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## Soil pollution in the European Union – An outlook

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### ABSTRACT

Soil pollution in the European Union (EU) is poorly quantified, because of several years of reduced attention and limited funding on soil research and monitoring. Moreover, issues such as different monitoring methodologies within Member States (MS), and quantification methods focused on pseudototal rather than the available fraction of pollutants, has been limiting our understanding of risk under soil pollution. Despite that, thanks to efforts from the scientific community, it was possible to achieve some progress, which is by far insufficient for the problem at hand. In the anticipation of future policy demands and towards a common strategy for tackling soil pollution in the EU, it seemed relevant to describe the limited knowledge and main uncertainties. Such analysis should provide evidence for the development of efficient policies, as well as updating current ones to better tackle the interdisciplinary of soil. This perspective provides our view on current knowledge on soil pollution at EU scale, by compiling the most updated assessments made at EU scale, identifying soil pollution drivers, impacts on health and the environment, and evaluating current state of knowledge. Allowing us to infer about current level of uncertainties and knowledge gaps and identify solutions through future research and policies. Our suggestions are in line with an increasing investment on research and innovation, but also more frequent updates of current legislation already tackling pollution and welcoming the new proposal for a Soil Monitoring Law as an important driver for soil knowledge development and implementation of a European monitoring system.

### 1. Introduction

Pollution has been widely recognized to have a significant impact to human health and the environment. However, despite the substantial progress in the identification and mitigation of sources of pollution, an estimation of 9 million deaths worldwide were attributed to air and water pollution alone (Fuller et al., 2022), evidencing how much we still need to do in the field of Environmental Policy. For soil pollution however, the absence of knowledge regarding its extent is such, that we are currently uncertain of its risks to humans and the environment.

According to Rodríguez-Eugenio et al. (2018), soil pollution refers to the presence in the soil of a chemical or substance out of place and/or present at a higher than normal concentration that has adverse effects on any non-targeted organism. To effectively comprehend and govern soil

as a multifaceted system, it is crucial to acknowledge the simultaneous occurrence of intricate chemical, physical, and biological processes. These are influenced by various soil constituents (solid, aqueous, gaseous, and non-aqueous liquid phases) and environmental factors (edaphoclimatic drivers). Consequently, to thoroughly examine any form of soil pollutant, it is essential to consider edaphoclimatic features using suitable extraction and quantification techniques.

In the context of soil pollution risk assessment, a comprehensive and scientifically sound approach is essential for informed risk management decision-making. Accurate assessment requires the inclusion of relevant soil indicators and processes that significantly impact the behaviour of pollutants. This includes a detailed quantification of soil processes, such as the available fraction and bioaccumulation for each pollutant within a specific soil and site. Such evaluations contribute to a robust

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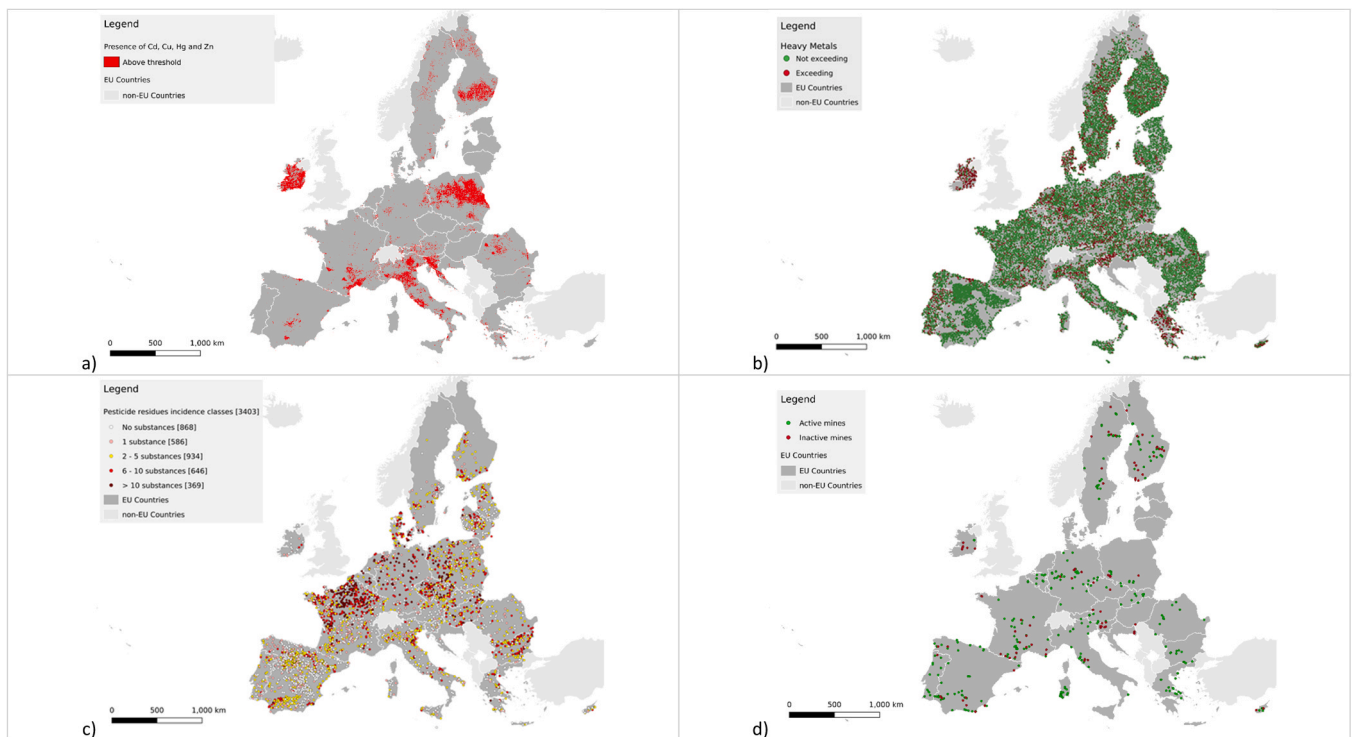
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**Fig. 1.** Compilation of soil pollution assessments at EU-scale. Indicators of diffuse pollution on a) Cadmium, Copper, Mercury, and Zinc combined (Ballabio et al., 2018, 2021, 2024; Van Eynde et al., 2023); b) Heavy metals exceedance for sewage sludge limit values (Yunta et al., 2024), c) Pesticides residues incidence, and for point-source pollution (Vieira et al., 2023) d) active and inactive Mine sites (Hudson-Edwards et al., 2023).

understanding of pollutant dynamics and facilitate the development of targeted mitigation strategies.

The European Union (EU), which is highly recognized as a global leader implementing environmental policies (Tosun, 2023; Zuazua Ruiz et al., 2023), stated its ambition through the Zero Pollution Action Plan (ZPAP), aiming for zero pollution for air, water and soil (EC, 2021a) under the umbrella of the European Green Deal (EC, 2021b). On soil pollution, the ZPAP specifically identified the urgency to develop a framework for a regular soil pollution assessment, followed up by actions to address its impacts and soil degradation. Despite that, the First 'zero pollution' monitoring and outlook report, identified significant difficulties in assessing soil pollution in the EU given the inexistence of a legal framework for monitoring and reporting (EC, 2022).

Few examples can be provided on directives and regulations preventing soil pollution in EU agricultural land, generally targeting substances used for improving plant productivity. The Fertilising Products Regulation (EU) 2019/1009 sets limit values for several substances (Cd, Cr (VI), Hg, Ni, Pb, As,  $C_2H_5N_3O_2$ ,  $ClO_4$ , Cu, Zn, Pathogens) present on Organic, Organo-Mineral, Inorganic Fertilisers, and Liming material. The Sewage Sludge Directive (86/278/EEC), sets limit values for several substances (Cd, Cu, Ni, Pb, Zn, Hg, Cr) present in the sludge and in soil, so that sludge application is allowed. The Regulation (EC) 1107/2009 concerning the placing of plant protection products on the market, evaluates and authorises the sale of substances that do not cause harmful effects on human health, animal health, groundwater nor cause unacceptable effect on the environment.

However, not always have been easy to reduce the risks and impacts of these substances in a sustainable manner. For instance, the Directive 2009/128/EC which sets a framework for the sustainable use of pesticides, paved the way in the sales decline of the most hazardous substances, but also allowed to assess an increasing number of derogations of non-authorized substances during the same period. Another example is the conclusion that pesticides containing copper can still fulfil the safety requirements despite EFSA classifications of high risk to surface

water and sediment organisms (EFSA (European Food Safety Authority et al., 2018), under the limit of application of 28 kg of copper per hectare over a period of 7 years (EC, 2018).

The preventive nature of the current regulations may not be sufficient for the problem at hands, whereas in turn a systematic assessment of soil pollution at the EU scale can potentially provide relevant information to prioritise areas under higher risk for soil pollution. Currently, the ongoing monitoring systems taking place in EU are represented by the Land Use/Cover Area frame statistical Survey (LUCAS) Soil Module (Orgiazzi et al., 2018) and a few others at Member States (MS) level, which were originally developed for national priorities, and therefore present limited comparability with other MS and even LUCAS (EJP Soil, 2021). Furthermore, the project Geochemical Mapping of Agricultural and grazing land Soil (GEMAS) also targeted the chemical quality of productive soils in 33 European countries, developing important datasets for diffuse pollution (Demetriades et al., 2021). However, only LUCAS Soil module presents a systematic and harmonized soil sampling and analysis, brought by a shared field protocol and a single laboratory analysis for all samples (Orgiazzi et al., 2018). Moreover, LUCAS soil repeated sampling in the same locations since 2009 allows developing a trend analysis, and the assessment of the progress of EU policies (Fernandes-Ugalde et al., 2021).

In what concerns the inventory of contaminated sites, the Soil strategy (EC, 2021c) and the recent proposal for a Soil Monitoring and Resilience Directive (SML) (EC, 2023), formalized the ambition of the European Commission (EC) towards a harmonized soil information system, given the need to identify contaminated sites, to assess their impacts and to plan the restoration of soils. To do so, the SML provides a set of criteria on healthy soils and sets the ambition towards healthy soils in the EU by 2050. The SML approaches point source pollution (contaminated sites) and diffuse pollution differently, while on contaminated sites a risk-based approach is applied, for diffuse pollution the use of indicators is line with remaining indicators for soil health. On the former, SML regulates the identification, assessment, and

**Table 2**

Main sectors or activities (adapted from FAO, 2021) driving soil pollution, respective substances or group of substances targeted, and examples of latest studies addressing the topic.

Sector or activity	Substance or groups of substances	Examples of studies (last 5 years)
Industry and mining <sup>a</sup>	Metals and metalloids Organic substances (PAH, PCB) Total petroleum hydrocarbons (TPH)	(Baragaño et al., 2022; Dvořáček et al., 2019; Hombrecher et al., 2021; Ilić et al., 2020; Kim et al., 2017; Moghadasi et al., 2023; Sacchi et al., 2020)
Urban areas and transport	Metals and metalloids Organic substances (PCB, PAH, PFAS) Plastic (macro, micro, nano)	(Binner et al., 2023; Cicchella et al., 2020; De Silva et al., 2021; Kibblewhite, 2018; Leifheit et al., 2022; Meixner et al., 2020; Sager, 2020; Smolewska et al., n.d.; Stojic et al., 2017; Tešić et al., 2022; Wieczorek et al., 2020; Zanchi et al., 2022)
Agriculture	Metals and metalloids Pesticides Pharmaceuticals Antimicrobial resistance genes (ARGs) Plastic (macro, micro, nano) Organic substances (PFAS)	(Cycoń et al., 2019; D Zheng et al., 2022; Medyńska-Juraszek and Szczepańska, 2023; Qi et al., 2020; Röhler et al., 2021; Sacchi et al., 2020; Silva et al., 2019, 2023; Wieczorek et al., 2020; B. Zhao et al., 2023)
Hazards and military activities	Metals and metalloids Organic substances (PCB, PAH, PFAS) Radionuclides Explosives (RDX, TNT, HMX)	(Briard et al., 2023; Koban and Pfluger, 2023; Meusbürger et al., 2020; Ré et al., 2021; Williams and Rintoul-Hynes, 2022; Yang et al., 2023)

Note:

a) Industry and mining for active and historical facilities. Frequently associated to contaminated sites after terminating activity.

management of contaminated sites. On the later, identifies a list of metals and metalloids (As, Sb, Cd, Co, Cr(total), Cr(VI), Cu, Hg, Pb, Ni, Tl, V, Zn), leaving to MS the inclusion of any other substances, as well as the definition of thresholds for contamination. While limit values for concentrations of a range of metals in soil are available in the Sewage Sludge Directive 86/278/EEC, as well as for individual MS transpositions laws, the same is not true for many other substances.

The impact of soil pollution on soil health should be assessed by using meaningful indicators and reference values that define the current state of soils and the associated risks from pollutants (EEA, 2020). Reference values such as background levels (Kabata-Pendias, 2010; Lindsay, 1980; Taylor and McLennan, 1995), threshold values (MEF, 2007; Reimann et al., 2018) and screening values (Carlson, 2007) have been already reported to differentiate between geogenic (natural) and anthropogenic content of various pollutants in soils and to lay down those concentrations affecting human health, but not always in a clear way (Egle et al., 2023; Yunta et al., 2024). Moreover, the terminology used to define polluting substances has also varied with time, but recently a consensus may have been found with the use of the term Potentially Toxic Elements (PTE) (Pourret and Hursthouse, 2019; X. Xiao et al., 2020).

To provide insights on soil pollution in the EU, we provide an overview on (i) the most updated soil pollution assessments made at EU scale, and on the limit values emerging from these studies, followed up by the identification of (ii) the main anthropogenic drivers of soil pollution, and (iii) the impacts from soil pollution to human health and the environment. In a second stage we evaluate the current level of uncertainties and knowledge gaps surrounding the assessment and monitoring of soil pollution in the EU and identify solutions to tackle these through future research and policies.

## 2. Assessments at EU scale

Despite there is a common understanding of the impacts of soil pollution in the EU, comprehensive, large-scale assessments are scarce. Most of the data on soil pollution at EU scale originates from the various LUCAS surveys (Fernandes-Ugalde et al., 2021), while data collection from individual Member States, or specific regions/locations, is often obtained under different methodological approaches (e.g. French Soil Quality Monitoring Network, Jolivet et al., 2022) hampering harmonization and potential comparisons between MS. Nonetheless, it is possible to recognize a set of indicators emerging from field assessments on diffuse and point source pollution (Fig. 1). Those are indicators on metals resulting from LUCAS 2009 (Fig. 1a, Fig. 1b), pesticides residues incidence from LUCAS 2018 (Fig. 1c) and mine sites from Water and Planetary Health Analytics (WAPHA) georeferenced global database updated in 2022 (Fig. 1d).

The spatial distribution and identification of potential thresholds of cadmium, copper, mercury, and zinc in the European Union (EU) and UK topsoil has been assessed by using the soil samples from the LUCAS 2009 soil survey (Fig. 1a, Table 2). Among the identified drivers for metals diffuse pollution in these soils, are natural factors such as soil pH, clay content, topography, and also natural processes such as leaching and soil erosion (Ballabio et al., 2018, 2024; Van Eynde et al., 2023). As anthropogenic factors, phosphorus inputs to agricultural lands were identified as important variables explaining cadmium and zinc levels (Ballabio et al., 2024; Van Eynde et al., 2023). While for copper this includes fungicidal treatments, liquid manure application, sewage sludge application, atmospheric deposition, mining activities, local industrial contamination and particles from car brakes (Panagos et al., 2018). In the case of mercury, 42 % of the hot spots were associated with well-known mining and metallurgical activities (e.g. mining and smelting) while the rest can be related either to coal combustion industries, chlor-alkali plants, or local diffuse pollution activities such as small-scale industries employing mercury (Panagos et al., 2021).

Moreover, another analysis of metal concentrations (Cu, Hg, Zn, Cd, Ni, Pb, As, Cr) in EU agricultural soils (LUCAS 2009) was performed under the Sewage Sludge Directive 86/278/EEC limit values, resulting in 10 %, 36 % and 19 % samples exceeding the concentration of at least one single metal (Fig. 1b, Table 2). Such divergence was found depending on the legislative document used for each assessment, such as the directive, the national legislation, or if the most restrictive limit in the EU was used (Yunta et al., 2024). A recent report concluded that current sludge management is not fully aligned with current EU policy objectives, particularly on environmental and human health protection and circular economy (Egle et al., 2023; Yunta et al., 2024).

Notably, metals and metalloids data originated from LUCAS 2009 and GEMAS soil databases only allow to partially assess the soil pollution in Europe by determining the pseudo-total concentration of metals and metalloids among other physical and chemical properties of soils located in EU agricultural lands. These were the first assessment made in EU soils, and since then, the analysis to soil diffuse pollution by metals and metalloids have not been repeated. However, the LUCAS 2022 survey contemplates the analysis of both extractable and bioavailable fractions of metals and metalloids in the EU soils, by revisiting the same points of 2009. These complementary data will significantly improve the knowledge related to soil pollution in Europe and allow a more efficient risk assessment analysis.

Pesticides residues are commonly found in the agricultural soils (74.5 % samples), whereas most of the assessed sites (57.1 %) present mixtures of residues, distributed across crops and farming systems (Vieira et al., 2023). In organically managed soils, we find mostly persistent residues, many of which were banned under the Stockholm Convention on Persistent Organic Pollutants. In conventionally managed soils we see a mix of currently used compounds, in addition to recently and long-banned substances. Glyphosate, its main metabolite AMPA, and DDTs are usually the most frequent compounds in soils

**Table 1**  
Overall thresholds used for the EU soil pollution assessments available.

	Soil pollution descriptor	Spatial reference (resolution/nr. points)	Limit value, classification or methodology used in the assessment
<b>Diffuse</b>	Cadmium	Spatially explicit model (100 m)	$\geq 1 \text{ mg kg}^{-1}$ (Ballabio et al., 2024)
	Copper	Spatially explicit model (100 m)	$\geq 100 \text{ mg kg}^{-1}$ (Ballabio et al., 2018)
	Mercury	Spatially explicit model (100 m)	$\geq 500 \text{ } \mu\text{g kg}^{-1}$ (Ballabio et al., 2021)
	Zinc	Spatially explicit model (100 m)	$\geq 100 \text{ mg kg}^{-1}$ (Van Eynde et al., 2023)
	Metals and Metalloids under Sewage Sludge Directive	Point (n= 14.726)	Cu 50–140 $\text{mg kg}^{-1}$ (Yunta et al., 2024) Hg 1.0–1.5 $\text{mg kg}^{-1}$ (Yunta et al., 2024) Zn $\geq 150\text{--}300 \text{ mg kg}^{-1}$ (Yunta et al., 2024) Cd 1.0–3.0 $\text{mg kg}^{-1}$ (Yunta et al., 2024) Ni $\geq 30\text{--}75 \text{ mg kg}^{-1}$ (Yunta et al., 2024) Pb $\geq 50\text{--}300 \text{ mg kg}^{-1}$ (Yunta et al., 2024) As $\geq 25.5 \text{ mg kg}^{-1}$ (Yunta et al., 2024) Cr (total) $\geq 100 \text{ mg kg}^{-1}$ (Yunta et al., 2024)
	Pesticides	Point (n= 3.473)	Incidence class (Vieira et al., 2023) $\geq 1$ Ecotox Risk indicator (Franco et al., in, 2024) (Hudson-Edwards et al., 2023)
<b>Point source</b>	Mine's location	Point (n= 3.200)	(Hudson-Edwards et al., 2023)
	Contaminated Sites	National	LSI003 indicator (Payá Pérez and Rodríguez Eugenio, 2018)

(Geissen et al., 2021; Knuth et al., 2024; Riedo et al., 2021). Comparison with past assessments (Silva et al., 2019) indicate higher incidence of pesticide residues, and an increased toxicity risk in 2018 when compared to 2015 (Franco et al., 2024). In addition, the current assessment also identifies the active ingredients driving the risk (Franco et al., 2024). Including several substances among those (Imidacloprid, Chlorpyrifos, Epoxiconazole, Dimoxystrobin, Clothianidin, Cyproconazole, Fluquinconazole) that, after the sampling campaign, the Commission decided not to renew their approval as active substances under Regulation (EC) No 1107/2009.

On what contaminated sites are concerned, in 2016 more than 650,000 registered sites have been identified where present and past polluting activities take place, in national and regional inventories under the 'progress in the management of contaminated sites in Europe' indicator (LSI003). However, the registers seemed to represent only one quarter of the contaminated sites, since about 2.8 million sites are suspected to be potentially polluted the European Union Member States (Payá Pérez and Rodríguez Eugenio, 2018). Alternatively, other databases seemed to be able to contribute on point source pollution assessment as a result to the access to the global database on mine sites (Hudson-Edwards et al., 2023).

These assessments altogether provide a rough estimate of the extent of soil pollution in the EU, with more prominent focus being given to metals and pesticides residues found in agricultural lands, and to a lesser degree to the identification of contaminated sites. Importantly, these assessments also provide a relevant list of thresholds, classifications, and identification of risk methodologies (Table 1).

### 2.1. Soil pollution drivers

Contrary to large scale assessments, site-specific research studies identifying contaminants in single ecosystems are substantially more frequent, as shown by the number of publications hits (4851) in the Scopus database following the search (soil AND pollution AND Europe) for publication title, abstract, and keywords (10/01/2024).

Overall soil pollution studies identify sources from four main groups of activities (Table 2), industry and mining, urban areas and transport, agriculture, and hazards and military activities (Adapted from FAO, & UNEP, 2021). In our qualitative assessment made through the Scopus database, it was possible to observe a greater frequency of studies focused on metals when compared to any other substances. This observation goes in line with the global publication trends assessed by Xiao et al. (2023), whereas the scientific community seems to publish (2010–2023) more (53 %) on metals (e.g. Pb, Cd, Ni, As, Cu, Zn, Fe, Cr, Hg), followed then by organic pollutants (16.3 %) and microplastics (8.2 %). Should also be highlighted that in Xiao et al. (2023) study,

pollution in soil is significantly less represented (5.7 %), when compared to food (37.7 %), organisms (20.8 %), and water (18.9 %), but equally represented by the air (5.7 %) compartment.

However, and despite such studies target specific study sites, when combined my means of systematic reviews or meta-analysis they can represent an important contribution to the existing knowledge. An example of such, is the study of Binner et al. (2023) that managed to compile data on metal contamination from 143 urban sites and 29 European countries. Evidencing 40 % of urban sites with background levels metals exceedance, originated mostly from anthropogenic sources, such as industry, traffic, and coal combustion. In a global example, Xiao et al. (2020) managed to identify serious contamination of soils from current and past coal production industry in South Europe (among other regions).

In a lesser extent, studies targeting agricultural lands often target contamination by metals, pesticides, pharmaceuticals, plastics, or a mixture of substances in soils, as a result of various farming activities typologies (e.g. conventional, organic), sewage sludge application, or husbandry (Cusworth et al., 2024; Rodríguez et al., 2022). These studies often shorten the connection between pollution and human health, via food production and farmers working conditions (Silva et al., 2023). Among those are studies focused on pharmaceuticals release to soils, alongside with antimicrobial resistance bacteria and antimicrobial resistance genes that can be transferred from pathogenic to commensal bacteria. Despite the absence of defined pollution indicators or limit values, various researchers have published geospatial data identifying hotspot areas for antibiotic contamination (De la Torre et al., 2012) and antimicrobial resistance genes (Zheng et al., 2022).

In the case of plastic pollution in soils, should be highlighted that despite the elevated number of studies targeting agricultural land, the identification of soil pollution by plastics is not exclusive from agricultural areas (Pérez-Reverón et al., 2023). In fact, the presence of micro and nanoplastics in soils is also linked to plastic inputs (atmospheric deposition, runoff, and abandoned debris plastic) in non-agricultural soils, adding up to micro and nanoplastics (e.g. plastic mulching, irrigation water, sewage sludge, biosolids application) contents in agricultural soils (Pérez-Reverón et al., 2023). Notwithstanding, the increasing awareness given to plastic pollution triggered research focused on quantifiable indicators on plastic pollution (Rillig et al., 2024).

In a minor extent, some studies target soil pollution triggered by natural hazards such as fires or earthquakes, but also by military activities or wars. Examples are those on the radionuclides emitted by the atmospheric nuclear tests and the Chernobyl accident in 1986 that are found ubiquitously in soils across Europe (Meusburger et al., 2020). Other example is soil pollution resulting from fires due to the release of toxic compounds during combustion, not only in forest lands (Ré et al.,

2021) but also in urban areas (Briard et al., 2023), and industrial wastes or other brown field sites (Abraham et al., 2017).

## 2.2. Impacts on environment

More than 50 % of people in European countries live in cities (Eurostat, 2022), but all of them depend on the soil health status for food supply and a healthy environment. While the potential impacts of pollutants in soils ecosystem's services provision have also been highly investigated, a quantification of ecosystems services losses in function of the degree of soil degradation is still missing (Rinot et al., 2019).

Soil health -including soil pollution- has been identified as main key-factor for soil biodiversity decline (Gardi et al., 2013; Tibbett et al., 2020). Within the most studied pollutants, metals and metalloids in soils have been shown to affect soil microbial communities, impacting carbon cycling and storage (Azarbad et al., 2015). For instance, contamination by Pb can decrease richness and abundance of arbuscular mycorrhizal fungal communities (Faggioli et al., 2019), while ground beetles were found to indicate extreme soil metal pollution (Cd, Pb and Zn) via metal uptake (Tózsér et al., 2019). Several studies have found that collembolas (Gospodarek et al., 2021; Shafea et al., 2023) or arthropods (Tóth et al., 2023) present an adverse response to soil pollutants, and may be useful in assessing soil pollution or to monitor remediation progress (Gospodarek et al., 2021). Notwithstanding, soils located under naturally high pollutants levels (e.g. arsenic, cadmium, lead) should not be considered as presenting unhealthy condition or that such ecosystem services provision is degraded, unless a disruption of their natural equilibrium occurs.

Notably, soil pollution is not limited within the boundaries of contaminated soils, and therefore can create off-site impacts elsewhere by becoming a source of pollution for groundwater, fresh water and the

marine environment through their transport by leaching, surface runoff and soil erosion by wind and water (Vieira et al., 2023). This reduced ability of soils to filter contaminants in water have been described for metals and metalloids (Panagos et al., 2021), pesticides (Li and Fantke, 2022; Vieira et al., 2023), and for plastics (Rillig et al., 2024).

Moreover, pollutants can affect crop yields and accumulate in the food chain (Shafea et al., 2023), as also can change chemical and physical properties of soil (Shafea et al., 2023; de Souza Machado et al., 2018), interact with other pollutants present in soil (Chen et al., 2024), and degrade and transform into other substances (metabolites) with distinct toxic effect (Costello and Lee, 2020). Such shifts in the environment can have a meaningful impact on the whole system (van Bruggen et al., 2021), eventually impacting food security and human health through the food chain, despite the limited current knowledge (Perković et al., 2022).

## 2.3. Impacts on health

The ultimate objectives of EU environmental regulations are human health protection and the protection of ecosystems in a sustainable development logic. However, some EU regulations addressing pollution are more advanced, by being established for longer alongside with the implementation of monitoring systems (e.g. Emissions Directive, Water framework Directive), when compared to the ones related to soil (e.g. Sustainable Use of Pesticides Directive, EU Fertilising products Directive). It seems that the inexistence of an EU soil dedicated policy might have been limiting our capacity to prevent and mitigate soil pollution, as evidenced by the outcomes of the following scientific studies linking soil pollution to human health.

Living in areas with a higher concentration of metals and metalloids in soil were associated with all-cause cardiovascular diseases mortality,

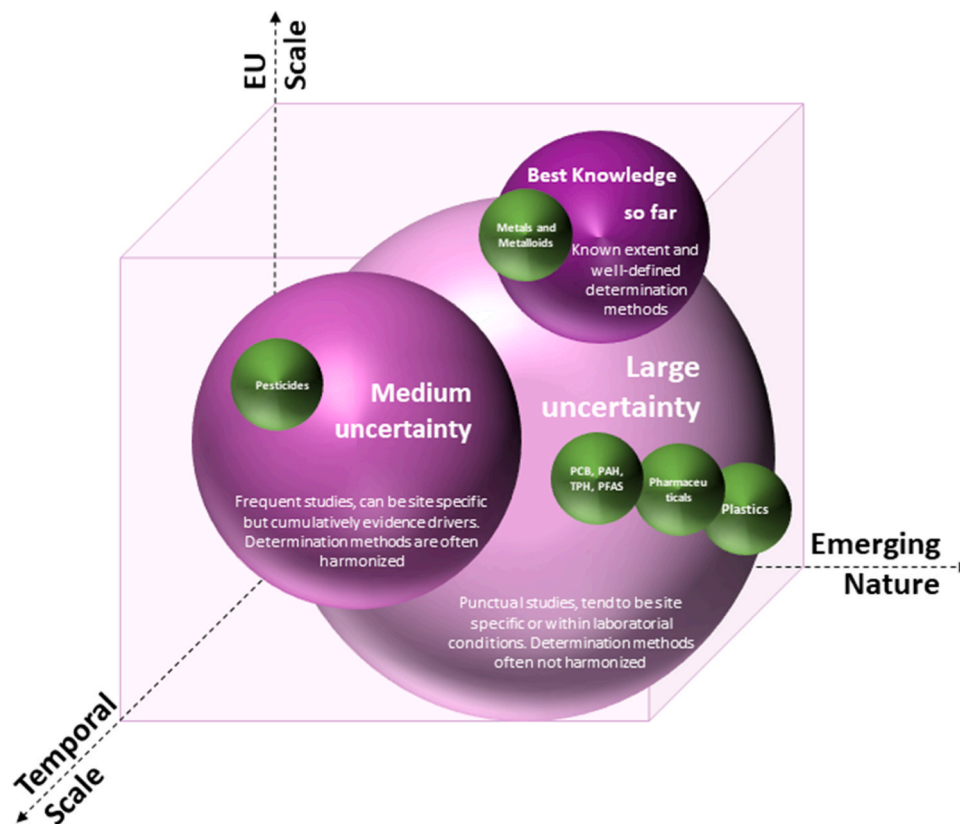


Fig. 2. Concept model for drivers of uncertainty in what concerns the extent (temporal and spatial scale) and the emerging nature of target substances in the EU. Classes of uncertainty are provided in purple, from best knowledge, to medium, and large uncertainty, while examples of substances in each class are provided in green.

Fields	Major gaps	Possible solutions
Scientific Knowledge	<ul style="list-style-type: none"> <li>- Lack of knowledge on individual substances, leads to uncertainties in the identification pathways to soil and interactions with soil properties.</li> <li>- Uncertainties affect residence, transport and fate of substances, limiting our perception of their toxicity, bioaccumulation, bioavailability, and the exposure and risk to humans and the environment.</li> <li>- Soils are often contaminated by several substances simultaneously, and very few is known regarding the combined effect of mixtures.</li> <li>- When defining reference values for soil health at EU scale, natural background pollution, variability of soils, as well as current ongoing pressures on soil should be considered.</li> <li>- Most studies assess soil pollution during short timeframes, leading to major uncertainties regarding to long-term impacts (Figure 2).</li> <li>- Impact assessment procedures do not include environmental exposures that an individual encounters throughout life (Exposome).</li> </ul>	<ul style="list-style-type: none"> <li>- Research and Innovation investment for knowledge development on contamination, transport and remediation of contaminated soils.</li> <li>- Research and Innovation I investment for novel determination and quantification methods.</li> <li>- More investment towards low-cost and nature based solutions, prioritizing substances or types of contamination with higher relevance according to monitoring results.</li> <li>- Create a network of field sites (e.g. lighthouses) to develop research on soil pollution remediation and integrate soil variability in this development.</li> <li>- Sharing information about soil pollution (open access) and increase the transparency is paramount for the development of solutions.</li> </ul>
Monitoring	<ul style="list-style-type: none"> <li>- Limited capacity to quantify and determine the level and spatial extent of various pollutants in EU soils, for both diffuse and point source pollution limits the development of knowledge and regulations. The lack of a harmonized inventory and impact assessment of contaminated sites across member states is an example.</li> <li>- Several Member States do not have an implemented soil monitoring system.</li> </ul>	<ul style="list-style-type: none"> <li>- Update and adopt novel methodologies with higher accuracy following knowledge development.</li> <li>- Monitor soil pollution in a harmonized way among MS, especially given the transboundary nature of pollution, whereas comparability is needed the most. Screening values (negligible, admissible, unacceptable) should include methodologies of determination.</li> <li>- Pollution should be considered a national priority, regardless of the existence of laws tackling this issue.</li> </ul>
Legislation	<ul style="list-style-type: none"> <li>- Legislation targeting soil is lacking. Currently, soil pollution is included in various regulations, resulting in a partial coverage of the problem.</li> <li>- Current regulations do not consider soil variability nor pedoclimatic conditions, which affect all EU regions in a different way. Current limit/thresholds values are often generic, and the transposition of the directives is generically done without national/regional soils characteristics.</li> <li>- Lack of a priority list for pollutants in soil, specifically addressing the emerging pollutants.</li> </ul>	<ul style="list-style-type: none"> <li>- Set up mandatory monitoring systems, SML as an example, more could be invested in soil pollution</li> <li>- The transposition process to MS laws could be used as an opportunity to fine tune limit values/thresholds according to national soil and pedoclimatic conditions.</li> <li>- Regulations on soil pollution should set up the same determination methodologies for the same parameters throughout MS.</li> <li>- Regulations on soil pollution should be updated following scientific evidences on methods, limits values and pollutants targeted (priority &amp; watch lists).</li> </ul>

Fig. 3. Major soil pollution gaps and possible solutions within Scientific Knowledge, Monitoring and Legislative fields.

the aetiology of some types of cancer, and increased probability of mental disorder (Ayuso-Álvarez et al., 2019, p. 20, Ayuso-Álvarez et al., 2022; Núñez et al., 2017). In another study, a preliminary analysis relating arsenic or cadmium, evidenced higher rates of lung cancer mortality in regions with high concentration of both metals in soil, when compared to regions with lower concentration (Bartnicka et al., 2023; Cusworth et al., 2024). Parviainen et al. (2022) have shown that higher carcinogenic risk due to As and Pb pollution in some locations was supported by the increased regional mortality rates, due to types of cancer normally associated with these pollutants.

Another example is the presence of pesticides residues in soil, which is often associated with lower soil biodiversity, with a more pronounced impact linked with the use of broad-spectrum and multiple substances (Beaumelle et al., 2023; Gunstone et al., 2021). Several pesticide residues are persistent in soil and toxicity to soil organisms may happen

even at recommended application rates (de Lima e Silva and Pelosi, 2024). Adverse effects may also result from the accumulation of pesticide residues in organisms, or via pesticide-driven alterations on habitat or ecosystem structure (Beaumelle et al., 2023; Morgado et al., 2018). Pesticides are also relevant for the human health dimension, being associated with neurological, carcinogenic, respiratory, reproductive, and endocrine effects, among others (Nicolopoulou-Stamati et al., 2016). Effects on humans are more likely due to occupational exposure, and via diet, while some with hazard-relevant classifications for humans, had been detected in homes near agricultural fields in ten European countries (Silva et al., 2023).

Should be emphasized that most of these studies refer to total or pseudototal concentration of pollutants in soil, and do not consider the bioavailable fraction that has the capacity to be incorporated and accumulate in the body (R. Zhao et al., 2020). Guillén et al. (2022) found

that As and Pb bioavailability fraction are mainly associated with high total concentration in soil, but the estimation of human health risks and exposure was more accurate with adjustment with site specific bioavailability and accessibility data. For example, soils with increasing Al and Fe (hydr)oxide contents show a decreasing As and Pb bioaccessibility (Lake et al., 2021), while Vasiluk et al. (2023) found that soil Ni bioaccessibility was significantly related to soil parameters such as SOC, Fe-oxides, and soil pH regardless of particle size or soil origin. Also Cachada et al. (2018) revealed that bioavailability of PAH to earthworms in Lisbon urban soils is linked to sequestration of PAHs due to various ageing processes.

As human exposure to soil and the environment is vast, there are many possibilities of assessment. The most common tools are the use of pollution indices e.g. enrichment factor, geoaccumulation index (Brtnický et al., 2019; Ferreira et al., 2022; Kowalska et al., 2018), human health risk assessments (Antoniadis et al., 2019) or bioavailability, bioaccessibility, and bioaccumulation tests. However, by only analysing the exposure characteristics of pollutants groups might not be sufficient to provide a comprehensive picture of the environmental exposome, i.e., human exposure to multiple pollutants to which an individual is subjected at different stages of life contributing to the occurrence and development of diseases. The exposome concept has been applied to the study of multifactorial diseases as allergies and cancer but it is in its infancy in the soil compartment (Ferrante et al., 2022; Haddad et al., 2019). As a result, current knowledge gaps on soil pollution limit current human health assessment accuracy, since exposure levels such as exposure time and variable environmental conditions also have an influence such analysis (Siemerling and Thiboldeaux, 2021).

#### 2.4. Knowledge gaps and policy status

Despite the numerous studies identifying and connecting soil pollution with impacts in human health and the environment, the few assessments made in soils at EU scale correspond mostly to the investigation of metals and pesticides residues in agricultural land, and to a lesser degree, the identification of potentially contaminated sites. Notwithstanding, the substances targeted in the various LUCAS soil surveys not only present less uncertainties regarding their extent, but are also in a better condition for a follow-up impact assessment and integration in a monitoring system when compared to other substances (Fig. 2).

On the opposite side, emerging contaminants and other substances opportunistically studied by the scientific community seem to have a long path ahead until their classification as a substance of concern (Fig. 2). One of the greatest obstacles found in the integration of emerging contaminants in ongoing monitoring systems is related with the lack of widely accepted determination methods (e.g. microplastics Editorial from Science of the Total Environment 912 (2024) 168465), and with it the associated risks in costs, comparability, and error determination. As an example, so far only a few studies have estimated the concentrations of microplastics in soils, whereas a large knowledge gap in the understanding of nanoplastic abundance is acknowledged (Pérez-Reverón et al., 2023). While the scientific community advances towards widely accepted methodology for the quantification of emerging pollutants in soils, it is of paramount importance to acknowledge determination uncertainties in scientific findings that get published in the meanwhile, for a trustable and clear knowledge transference to the policy makers and citizens (Howe et al., 2019).

Should be highlighted that in this perspective we are approaching uncertainties by comparing relative positioning of various substances, which does not mean necessarily we are close from achieving total knowledge on the substances assessed in LUCAS survey. In fact, there are several unaccounted processes just by the fact that LUCAS sampling is restricted to the topsoil 20 cm (now 30 cm for LUCAS 2022), while long-term assessments on soil pollution are also hardly found for diffuse pollution. Despite that, we believe that the steady progress and

development of the survey through time is in the right direction, by increasing complexity and detail in every new campaign.

Altogether, the never-ending list of substances known to pollute (estimated to be 350,000), together with emerging substances and those yet to be identified and quantified, can create an overwhelming effect among scientist and decision-makers when tackling this problem (Naidu et al., 2021). Which cumulatively with publication bias can limit the knowledge advancement of soil pollution. Either by not being able to exclude substances due to the reduced reporting and citation on no-effects (Hanson et al., 2018), or due to an amplifying impact of specific substances in comparison with other (Kepes et al., 2023; C.-H. Xiao et al., 2023).

Globally, although some pollution control measures exist already, these regulations may have not been adopted, nor updated, at the required rate to prevent chronic and acute effects on human health in the present, nor in coming decades (Naidu et al., 2021). At the EU level, should be highlighted that the existence of policies addressing any given environmental issue, often push the scientific community for knowledge development (Sienkiewicz, 2020). However, the EU large scale assessment on soil pollution mentioned in this perspective evidence that current policies have not been able to prevent pollution input pathways to soils. Having that said, the recent proposal on Soil Monitoring and Resilience Directive increases importance for soil pollution, not only because it will improve the current assessments on soil, but also will foster the scientific advances for indicators and limit values.

#### 2.5. Way forward

Until now, and despite the existent knowledge gaps (Fig. 3), the development of EU soil pollution knowledge have been mostly carved under large scale initiatives (e.g. GEMAS, LUCAS) (Panagos et al., 2022; Reimann et al., 2018). In fact, the data originated from LUCAS allowed to create the scientific base for the SML proposal, but also for a harmonized monitoring system among MS, in which LUCAS will contribute with 20 % of the sampling sites (EC, 2023). This will allow a significant development of soil knowledge via increasing data availability, but also by allowing LUCAS to continue performing pilot studies on novel soil health indicators.

For the future, LUCAS will keep assessing current and additional polluting substances every new campaign towards a watch list development. This approach is also applied to the development of determination methodologies, such as the quantification of mobile fractions of each metal and metalloid to be either uptake by crops or to be leached into the groundwater. Improving thus, the knowledge on the behaviour and reactivity of metals and metalloids in soils, but also allowing a more efficiently design in remediation strategies and sustainable soil management practices.

Despite EUSO and LUCAS push for knowledge development on soil pollution at EU level, various research teams are currently working and collaborating (e.g. Mission Soil) on the front-line research under this thematic (Fig. 3). However, we believe that additional funding could allow even further progress, by including soil pollution in MS research agendas. Addressing research gaps in fundamental research (e.g. investigation of contamination processes, determination methods), applied sciences (e.g. improving risk assessment, remediation techniques), but also on research for policy (e.g. definition of limit values), could improve local action (Table 1).

Besides the forthcoming developments expected under the SML, a more frequent and systematic update of the current legislation tackling pollution should be considered, ensuring a better follow-up of emerging pollutants (e.g. 3 new potential toxins per day (Naidu et al., 2021)).

Over the next years, we anticipate important dataflows (Soil Mission projects, LUCAS, EUSO) which will help us paving the way for better assessments on Soil Health in the EU. Among them, we should highlight the development of novel soil pollution assessments, inventory of contaminated sites, the prioritization of emerging contaminants and



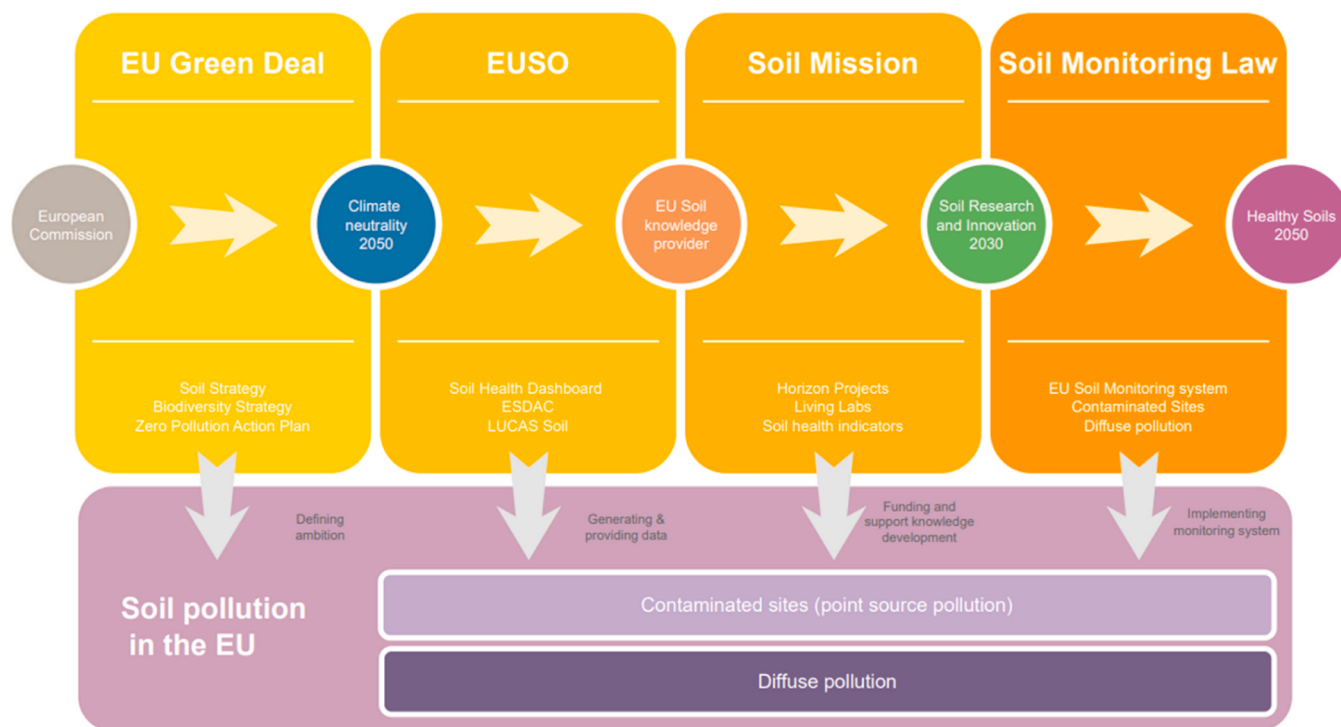


Fig. 4. Overview of main policy actions taken towards the accomplishment of healthy soils in EU by 2050, and specific input on Soil Pollution.

watchlist, and improved guidelines for ecosystems services restoration, supporting the implementation of the SML towards our Healthy soils ambitions by 2050 (Fig. 4).

#### Declaration of Competing Interest

The authors of this publication declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this perspective.

#### Data Availability

data used is already available.

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