of being degraded. However, this indicator is only a first attempt to map where in the EU peatlands are under risk, and comes with a lot of uncertainties. Better indicators and datasets are needed to be able to better assess the actual state of peatlands in the EU.

Soil sealing

Soils are sealed by their covering with an impermeable material, buildings, constructions, roads, etc. Soil sealing is causing a loss of soil functions and ecosystem services. The indicator included in the EUSO dashboard shows the built-up areas in the EU. The indicator is based in the Impervious Built-up 2018 data layer of the European Environmental Agency (EEA). Currently, 7% of EU land is sealed.

4 Discussion and planned updates

Uncertainties linked to the selected indicators and thresholds

The presented indicators all come with a certain degree of uncertainty and underlying assumptions. This includes uncertainties related to the scale, resolution, and method of assessment. In the upcoming years, EUSO and the Mission Soil projects will work on identifying and quantifying these uncertainties and on improving the included datasets.

Especially the current indicators for peatland degradation, soil compaction and soil salinization come with a lot of uncertainties. Better indicators and better refinement of these datasets are needed to fully access and monitor these specific soil degradation processes. When such new indicators and datasets become available, the EUSO Soil Degradation Dashboard will be updated accordingly. Next, regarding the soil biodiversity indicator, spatial indicators of the richness and diversity of soil microorganisms and associated functional groups are currently being developed. When available, these indicators will be used to refine the soil biodiversity indicator currently included in the dashboard and in this report.

Also the selected thresholds come with uncertainties, especially given the EU-wide thresholds. In the upcoming years, the EUSO and Mission Soil projects will also work on locally based thresholds. The goal is to come up with thresholds for different soil types given the land use, ecosystem and climatic context, where feasible.

Collaboration with Mission Soil projects

The EUSO will continue to work in close collaboration with the Mission Soil projects. The interactions will mainly be organised through the Mission Soil Cluster on Indicators and Monitoring, next to bilateral meetings and interactions during the EUSO Stakeholders Forum and EUSO Working Groups.

This collaborative work will focus on the further development and refining of the indicator framework for soil health in the EU. This includes:

- **Refining and updating datasets** for the indicators. When new datasets for indicators will become available, the indicator list and the EUSO Soil Degradation Dashboard will be updated. For this, first focus will be on the knowledge gaps in the Mission Soil indicators and the descriptors of the SML. Currently, not all indicators of the Mission Soil Implementation Plan nor all descriptors in the proposed SML are yet included in the dashboard (**Table 2** and **Table 3**). It is intended to fill these gaps in the upcoming years.
- **Refining thresholds**. This also includes adjusting thresholds to soil type, climatic context and ecosystem type. Such locally based thresholds will decrease the uncertainties and will increase the applicability of the proposed indicator framework to the local scale. For this, integration of the latest research outcome of the Mission Soil and other relevant projects (including results from field experiments) will be needed.

— Developing a composite **soil health index**, replacing the 'one out all out' strategy currently used in the EUSO Soil Degradation Dashboard. Such a soil health index should combine all information from the individual indicators in one single index. In this index, soils that are highly affected by several soil degradation processes will have a lower score than soils that are only affected by one soil degradation process. This index should also take into account the actual value of the indicator, not only whether it is above or below a certain threshold. Ideally, the soil health index should take into account the pedo-climatic conditions. As a result, the soil health index will be a better and more nuanced representation of soil health in the EU.

Soil health promoting management practices

Activities are planned to identify a set of soil health promoting management practices including targets for their uptake. These activities will include collaboration with ongoing and future Mission Soil projects working on management practices promoting soil health.

5 Conclusions

This report proposes a list of indicators for soil health at the EU-level. It also proposes thresholds to benchmark soil health for these indicators. Nineteen indicators are presented, representing the main soil degradation processes. These nineteen indicators represent the latest state-of-the-art of soil health indicators, for which published EU-wide geo-spatial data are available. The indicators, together with their thresholds, allow to monitor the state of soil health at the scale of the EU.

The EUSO Soil Degradation Dashboard is the main platform for presenting these indicators. The dashboard, launched in March 2023 and updated in June 2024, provides a spatial assessment of the indicators and thus of unhealthy soils in the EU. The dashboard shows where current scientific evidence indicate areas that are likely affected by soil degradation. Results from the dashboard show that at least 60% of EU soils are unhealthy. The most prevalent types of soil degradation are the loss of soil biodiversity, soil erosion by water, and the loss of soil organic carbon.

Further updates and improvements to the indicator framework require close collaborations with the Mission Soil and other relevant projects. Planned updates include (i) refining and updating datasets for the indicators and adding new indicators, (ii) refining thresholds, ideally adjusted to pedo-climatic context, and (iii) developing a composite soil health index. The Mission Soil Cluster on Indicators and Monitoring will be crucial for these collaborative works.

Overall, the presented indicator framework is a useful tool to monitor soil health in the EU. In addition, the EUSO Soil Degradation Dashboard provides a comprehensive and easily understandable platform for this framework. Together with the planned updates, the presented indicator framework can be a significant contribution towards reaching the objectives of the Mission Soil.

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List of abbreviations and definitions

Abbreviations	Definitions
cm	centimetre
Cu	Copper
EEA	European Environmental Agency
EU	European Union
EUSO	EU Soil Observatory
G	gram
ha	hectare
JRC	Joint Research Centre
Kg	kilogram
LUCAS	Land Use/Cover Frame Area Survey
Mg	milligram
SML	Soil Monitoring Law
N	Nitrogen
P	Phosphorous
SOC	Soil Organic Carbon
UNEP	United Nations Environment Programme
yr	year
Zn	zinc
µg	microgram

List of figures

List of tables

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